AIEE ASSOCIAZIONE ITALIANA ECONOMISTI DELL'ENERGIA

the Italian Affiliate of the IAEE International Association for ENERGY ECONOMICS

in cooperation with

Interdepartmental Centre "Giorgio Levi Cases" for Energy Economics and Technology at University of Padova (Italy)

Conference Proceedings

Current and Future Challenges to Energy Security

Conference sponsors

EDISON

Conference Gold Sponsor

axpo

enel

ERG
EVOLVING ENERGIES

snam

UTILITALIA
imprese acqua ambiente energia

Patronages

MINISTERO DELL'AMBIENTE
E DELLA TUTELA DEL TERRITORIO E DEL MARE

Commissione europea

under the patronage of the European Parliament

ENEA
Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

Enerdata
intelligence + consulting

Comune di Padova

WORLD ENERGY COUNCIL ITALIA

Media partners

MARCO POLO EXPERIENCE
GLOBAL VIEWS & BUSINESS STRATEGIES

EPR COMUNICAZIONE

STAFFETTA QUOTIDIANA
DAL 1933 - QUOTIDIANO DELLE FONTI DI ENERGIA
www.staffettaonline.com

QUOTIDIANO ENERGIA
www.quotidianoenergia.it

nuova energia

AIEE ASSOCIAZIONE ITALIANA ECONOMISTI DELL'ENERGIA

the Italian Affiliate of the IAEE International Association for ENERGY ECONOMICS

8th AIEE Energy Symposium

Current and Future Challenges to Energy Security

– the energy crisis, the impact on the transition –

28-30 November 2024, Italy
conference organized with the scientific contribution of the Interdepartmental Centre "Giorgio Levi Cases" for Energy Economy and Technology at the University of Padua

Published by: AIEE - The Italian Association of Energy Economists, Rome, Italy

8h AIEE Energy Symposium - Current and Future Challenges to Energy Security - Executive Summaries.
international conference, 28-30 November, 2024, Italy.
Published 2024 by: The Italian Association of Energy Economists (AIEE), Rome , Italy

ISBN: 978-88-942781-8-7

The 8th AIEE Energy Symposium - Current and Future Challenges to Energy Security was organized by AIEE (Associazione Italiana Economisti dell'Energia) with the scientific contribution of the Interdepartmental Centre "Giorgio Levi Cases" for Energy Economy and Technology at the University of Padua
(www.aieesymposium.eu)

ACKNOWLEDGEMENTS

The editors and the publisher acknowledge the support of the following Sponsors of the **8th AIEE Energy Symposium on Current and Future Challenges to Energy Security**

Edison

(gold sponsor)

Axpo

Enel

ERG

Snam

UTILITALIA

Conference Patrons:

Conference Media Partners

ORGANIZATION

Conference General Chair:
MATTEO DI CASTELNUOVO**,** AIEE President, Professor SDA Bocconi University

Organization Committee Chair:
CARLO DI PRIMIO, AIEE Past President and Council Member, Italy

Scientific Committee co-Chairs:
ARTURO LORENZONI, Professor University of Padua, Italy
LUCIA VISCONTI PARISIO, Professor Bicocca University and AIEE Council Member, Italy

Programme Committee Chair:
CECILIA CAMPOREALE, Research scientist, Technical and Strategic Support Unit of Department for Sustainability (SSPT-STS), ENEA, Italy

Organization and coordination:
ANKA SERBU, Head of External Relations & Communication, AIEE

THE SCIENTIFIC COMMITTEE

Amela Ajanovic, Assiociated Professor, Vienna University of Technology, Austria
Massimo Beccarello, Associate Professor of Applied Economics, Biccoca University of Milan, Italy
François Benhmad, Associate Professor, University of Montpellier, France
Federico Boffa, Professor of Applied Economics Faculty of Economics and Management, Free University of Bolzano, Italy
Cecilia Camporeale, Research scientist, Technical and Strategic Support Unit of Department for Sustainability (SSPT-STS), ENEA, Italy
Pantelis Capros, Professor, E3MLab – Energy Economy Environment Modelling Lab, Greece
Çiğdem Çelik, Professor, İstanbul Okan University, Turkey
Leila Dagher, Associate Professor Lebanese American University, Lebanon
Edmar Luiz Fagundes de Almeida,Professor and Researcher Energy Institute (IEPUC) of the Catholic University of Rio de Janeiro – PUC-Rio, Brasil
Eric Delarue, Professor, KU Leuven Department of Mechanical Engineering, Belgium
Vittorio D'Ermo, Lecturer, Energy Consultant, Italy
Valeria Di Cosmo, Associate Professor, Department of Economics and Statistics "Cognetti de Martiis" University of Torino, Italy
Susanna Dorigoni, Professor Bicocca University, Italy
Paul Ekins, Professor of Resources and Environmental Policy UCL Institute for Sustainable Resources, U.K.
Angelo Facchini, Professor, IMT Scuola Alti Studi Lucca
Massimo Filippini, ETH Zurich and Università della Svizzera Italiana, Switzerland
Fulvio Fontini, Professor, University of Padova, Italy
Elena Fumagalli, Assistant Professor, Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands
Marzio Galeotti, Professor of Economics University of Milan Department of Environmental Science and Policy (ESP)
Antonio Geracitano, Adjunct Professor, University Tor Vergata, Italy
Angelica Gianfreda, Associate Professor, University of Padova
Monica Giulietti, Professor, Head of the Economics discipline group, Loughborough
Jean-Michel Glachant, Professor, Florence School of Regulation, European University Institute
Reinhard Haas, Professor, Technical University of Vienna, Austria

THE PROGRAMME COMMITTEE

CONFERENCE SECRETARIAT

Phone: +39.06.3227367 - e-mail: aiee@aieesymposium.eu; assaiee@aiee.it

INTRODUCTION:

CURRENT AND FUTURE CHELLENGES TO ENERGY SECURITY

– the energy crisis, the impact on the transition –

The AIEE - Italian Association of Energy Economists (Italian affiliate of the IAEE - The International Association for Energy Economics) has organized this international conference with the scientific cooperation of the Interdepartmental Centre "Giorgio Levi Cases" for Energy Economy and Technology of the University of Padua.

The previous editions of the AIEE Symposium on Energy Security, organized in Milan and Rome, and as virtual events during the pandemics, were an opportunity to explore new energy trends, challenges and creative solutions for the energy security, the availability of new technologies, the emergence of new market conditions and of new market operators.

This edition explored the emerging security challenges and opportunities resulting from global efforts to lower CO_2 emissions by reducing consumption of high-carbon energy sources, focusing on the impact of climate change on the global energy system considering both mitigation and adaptation actions and their possible impacts on the transition roadmap toward a decarbonisation system.

There is a strong link between energy policy and national security and the forthcoming dangers of climate change focused the attention on the international and national dimensions of the future of energy-security nexus.

Various interest groups, intergovernmental organizations, industry leaders, and security experts debate on energy security and although there is a wide consensus regarding the need to a net zero emission society, the points of view regarding the path of this transition are not always the same.

A boosting development of renewable energy sources is necessary to contrast the climate change, that together with the actions to accelerate the improvements in energy efficiency are two fundamental pillars of a win-win strategy to reduce energy bills, dependence on imported fuels and speed up reductions in greenhouse gas emissions. At the same time this will support the economy and the industrial sectors, with the creation of new job opportunities and a national industrial supply chain. However, there are also many critical challenges, including the energy crisis, inflationary pressures, availability of some critical raw materials.

The event was an opportunity to discuss all these issues and bring together prominent academic voices as well as experienced practitioners and policymakers, offering an opportunity to "bridge the gap" between these sectors.

CONTENT

PLENARY SESSIONS KEYNOTE SPEAKERS

Opening Session

Matteo Di Castelnuovo, Conference General Chair and AIEE President
Arturo Lorenzoni, Scientific Committee Chair, Professor of the University of Padua
Fabrizio Dughiero, Director of the Industrial Engineering Department, University of Padua

Keynote speakers:
Alessandro Blasi, Special Advisor to the Executive Director, International Energy Agency – IEA
Francesco La Camera, Director General IRENA

Grid security and energy storage

Chair: **Luca Magnanelli**, Head of Management Service of Axpo Servizi Produzione, Italy
Federico Gallo, Senior Consultant, En-creative, Italy
Giuseppe Cicerani, Head of BD Energy Storage, Enel, Italy
Daniele Castiglia, Head of Front Office – Energy Management & Sales DPT, ERG, Italy

Renewable energy, clean energy technologies and critical raw materials

Chair **Georg Erdmann**, Professor, Institute for Energy Technology, Berlin University of Technology, Germany
Alberto Pasanisi, Director Research Development & Technological Innovation, Edison, Italy
Ionut Purica, Professor Hyperion University, Member Academy of Romanian Scientists, Romania
Fereidoon Sioshansi, President Menlo Energies, USA

The energy security concerns in an ever-changing geopolitical context: The EU strategy

Chair: **Patrizia Marin**, Chairman, Marco Polo Experience. Professor of International Relations IULM University, UAE
Maël Gouret, Energy Analyst CleanTech of Enerdata, France
Gabriele Marchionna, Cyber Strategy & Technology Advisor Tech Geopolitics & Security Researcher,Italy
Adnan Shihab-Eldin, Research Associate at the Oxford Institute for Energy Studies

Regulatory challenges for the electricity markets in a renewable-based energy system: the EU new market design

Chair: **Jean Michel Glachant**, Professor EUI Florence School of Regulation, IAEE Past President
Derek Bunn, Professor of Decision Sciences, Management Science and Operations London
Giordano Colarullo, Director General, Utilitalia, Italy
Fulvio Fontini, Università del Salento, ItalySilvia Piana, Head of Regulatory Synergies and Strategies, Enel, Italy

The gas role in the transition: natural gas, hydrogen and other renewable gases

Chair: **Carlo Di Primio**, AIEE Past President and Managing Partner Horus Green Energy Investment, Italy
Umberto Berzero, Senior Manager Market Analysis and Energy Scenarios, Snam, Italy
Carlo Andrea Bollino, Professor LUISS University, Italy
Guido Bortoni, President CESI, Italy
Reinhard Haas, Professor TU Wien, Austria
Andrea Qualiano, Head of Green Gas Origination & Gas Supply Portfolio Decarbonization, Edison, Italy

Sustainable mobility challenges for the transition targets

Chair: **Gabriele Gre**a, Expert Fellow at the Department of Institutional Analysis and Public Management, Bocconi University, lecturer in Urban Mobility
Amela Ajanovic, Assistant Professor & Senior Research Scientist, Energy Economics Group, Vienna University of Technology, Austria
Franco Del Manso, International Environment Affairs manager of UNEM – Unione Energie per la Mobilità, Italy
Gabriele Grea, Expert Fellow at the Department of Institutional Analysis and Public Management, Bocconi University, lecturer in Urban Mobility

CONTENTS

ABSTRACTS INDEX - by session

PAPERS INDEX - by Session

Abstracts

Agatino Nicita, Gaetano Squadrito and Gaetano Maggio

HYDROGEN-BASED TECHNOLOGIES: LIMITS AND POTENTIALS OF LIFE-CYCLE COST APPROACHES

Agatino Nicita, Technologist CNR–ITAE Via Salita S. Lucia sopra Contesse 5, 98126 Messina (ME)
Gaetano Squadrito, Researcher CNR–ITAE Via Salita S. Lucia sopra Contesse 5, 98126 Messina (ME)
Gaetano Maggio, Researcher CNR–ITAEVia Salita S. Lucia sopra Contesse 5, 98126 Messina (ME)

Overview

Hydrogen is considered to be one of the most promising energy carriers to satisfy the energy requirements of the world and reduce the impact of carbon emissions on environment and global warming [1].
The growing interest on hydrogen economy is testified by the plans of the European Union which include hydrogen as a clean energy source. In fact, the EU ambitious objective is to produce green hydrogen by installing at least 40 GW of water electrolysis plants by 2030 [2].
Besides, life-cycle cost (LCC) approaches are a powerful tool to understand the economic sustainability of the existing or under-development hydrogen-based technologies and the potential key role of hydrogen.
Based on these considerations, we believe that a comprehensive and systematic review on the use of LCC applied to hydrogen technologies is timely and opportune, since this covers a lack of current literature. In particular, our objective is to analyse the evolution of these studies in the decade from 2012 to 2021, to elucidate limits, strengths, common aspects and differences of the approaches.
Some details of the present study have been previously published in Ref. [3].

Methods

To identify relevant studies of interest for our review we used the SCOPUS database owned by Elsevier. It has a broad coverage of peer-reviewed literature, covering a total of 43,400 titles from approximately 13,400 publishers [4].
The criteria adopted for the identification of pertinent documents included in the search string the term "life cycle cost" (and variants) combined with the words "hydrogen", "electrolyzer" and "fuel cell". We searched for inclusion of these terms in either the title, abstract or keywords of the papers. Besides, the search was limited to articles and reviews published between 2012 and 2021. In particular, this timeframe was chosen because we realized that older studies present just some rough cost estimations, but they cannot be considered as rigorous LCC studies.
The search in SCOPUS was performed on 18 November 2022 and allowed us to preliminarily identify 170 documents in the mentioned period (2012-2021). The final selection was made by adopting some inclusion/exclusion criteria. On this purpose, a screening was made by reading the title and abstract of the papers, which allowed us to select 74 papers. In particular, more than 40 papers were excluded since the acronym LCC refers to a variety of things: "lignin-cellulose composite", "lignin-carbohydrate complex", "lanthanum calcium chromite", "layered corrugated carbon", "linear carbon chain", etc. Articles written in languages other than English and/or not accessible through our institutional repository (4) were also excluded. Finally, some studies (3) were excluded after reading the full text, because they just mention LCC but do not perform a life-cycle cost analysis. Therefore, after applying inclusion/exclusion criteria, a total of 67 papers published in the mentioned timeframe (2012-2021) have been selected for our review.

Results

The 67 selected papers have been analysed to derive both non-content-related (descriptive) and content-related (qualitative) information.

Main results can be summarised as follows:

- The number of LCC studies applied to hydrogen technologies has increased in the period investigated.
- China is the leading country for number of publications on the subject.
- Fuel cells and/or electrolysers based on proton exchange membranes (PEM) are the most studied technologies.
- Cradle-to-consumer is the prevalent system boundary approach.
- Almost all the studies included initial, operation and maintenance costs; while other costs (replacement, external, end-of-life) are only included in a limited number of them.
- Net present value (NPV) is the most used financial tool.

In particular, the increasing number of LCC studies for hydrogen-based technologies in the decade 2012-2021 – passing from 2-3 papers in 2012-2015 to 14 papers in 2021 – clearly evidenced a growing interest in the topic. Besides, one can imagine that this increasing trend will be also confirmed in recent years. For instance – extending the same search criteria to 2022 and 2023, and assuming the same percentage of relevant LCC studies (about 40%) – we roughly estimated a number of papers equal to 17 for 2022, and 29 for 2023.

We also noticed that about 52% of the studies (35 papers) received a financial support, and the top funder institution is the National Natural Science Foundation of China (9 papers).

Content-related information were derived from full-text reading. Our analysis revealed a lack of information about the typology of fuel cells and/or electrolysers included in the LCC studies. In fact, almost a third of the reviewed papers (21) did not mention them. The remaining papers, as above evidenced, are focused on systems based on polymer electrolyte membrane (PEM): 21 papers included PEM fuel cells, and 12 papers included PEM electrolysers. This can be related to the maturity and advantages of these technologies compared to the alternatives (e.g., PEM electrolysers are currently more expensive than alkaline ones, but they can operate at higher current density, have higher hydrogen purity, are more efficient, more compact and easier to be integrated with variable/intermittent power sources like renewables). In some papers (15), hydrogen production technologies different from water electrolysis (e.g., steam methane reforming, dark-fermentation and/or anaerobic digestion of biomass or waste) are included in the LCC analysis. Over half (51%) of the selected papers included some hydrogen storage system (compressed gas, cryogenic liquid, metal hydride, etc.) in the LCC analysis. About 27% of the reviewed papers (18) included hydrogen distribution in the LCC approach. The majority of the papers (28) are devoted to stationary applications.

As concerns the characteristics of the LCC approaches, once again we observed a lack of information and uniformity, as a consequence of the limited adoption of LCA or LCC standards (only 7 papers). Conventional life-cycle cost (CLCC) is the predominant approach (53 papers), followed by environmental life-cycle costs (11 papers), and a very limited number of social life-cycle costs (3 papers). Even if some papers (15) integrated LCC with LCA approaches, in most cases the life-cycle cost has just a complementary role. In addition, as already evidenced in the literature [5], LCA and LCC can lead to opposite conclusions, because environmental sustainability is not always associated with economic sustainability and vice versa. In particular, for hydrogen-based technologies the economic aspects are often a critical concern.

Cradle-to-consumer was the most widely used system boundary approach (37 papers), followed by cradle-to-grave (15 papers), cradle-to-farm gate (8 papers), and cradle-to-cradle (3 papers). The preference for cradle-to-consumer approach can be interpreted as a compromise between an inadequate description of the systems provided by the cradle-to-farm gate approach, and the complexity of the approaches which include more stages of the life-cycle.

The life span used for the determination of life-cycle costs ranges from 3 to 40 years, with a majority of studies which assumed 20 years. This is again a compromise between short time horizons not allowing economic benefits, and long ones that require evaluation of critical costs and could make the estimate unrealistic or unattractive for potential investors that demand for a relatively brief return on investment.

As already mentioned, the net present value (NPV) is the most used financial tool (25 papers), but in general there is a lack of information in the use of functional units and financial tools.

Conclusions

LCC analysis for application to hydrogen technologies has gained interest in recent years. However, the number of studies that explicitly follow LCC or LCA guidelines is very limited (only 7). The life-cycle cost analyses performed are quite incomplete in terms of costs included in the life-cycle stages. Besides, there is a lack of information and uniformity, which is often related to the limited adoption of standard guidelines.
Based on the findings of our investigation, we suggest some recommendations for a more comprehensive LCC analysis of hydrogen technologies and to facilitate comparison among similar studies. In particular, further studies should: have greater adherence to standard methodologies, prefer the adoption of approaches covering the whole life-cycle stages (cradle-to-grave, or cradle-to-cradle), use various financial tools to complement LCC analyses, and promote uniformity on the use of functional units and financial tools.

References

[1] Demirbas, A. (2017), Future hydrogen economy and policy, Energy Sources, Part B: Economics, Planning, and Policy 12(2):172-181.

[2] European Commission (2023), How the EU supports hydrogen research, funded projects, related policies and initiatives. Available at: https://research-and-innovation.ec.europa.eu/research-area/energy/hydrogen_en

[3] Nicita, A., Squadrito, G., and Maggio, G. (2024), Life-cycle cost (LCC) applied to hydrogen technologies: A review, The International Journal of Life Cycle Assessment 29(1):46-79.

[4] ELSEVIER (2023), Source title list (extlistFebruary2023.xlsx). Available download at: https://www.elsevier.com/products/scopus/content

[5] Peña, A., Rovira-Val, M.R (2020), A longitudinal literature review of life cycle costing applied to urban agriculture, The International Journal of Life Cycle Assessment 25(8):1418-1435.

Sukriti Sharma, Pragya Singh and Asad. H. Sahir

TECHNO-ECONOMICS AND PROCESS ENGINEERING ANALYSIS OF INTRODUCING HYDROGEN IN NATURAL GAS PIPELINE INFRASTRUCTURE: A CASE STUDY FOR NEW DELHI, INDIA

Sukriti Sharma: Department of Chemical Engineering, Indian Institute of Technology Ropar, Rupnagar, India, 140001
Pragya Singh: Department of Chemical Engineering, Indian Institute of Technology Ropar, Rupnagar, India, 140001
Asad H. Sahir: Department of Chemical Engineering, Indian Institute of Technology Ropar, Rupnagar, India, 14000

Overview

Global warming and climate change require and demand scientists and engineers to devise solutions for their immediate addressal. Hydrogen fuel is an efficient, clean, secure, affordable, and versatile form of energy. According to the International Energy Agency (IEA), the demand for hydrogen will rise fivefold to 500-680 million metric tonnes (MT) by 2050 globally. Currently, nearly 90% of the hydrogen consumed in India comes from fossil fuels and is categorized as black and gray hydrogen. Supplementary to this, hydrogen produced from renewable sources is called "green hydrogen." The momentum of hydrogen technologies is accelerating, with different production pathways focused prominently on renewable sources like water electrolysis, wind energy, and solar energy. In the race to develop clean energy systems, hydrogen production pathways are enjoying unprecedented momentum with full support from the government.

India is the 4th largest consumer of energy in the world after the USA, China, and Russia. However, India is not endowed with abundant energy resources. One of the major challenges faced by India is meeting its energy needs while achieving 8% economic growth and also meeting the energy requirements of its population (which is the world's second-largest, at affordable prices). It requires a sustained effort to increase energy efficiency while increasing domestic production, especially in clean energy systems. Hydrogen is considered the most promising energy carrier and is reckoned to be a supplement for natural gas in the future. Hence, it is imperative to study the economic production of hydrogen, delivery infrastructure, and storage options from a country-specific point of view. In its efforts to develop a sustainable economy, India is looking at a variety of renewable energy sources, with hydrogen standing out as a promising fuel for the transportation industry. However, using hydrogen as a fuel in an urban environment presents several difficulties that must be recognized and resolved. Through a combination of first principles engineering optimization and techno-economic analysis, this study seeks to comprehend the integration of hydrogen into the current energy infrastructure.

This research proposes techno-economics and engineering insights into the existing natural gas pipeline network between the Dadri-Bawana-Nangal region for hydrogen blending. The pipeline spans 900 km and traverses Delhi, Punjab, Uttarakhand, and Uttar Pradesh states of India and also serves Delhi metropolitan area and major airports.

The DWSIM model and HDSAM (Hydrogen Delivery Scenario Analysis Model) developed by the US Department of Energy are among the primary tools presented in this research for analyzing the cost of transferring hydrogen from a central production site to a fueling station. The study aims to highlight the difficulties in implementing hydrogen as a fuel for transportation in an Indian city. It also provides knowledge that could help urban planners and building scientists work toward a sustainable future. One of the key aspects of this research is determining the optimal interstage pressures to minimise compressor work and enhance energy efficiency. By optimising interstage pressures using a steady-state simulator e.g. DWSIM, the study aims to reduce the energy required for compression, thereby lowering operational costs and improving the overall efficiency of the pipeline system.

Methodology

A comprehensive model for natural gas-hydrogen blending pipelines using a multi-software engineering approach, specifically targeting the Dadri-Bawana-Nangal region has been developed. The methodology is structured around four key components:

1. **Fundamental Pipeline Modeling**: This section involves steady-state, non-isothermal modeling of natural gas-hydrogen pipelines with a 20% hydrogen blend. The pipeline model focuses on a section with a length of 180 km. The initial pressure is set at 85 bar. Utilizing a steady-state, non-isothermal model, the pressure drop along the pipeline has been calculated.

2. **Optimization and Compressor System Development:** This section focuses on optimizing and designing effective compressor systems to enhance performance and efficiency. The system under various scenarios, including single-stage, two-stage, and three-stage compression systems, has been modelled using optimization techniques in MATLAB. The results from these models are then integrated into DWSIM for process design simulation. This simulation helps in determining the minimum energy consumption required for compressing natural gas-hydrogen blends effectively.

3. **Energy Efficiency Calculations for Compressors** - The section demonstrates the role of energy efficiency in compression. This section involves designing and simulating the pipeline processes to gain insights into the energy generated by the compressor systems and overall system performance.

4. **Techno-Economic Analysis:** This section assesses the economic feasibility and technical aspects of hydrogen pipelines, evaluating cost, efficiency, and economic impacts. In our study, we have also utilized the Hydrogen Delivery Scenario Analysis Model (HDSAM). The study aims to highlight the difficulties in implementing hydrogen as a fuel for transportation in an Indian city. It also provides knowledge that could help urban planners and building scientists work toward a sustainable future.

Results

The results demonstrated are based on the assumptions for the low-carbon scenario analysis for road transportation in New Delhi. The analysis is concentrated around the National Capital Territory (NCT Delhi). The city area is 573 square miles. The hydrogen market is urban and the population data is taken from the census of India. Figure 1 shows the delivery cost of hydrogen in New Delhi at the present year at 10% market penetration. The cost parameters are determined for 3 scenarios, viz., cost of gaseous hydrogen with pipelines as the transmission and distribution medium, cost of gaseous hydrogen with tube trailers as the transmission and distribution medium, and cost of liquid hydrogen from delivery and transmission by trucks. The cost is highest when the refuelling station capacity and the desired dispensing rate is 100 kg/day and it goes on decreasing when the demand is increased to 2000 kg/day. In Figure 2 and Figure 3 show the cost of hydrogen when the market penetration is increased to 50% and 75%, respectively. The delivery cost of both liquid and gaseous hydrogen is estimated to be between $2-5 per kg when the dispensing rate is highest and market penetration is the highest. From the analysis of New Delhi, it can be concluded that market penetration does not play a significant role in determining the delivery cost of hydrogen, but it is the desired dispensing rate that plays a major role in determining the delivery cost. Figure 4 shows the difference between the cost of gaseous hydrogen and the cost of liquid hydrogen for New Delhi. It can be concluded that for the low refueling station capacity of 100 kg/day, there is a significant difference between the cost of gaseous and liquid hydrogen. However, when the capacity is increased, the cost comes down between $2 and $4 per kg. With a high market penetration rate and high refueling station capacity, the cost of hydrogen is at par with the cost of conventional fuels like natural gas.

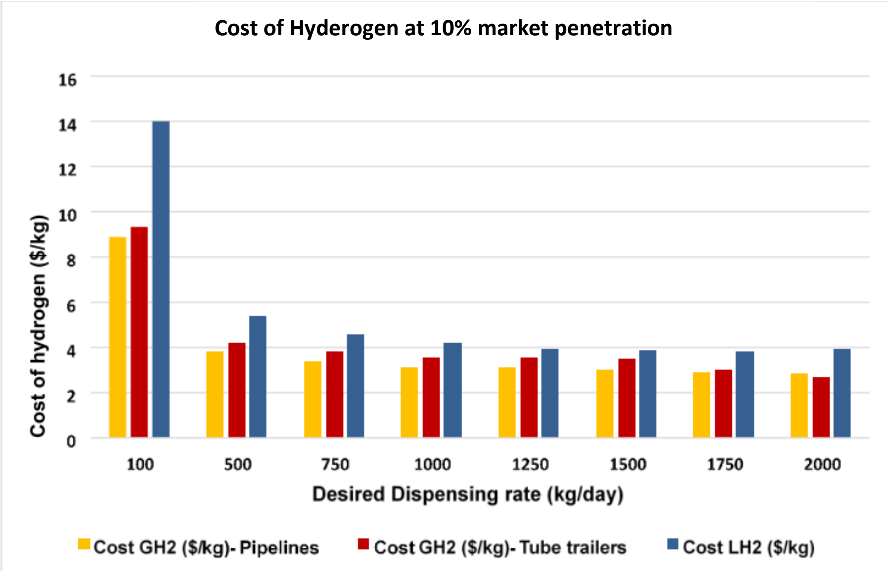


Figure 1*: Delivery cost of hydrogen at 10% market penetration*

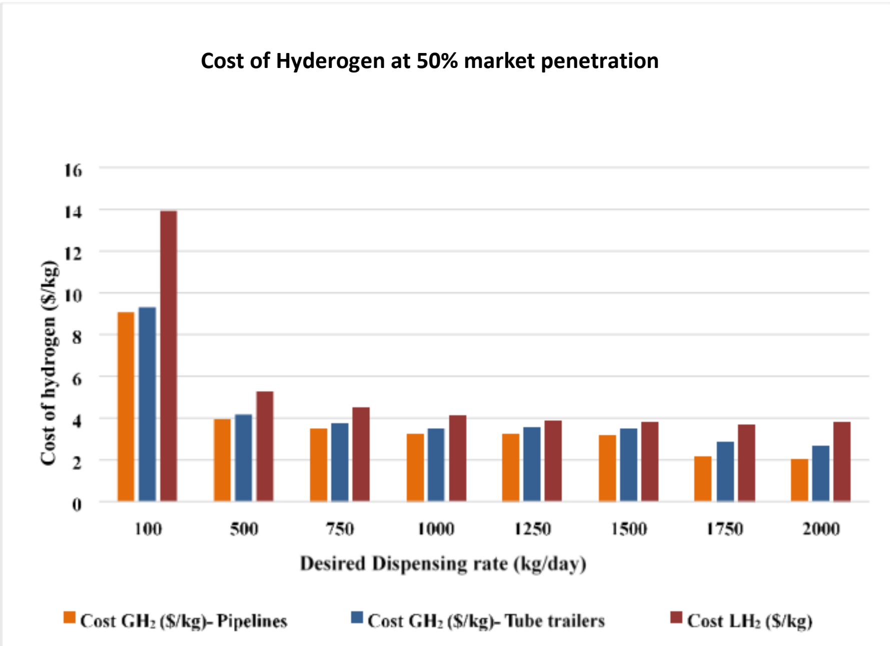


Figure 2*: Delivery cost of hydrogen at 50% marketpenetration*

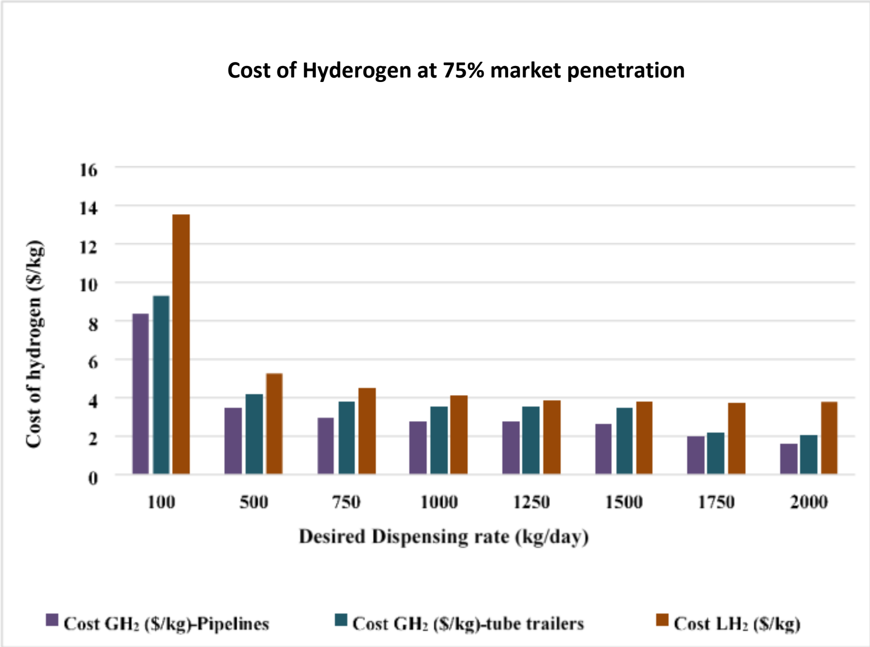


***Figure 3**: Delivery cost of hydrogen at 75% market penetration*

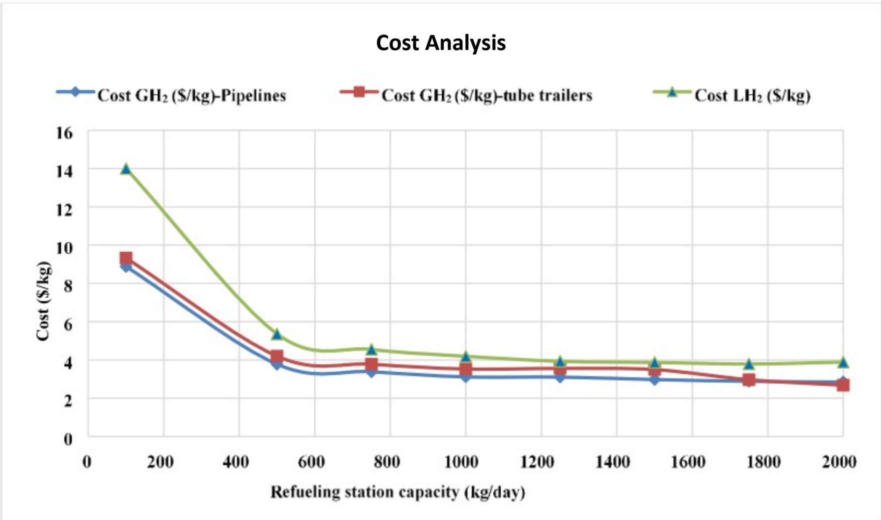


***Figure 4** : Delivery cost of liquid and gaseous hydrogen*

Conclusions

The initial DWSIM modeling results indicate that although multi-stage compression reduces the power needed per stage by enhancing thermodynamic efficiency, it slightly increases the total power required due to additional inefficiencies. The strategic use of multi-stage compressors helps maintain consistent pressure throughout the pipeline, ensuring efficient and reliable operation of the system.

The modeling of 900 km natural gas-hydrogen pipeline demonstrates the importance of understanding pressure dynamics and temperature variations for developing a pipeline network. With an initial pressure of 85 bar and a calculated outlet pressure of 72 bar, maintaining optimal pressure levels is critical for pipeline efficiency. Temperature variations, influenced by external soil conditions (30°C) and inlet temperatures (42.5°C), highlight the importance of effective thermal management in pipeline design. The integration of optimized compression system results into DWSIM simulations demonstrates a methodical approach to minimizing energy consumption. For the Indian hydrogen industry, this approach is crucial for achieving cost-effective and energy-efficient compressor designs. Lower energy usage translates to reduced operational costs and improved economic feasibility, aligning with the industry's goal for a sustainable energy future. These include cost analysis and sustainability benefits for designing a hydrogen pipeline infrastructure in the Dadri-Bawana-Nangal region serving key metropolitan regions and airports where hydrogen can be utilized directly. By focusing on energy-efficient systems and reducing operational costs, the study aligns with sustainability goals and helps industrial partners make informed decisions about hydrogen infrastructure investments. In the context of urbanization and its planning, this analysis is a first step in planning leveraging the gas distribution network for hydrogen. An early adoption of these models in planning the urban infrastructure for hydrogen fuel distribution shall be of immense value in the Indian context.

References

Sharma, S., Chauhan, B., Sahir, A. (2024). Analysis of Hydrogen Delivery Costs: PEM Electrolysis as a Case Study for India. In Proceedings of Energise 2023- Lifestyle, Energy Efficiency, and Climate Action, pp 226-233, Alliance for an Energy Efficient Economy. https://doi.org/10.62576/YXYU9665

Mauro Giorgianni, Agatino Nicita, Gaetano Maggio and Stefano Trocino

ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY OF A PHOTOELECTROLYSIS CELL FOR HYDROGEN PRODUCTION

Mauro Giorgianni, Researcher CNR – ITAE, Via S. Lucia Sopra Contesse, 5, 98126 Messina (ME)
Agatino Nicita, Technologist CNR – ITAE, Via S. Lucia Sopra Contesse, 5, 98126 Messina (ME)
Gaetano Maggio, Researcher CNR - ITAE, Via S. Lucia Sopra Contesse, 5, 98126 Messina (ME)
tefano Trocino, Researcher CNR - ITAE, Via S. Lucia Sopra Contesse, 5, 98126 Messina (ME)

Overview

This work includes the first results of research carried out within the framework of the "Piano Triennale di realizzazione 2022-2024 della Ricerca di Sistema Elettrico Nazionale" programme, funded by the Italian Ministry for the Environment and Energy Security. It consists of an Environmental LCC (eLCC) [1] analysis of a novel photoelectrolysis cell.
Calculations were performed on a laboratory prototype cell of 10 cm^2 and scaled up to a commercial cell of 80 cm2. The analysis included the calculation of capital expenditure (CAPEX), such as the purchase of equipment, and operating expenditures (OPEX). In particular, based on an approach already used in the literature [2], the Net Present Value (NPV) was calculated to assess the economic viability of the investment.To economically evaluate the cost of externalities, and thus monetise the environmental impact, reference was made to the calculation methods of the Intergovernmental Panel on Climate Change (IPCC) through the 'EVR' and 'Environmental Price' of emissions using the IDEMAT 2023 tool (Industrial Design & Engineering MATerials database) [3].

Methods

In order to quantify the environmental impacts of the project's raw materials and processes, it was decided to establish the boundary by analysing the "Cradle to Gate" life cycle, defining Carbon Footprint and Total-Eco-Costs as impact categories over 20 years. Two different European models were used to estimate the impacts of externalities in economic terms:
- The first method is called 'EVR - Eco Costs value ratio', and expresses the environmental impact in economic cost by measuring the cost of preventing a specific amount of environmental damage [4].
- The second method is called 'Environmental Prices' (EP), and expresses the willingness to pay for less pollution in euros per kilogram of pollutant; developed by the Dutch research and consultancy company CE Delft in 2018 and applicable to the European territory [5].

The steps followed in adopting the two methods are described below:

1) The input materials used within the project for the production of a single cell were determined and quantified (in g/cm^2).
2) Subsequently, the materials (referring, in some cases, to equivalent materials) present in the Idemat 2023 database were searched and transcribed, reporting the value of the impacts (in €/kg).
3) Similarly, for the same materials, the corresponding carbon footprint values were reported (in kg CO_2 eq.)
4) The quantity of material (in kg/cm2) was multiplied by the cell size (e.g. 80 cm^2) to obtain the quantity of each individual material within a cell (kg).
5) The quantity of material in the individual cell was multiplied by its environmental impact (in €) to obtain the total eco cost of the materials used per individual cell

6) Finally, the value of the 'environmental cost' (in €/kgCO_2eq.) of the individual element, corresponding to both the EVR and EP methods, was multiplied by its carbon footprint (in kg CO_2 eq.), so as to obtain the total value of the environmental cost (in €) for the production of the cell, according to two different indicators:
   a) climate change eco-costs;
   b) climate change Environmental Price.

In order to determine the overall cost and affordability of the investment in a semi-craft process, the NPV was calculated, i.e. the discounted value at a discount rate, of all cash flows (negative and positive) generated over the life of the project.

The following formula was used to determine the NPV:

$$\text{NPV} = -CAPEX + (1 - TR) \sum_{n=1}^{N} \frac{REV_n - OPEX_n}{(1+r)^n}$$

where CAPEX is the initial investment cost, TR (*tax rate*) is the tax rate on profits, REV_n (*revenues*) are the annual profits obtained from the project, $OPEX_n$ are the operating costs (fixed and variable) at time *n*, e *r* (*rate*) is the discount rate.

Results

From the study conducted, in absolute value, the most polluting materials in terms of 'Total Eco costs' are the compounds containing Nickel and Titanium (Fe_2O_3+Ti+P, NiFeOx, NiCu), but their use within the project is of minimal quantities, thus resulting in a very low incidence. The quantity that, relative to the project, has the greatest weight in terms of 'total eco costs' is electricity, which accounts for 54% of the total. The second material is polyvinyldenfluoride, which represents 34% of the total. The lowest is distilled water, which contributes a negligible 0.002%.
Using as an indicator the Carbon Footprint, both with the EP (Environmental price) and Eco costs method, the value that has a greater incidence on the environmental costs of the project is always the electric energy in both cases with an incidence percentage of about 60%. The second is also unchanged, in fact Polyvinyldenfluoride, in both cases has an incidence percentage of about 25%, while the value that has a lower incidence is NiCu (about 0.001%).
The analysis assumed a semi-artisanal production, with production volumes not exceeding 4,000 units per year. The target market is not only industry, but also research institutions that commission cells for experiments. The NPV calculation showed that the break-even point was reached within 8 years.

Conclusions

Despite the low level of technology readiness, the study simulated a real production and commercialisation process.

The following study assessed the possibility of considering externalities as costs affecting the production value of the photoelectrolysis cell. So these are the maximum percentages of the cell's production costs, considering the highest environmental impact (Total Eco Costs):

• OPEX 91.88%
• CAPEX 7.98%
• External Costs (Total Eco Costs) 0.14%

Therefore, on the basis of this analysis, we can define the product and production process under investigation as virtuous and sustainable in terms of environmental impact, an investment with a good return potential in purely economic terms.

References

[1] D. Hunkeler, K. Lichtenvort, G. Rebitzer, 2008. Environmental Life Cycle Costing. CRC Press.
[2] A. Nicita, G. Maggio, A.P.F. Andaloro, G. Squadrito, Green hydrogen as feedstock: financial analysis of a photovoltaic-powered electrolysis plant, Int. J. Hydrogen Energy 45 (20) (2020) 11395-11408.
[3] Sustainability Impact Metrics. A spin-off of the Delft University of Technology . https://www.ecocostsvalue.com/ecocosts/
[4] J.G. Vogtländer, H.C. Brezet, C.F. Hendriks, The virtual eco-costs '99 A single LCA-based indicator for sustainability and the eco-costs-value ratio (EVR) model for economic allocation. Int. J. Life Cycle Assess. 2001, 6, 157–166.
[5] S. De Bruyn, M. Bijleveld, L. de Graaff, E. Schep, A. Schroten, R. Vergeer et al. Environmental Prices Handbook EU28 Version, CE Delft, Delft, The Netherlands, October 2018.

Niels Oliver Nagel, Eirik Ogner Jåstad

BLUE AND GREEN HYDROGEN IN THE EUROPEAN ENERGY TRANSITION – A TECHNO-ECONOMIC ANALYSIS OF COMPETITIVE CAPACITY INVESTMENTS

Niels Oliver Nagel, Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway
Eirik Ogner Jåstad, Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway

Overview

In the European energy transition, hydrogen holds great promise to help reduce GHG emissions across energy, transport, and agriculture sectors and reduce the reliance on imported fossil fuels (European Commission, 2024). To unlock the promise of hydrogen as an emission free energy carrier it will require great investments into electrolyzers powered by renewables (green hydrogen) and/or steam methane reforming plants using carbon capture and storage (blue hydrogen) (Koneczna & Cader, 2021). Aiming at achieving the European Union's (EU) ambitious hydrogen plans, of producing 10 million tons emission free hydrogen by 2030 (European Commission, 2024) and further increasing amounts thereafter leads to several important questions regarding technology choice, location, and the impact on the European energy system towards 2050:

1. How does the cost-competitiveness of blue and green hydrogen unfold in the European energy system?
2. What regions and hydrogen technologies are economically favorable for capacity investments?
3. How will the electricity demand, electricity prices, and consequently capacity investments in power generating technologies be affected by increasing hydrogen demands? What roles do green and blue hydrogen play in this respect?
4. How will the market value of weather dependent renewables (wind and solar PV) and flexible generation (hydropower with reservoirs) be affected by the expected hydrogen demand?

Previous work modeling the investment decision in blue and green hydrogen technologies in a detailed energy system model approach with a fine spatial and temporal representation of production and demand was only found in one study (Durakovic, del Granado, & Tomasgard, 2023). Our study has, however, more of a focus on the energy system impacts, highlights regional data more specifically, and models green hydrogen in competition with a broad set of flexibility options. For example, we identify the most suitable regions for new electrolyzers, which heavily depend on the generation mix in the energy system and to a lesser degree on the proximity to demand centers.

Method

To achieve the objectives of this study it is essential to model the impacts of electricity demand from electrolyzers on the energy system in a comprehensive energy system model. The model needs to include a high level of detail with regard to temporal, spatial, and techno-economic considerations to provide results to answer the research questions. Additionally, the economic competition between blue and green hydrogen had to be represented. The Balmorel energy system model is found to be appropriate for this task, a cost minimizing partial equilibrium model with a detailed representation of Europe's electricity and district heating sector, which is highly customizable, and includes flexibility options from private electric vehicles, demand response and has been extended to also cover hydrogen production, storage, transmission, and consumption. Wiese et al. (2018) provide a detailed description of the core model. For the sake of this study, the model regions were extended to cover the whole European energy system. Scenarios allow for investment into both blue and green hydrogen, or only green hydrogen, and are supplemented by several sensitivity model runs that focus on natural gas prices and hydrogen demand to improve the robustness of the results.

Results

The results show that green and blue hydrogen production can coexist in the least cost solution in the European energy system. Electricity prices across high VRE market regions in Europe are most impacted by green hydrogen production. It is here where most investments into green hydrogen electrolyzers happen (due to good renewable resources). We find that under our cost assumptions for transport and storage the proximity to demand centers plays a smaller role. Additionally, we find that blue hydrogen can contribute to a significantly lower average electricity price than when we analyze a scenario where we only invest in green hydrogen electrolyzers in Europe. Analyzing the different technologies, we find that green hydrogen will become more competitive in 2040 with higher shares of variable renewables in the system because it is well suited to take advantage of low-price periods. However, green hydrogen faces competition from other flexibility providers and thus its profitability may be reduced by other changes to the energy system such as large-scale adoption of battery storages or vehicle to grid. A main benefit of green hydrogen is that (given enough capacity) it can provide a price floor for renewables, increasing their market value and reducing curtailment. On the other hand, more green hydrogen will also require significantly higher capacity investments into wind and solar PV which may result in land use and social acceptance problems.
High uncertainty persists regarding the level of competitiveness of blue hydrogen as shown in this study by analyzing sensitivities with regard to feedstock prices and hydrogen demand. These will play a significant role for the profitability of blue and green hydrogen and thus lead to significantly different capacity investments into the respective capacities.

Conclusions

To meet the European hydrogen ambitions a combination of blue and green hydrogen is ideal from a cost perspective, with investments in green hydrogen increasing more rapidly after 2030. Blue hydrogen is important to reach the EU targets, as it reduces the need for capacity investments in the energy system and may be more beneficial if land-use conflicts and social acceptance of renewable infrastructure increase. Green hydrogen can help utilize excess electricity production by providing demand side flexibility, thus improving the market values of renewable producers (with the exception of flexible hydropower) significantly. This could help spur further renewable investment. We find that while the bulk of hydrogen demand can be expected in central Europe, production is most cost effective in southern and Northern Europe where solar and wind resources are better.

References:

Durakovic, G., del Granado, P. C., & Tomasgard, A. (2023). Are green and blue hydrogen competitive or complementary? Insights from a decarbonized European power system analysis. *Energy*, *282*, 128282. https://doi.org/https://doi.org/10.1016/j.energy.2023.128282

European Commission. (2024). *Hydrogen*. https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en#:~:text=European%20Clean%20Hydrogen%20Alliance&text=The%20alliance's%20objective%20is%20to,and%20hydrogen%20transmission%20and%20distribution

Koneczna, R., & Cader, J. (2021). Hydrogen in the strategies of the european Union member states. *gospodarka surowcami mineralnymi*, *37*(3), 53-74.

Wiese, F., Bramstoft, R., Koduvere, H., Alonso, A. P., Balyk, O., Kirkerud, J. G., Tveten, A. G., Bolkesjo, T. F., Munster, M., & Ravn, H. (2018). Balmorel open source energy system model. *Energy Strategy Reviews*, *20*, 26-34. https://doi.org/10.1016/j.esr.2018.01.003

Karen Villarroel, Inês Carrilho-Nunes, Margarida Catalão-Lopes

THE RELATIONSHIP BETWEEN ENERGY ACCESSIBILITY AND INCOME INEQUALITY IN LATIN AMERICA AND CARIBBEAN COUNTRIES

Karen Villarroel, Instituto Superior Técnico, Universidade Lisboa, Portugal,
Inês Carrilho-Nunes, CEGIST, Instituto Superior Técnico, Universidade Lisboa, Portugal,
Margarida Catalão-Lopes, CEGIST, Instituto Superior Técnico, Universidade Lisboa, Portugal,

Overview

Access to modern energy services is crucial for well-being, health, and economic development, yet it remains out of reach for many marginalized communities. This article explores the relationship between access to modern energy services and income inequality within Latin America and the Caribbean (LAC), a region marked by pronounced income disparities and significant variations in energy access.

Methods

We employ an econometric approach with Granger causality testing over the years 2000 to 2019 for Bolivia, Brazil, Colombia, Costa Rica, El Salvador, and Honduras, which are included in the income ranges lower-middle and upper-middle, according to the United Nations classification. The total population of the LAC region surpassed 659 million people in 2022, and the countries selected represent almost half of this figure, around 47% (The World Bank, 2022).

Results

The results suggest that enhancing access to electricity and clean cooking fuels can significantly reduce income inequality within the LAC region. However, the magnitude and direction of these effects are found to be country-specific, underscoring the complexity of the energy-inequality nexus.
Particularly, the case of Costa Rica is highlighted for its unique bidirectional causality between energy access and income inequality, fostering a virtuous cycle where development becomes endogenous. Conversely, in Bolivia, Brazil, and Honduras, this endogeneity does not occur, indicating a greater need for government policy intervention. Additionally, in El Salvador, while increased electricity access positively affects access to clean cooking fuels, no direct link between energy access and income inequality is observed.

Conclusions

Highlighting the connection between energy access and income inequality underscores the need for policy interventions specifically designed for the unique socio-economic and energy landscape of each country. These strategies must leverage energy access as a powerful means to combat income disparity effectively. While the study focuses on the LAC region, its implications extend far beyond, offering insights relevant to other middle-income nations facing similar challenges.

References

Acheampong, A. O., Dzator, J., & Shahbaz, M. (2021). Empowering the powerless: Does access to energy improve income inequality? *Energy Economics*, *99*, 105288. https://doi.org/10.1016/j.eneco.2021.105288

Aiyar, S., & Ebeke, C. (2020). Inequality of opportunity, inequality of income and economic growth. *World Development*, *136*. https://doi.org/10.1016/j.worlddev.2020.105115

Hassan, S. T., Batool, B., Zhu, B., & Khan, I. (2022). Environmental complexity of globalization, education, and income inequalities: New insights of energy poverty. *Journal of Cleaner Production*, *340*(January), 130735. https://doi.org/10.1016/j.jclepro.2022.130735

Sovacool, B. K., Burke, M., Baker, L., Kotikalapudi, C. K., & Wlokas, H. (2017). New frontiers and conceptual frameworks for energy justice. *Energy Policy*, *105*, 677–691. https://doi.org/10.1016/J.ENPOL.2017.03.005

Mohaman Dan Azimi, Eloisa Disipio, Giorgia Dalla Santa, Antonio Galgaro

SUSTAINABLE GEOTHERMAL SOLUTION FOR THE DECARBONIZATION OF THE EUROPEAN ISLANDS: CASE OF VULCANO ISLAND IN ITALY

Mohaman Dan Azimi, Dep. of Geosciences, University of Padua, Via Gradenigo, 6, 35131 Padova, Tel: +39 3270598177, Email: Mohaman.danazimi@studenti.unipd.it .
Monia Procesi, National Institute of Geophysics and Volcanology (INGV-Roma), Tel: +39 0651860761, Email: monia.procesi@ingv.it .
Eloisa Disipio, Dep. of Geosciences, University of Padua, Via Gradenigo, 6, 35131 Padova, Tel: +39 049 8279164, Email: eloisa.disipio@unipd.it .
Giorgia Dalla Santa, Dep. of Civil, Construction and Environmental Engineering, University of Padua, Via Ognissanti 39, 35131 Padova, Tel: +39 339 8126586, Email: giorgia.dallasanta@unipd.it .
Antonio Galgaro, Dep. of Geosciences, University of Padua, Via Gradenigo, 6, 35131 Padova, Tel: +39 3395441945, Email: antonio.galgaro@unipd.it .

Overview

Due to unique landscapes, volcanic islands worldwide are very attractive for tourists, which in turn put stress on the islands' energy supply (EGEC). For majority of these islands, the imported fossil fuels and its related products is still the main energy sources for their energy needs, and others are dependent on weak electricity grid connexions with their mainland. This leads to high power costs and environmental emissions associated with oil consumption (Duić et al. 2008). Given a look at the islands about the climate change, it is fundamental today to understand how to replace energy production from fossil sources with renewable energy. There are many islands in the world that are betting on different models of development with zero emissions and with adaptation interventions to the phenomena related to climate change (Biondo et al., 2020). A direction of intervention that today also represents a great opportunity to attract the growing share of tourism in search of a quality offer in the smaller Italian islands where the landscape and history, biodiversity and gastronomic typicality are at the center, but also the innovation given by solar systems, energy storage systems and geothermal energy. With their volcanic nature characterised by high temperatures at shallow depth, these regions have a great potential for the development of geothermal energy. This study investigates Coaxial Borehole Heat Exchangers (CBHE) systems in Vulcano island mainly for sustainable geothermal power generation.

Method

The long-term thermal response period is a characteristic of heat transfer between ground heat exchanger and the surrounding rock and soil. Thus, the research utilizes a combination of field data, laboratory analysis, and computer simulations to evaluate system performance under varying geological and operational conditions. In addition, the design parameters play an important role in thermal response of the system, which depends on inlet fluid temperature, inlet flow rate as well as pipe diameters. Therefore, sensitivity analysis conducted enables to characterise the influences of the above-mentioned parameters on thermal behaviour of the CBHE model developed.

Results

The evaluation of the effects for different operation scenarios on the long-term performance of the heat exchanger system developed still deserves further study. Nonetheless, our preliminary results with a fixed inlet fluid temperatures for an operating time of 1 year and with agreement with numerous studies indicate that:

- The CBHE produced a very early high temperature, but the heat has declined rapidly to reach a pseudo-steady state.
- A higher flow rate can extract more heat from the formation. However, will reduce the outlet fluid temperature. The outlet fluid temperature can be controlled by adjusting the flow rate in real-time to meet the thermal output for electricity production.

- A reverse heat conduction will occur in shallow formations because the inlet temperature is greater than the surrounding soil, and that the thermal equilibrium points will move downward with the decrease of the radial distance. This result demonstrates that the thermal process is enhanced at depths with higher soil temperatures, at which the fluid can be heated to a maximum.
- The heat extraction process results in the cooling of the soil surrounding the CBHE up to a radial distance of about 5 m. With the increase of the radial distance, the effect of fluid heat conduction on the soil temperature was smaller.

Conclusions

The evolutions of the fluid temperature and thermal process were performed. Some conclusions can be drawn as follows:

- - A reasonable flow rate can not only ensure an effective heating area, but can also increase the operation life of the thermal reservoir.
- - In order to maintain stable, the inlet fluid temperature, an insulation cab be applied at shallow depth to reduce the heat loss to the surrounding soil. Similarly, the use of an insulating material in the upper part of the inner pipe could reduce the heat losses from the rising working fluid, ensuring a high outlet temperature.
- - The heat recovery of the formation during no extraction period is essential when considering the lifetime of CBHE.

Through sensitivity analysis, some key parameters affecting efficiency and performance of the system can be further outlined. This developed model offers a promising solution in harnessing geothermal energy aiming to enhance safety, mitigate environmental risks, and increase sustainability without extracting fluids from the ground.

References

Biondo, C., & Zanchini, E. (2020). Energy, Water, Mobility, Circular Economy, Sustainable Tourism. 2020 Edition CNR-IIA.

Diao, N. R., Zeng, H. Y., & Fang, Z. H. (2004). Improvement in modelling of heat transfer in vertical ground heat exchangers. HVAC and R Research, 10(4), 459–470. https://doi.org/10.1080/10789669.2004.10391114.

European Geothermal Energy Council. (2020, October). Geothermal Energy Use for Heating and Electricity in Volcanic Islands. Retrieved from https://www.egec.org/events/geothermal-energy-use-for-heating-and-electricity-in-volcanic-islands/.

Huang, Y., Zhang, Y., Xie, Y., Zhang, Y., Gao, X., & Ma, J. (2021). Long-term thermal performance analysis of deep coaxial borehole heat exchanger based on field test. Journal of Cleaner Production, 278, 123396. https://doi.org/10.1016/j.jclepro.2020.123396.

Marco Cappellari

FLOATING O, SHORE WIND: OPPORTUNITIES AND CHALLENGES OF THE ITALIAN ENERGY FRAMEWORK

Marco Cappellari, Unversity of Padua, Italy,

Abstract

Europe set a target of renewable generation at 42% of its consumption in 2030. Italy has to almost double its renewable production in this decade. A mix of technologies is necessary to achieve such a challenging goal and innovation is necessary to enhance the dispatchability of new sources.

Among the multiple possibilities, oBshore wind energy has been identified as one of the technologies of greatest interest and highest developing potential. In particular, Floating OBshore Wind Farms (FOWF) have become the most promising wind energy generation kind in Italy, due to many positive aspects: higher wind performances and capacity factor, lower cost and ease of installation compared to fixed-bottom ones, independence from water depth, shorter authorization procedures for environmental and touristic-related criticalities. Especially for the Italian territory, characterized by low wind speeds onshore and deep national waters, the floating solution could represent a perfect fit for the carbon- neutral trend.

Nevertheless, these technologies still face multiple challenges: electrical transmission issues, large-scale manufacturing, materials choice, suitable ports identifications, substation and floating platform layouts, all convey on making this generation not commercially mature at present time.

The aim of this paper is to provide a mapping as complete as possible of the actual state of the art of the floating generation in its fundamental aspects, from the electrical to the economical ones, with particular focus on the Italian area. The goal is to define where scientific research should be addressed to obtain technically and economically available technology.

The work is not only based on previous literature, but it comes from the direct confrontation and meeting with multiple companies working on diBerent aspect of the floating generation, in order to provide a complete and real understanding of the issues and limitations associated to these technologies, for giving diBerent points of view, and to combine the academic knowledges with the actual perspectives of the firms operating in this field.

José Venal, António Marques, Tiago Afonso

ENERGY ACCESS IN DEVELOPING COUNTRY: THE ROLE OF ELECTRICITY GENERATION

José Venal, NECE and Management and Economics Department/University of Beira Interior, Portugal,
António Marques, NECE and Management and Economics Department/University of Beira Interior,
Tiago Afonso, NECE and Management and Economics Department/University of BeiraInterior,

Overview

Access to the energy that many developing countries use depends on certain sources of production, which leads to the diversification of various energy sources in production. Consequently, different energy sources can allow for different types of energy access, when analyzed through the source of production. To accomplish Sustainable Development Goal 7 (SDG 7) 2030, the world, especially developing countries, must achieve certain levels of access to modern and reliable electricity. To contribute to the sustainable development agenda, the main goal of this research is to analyse the circumstances of access to energy in developing countries.
In today's world, constant electricity shortages or blackouts are often considered synonymous with energy poverty. Although the world is moving towards universal access to energy, the main target of Sustainable Development Goal 7 (SDG 7), more than 600 million people will still not have access to electricity in 2030 if expansion trends continue. This could have devastating impacts on the health, education and economic prospects of a significant part of the world's population.
In the literature review focusing on access to electricity in developing countries, there appears to be a "gap" in the analysis and evaluation of metrics that influence energy poverty (access to electricity) at the generation level. Another contribution of this proposal is that, in order to validate the relationships/equations formulated in the econometric estimation, several quantile regression models will be applied to the panel of developing country economies considered in the analysis.

Method

The sample was initially selected from thirty-five (35) countries, both African and Asian, but due to lack of data, 15 countries were excluded from the 35 previously selected, resulting in a representative sample of twenty-five (25) countries, of which fourteen (14) belong to Africa and eleven (11) belong to Asia. The time horizon is from 2000 to 2020. The use of annual data from the last two decades has made it possible to build two ordered country panels, namely: Angola, Cameroon, Cape Verde, Egypt, Ethiopia, Ghana, Morocco, Nigeria, Mozambique, Rwanda, Senegal, Tunisia, Zambia, and South Africa. At the level of Asian countries, namely: China, South Korea, India, Pakistan, Nepal, Malaysia, Israel, Kazakhstan, Iran, Lebanon, Bangladesh. Regarding the relationship between access to electricity, energy poverty was measured by access to electricity analysed from two perspectives: i) access to electricity in developing countries, ii) access to electricity in African and Asian developing countries.
To analyze the inequality in access to electricity in developing countries, through the source of its generation, quantile regression (QR) models were chosen. The application of this method will minimize the econometric problems associated with the application of linear models. In addition, it is appropriate to use the QR because it is more conservative and robust in identifying inequalities.
The effect that independent variables could have on the conditional distribution of the dependent variable can be seen through quantile regression (Afonso et al., 2019). Using the conventional regression model, these various effects can result in useful information that cannot be captured (Bitler, Gelbach, & Hoynes, 2006; Hübler, 2017).
Thus, the basis of traditional regression is in the mean, while the basis of quantile regression is in the median. Thus, when residuals do not follow a normal distribution, quantile regression is robust in the presence of out-liers (Koenker & Hallock, 2001) and may actually be more efficient than the ordinary least squares (OLS) method.

Results

The QR captures different effects on the same variable and indicates the validity of some theories, enriching our results, as they offer contributions on the energy mix that some developing countries have made regarding access to electricity.
The results suggest that developing countries currently tend to use coal and certain renewable energies (namely hydroelectric) to provide access to electricity. Other important findings show that there is less access to energy from gas, oil, and nuclear sources. However, these sources may become smaller and more limited over time. These findings make it possible to affirm that access to energy is differentiated and adjusted energy policies can contribute to achieving the SDG 7 2030 target.

Conclusions

This research used the quantile regression (QR) method to investigate developing countries' access to electricity. Significant differences were found in the estimates between quantiles. The QR estimator indicates that it does not follow the general trend observed in previous studies, which demonstrates the importance of using this method.
However, through the QR method, we found that the effect of access to electricity is smaller when generation comes from renewable energy, especially in the first quantile (lowest quantile) and higher for more developing countries with access to electricity from fossil sources, for example, coal (highest quantile).

References

Afonso, T. L., Marques, A. C., & Fuinhas, J. A. (2019). Energy-growth nexus and economic development: A quantile regression for panel data. In *The Extended Energy-Growth Nexus: Theory and Empirical Applications* (pp. 1–25). Elsevier. https://doi.org/10.1016/B978-0-12-815719-0.00001-2

Bitler, M. P., Gelbach, J. B., & Hoynes, H. W. (2006). What mean impacts miss: Distributional effects of welfare reform experiments. American Economic Review, 96(4), 9881012. Available from: https://doi.org/10.1257/aer.96.4.988.

Hübler, M. (2017). The inequality-emissions nexus in the context of trade and develop- ment: A quantile regression approach. Ecological Economics, 134, 174185. Available from: https://doi.org/10.1016/j.ecolecon.2016.12.015.

Koenker, R., & Hallock, K. F. (2001). Quantile regression. Journal of Economic Perspectives, 15(4), 143156.

Oliveira, G. R., Tabak, B. M., de Lara Resende, J. G., & Cajueiro, D. O. (2013). Determinants of the level of indebtedness for Brazilian firms: A quantile regression approach. *Economia*, *14*(3–4), 123–138. https://doi.org/10.1016/j.econ.2013.11.002.

Vitor Benfica and António Marques

LATIN AMERICA ENERGY TRILEMMA: PERSPECTIVES ON THE ENERGY TRANSITION

Vitor Benfica, Universidade Beira Interior, R. Marquês de Ávila e Bolama, 6201-001, Covilhã, Portugal
António Marques, Universidade Beira Interior, R. Marquês de Ávila e Bolama, 6201-001, Covilhã, Portugal

Overview

The climate emergency has increasingly become the centre of attention for policymakers. Crises such as COVID- 19 and the conflict in Ukraine have highlighted the vulnerabilities in the energy security of various nations, firstly within Europe. Nevertheless, these crises indirectly affect economically dependent, less affluent countries through external market dynamics. This exacerbates poverty and inequality, diminishes energy security, and poses setbacks in the energy transition process. In this paper, we develop an indicator of the Energy Quadrilemma, an extension of the trilemma concept formulated by the World Energy Council (2023). This expanded framework incorporates variables sensitive to the social context of Latin America, enabling a more comprehensive analysis of the regional challenges faced in the energy transition.

Methods

We adhere to the procedures outlined in the OECD manual (2008) to compute the Energy Quadrilemma Index. The analysis spans from 2014 to 2020 and only includes Latin American countries for which data are available. Twenty-five variables have been selected and grouped into four sub-indicators: Energy Security, Energy Equity, Sustainable Environmental Development, and Social Context. Lazaro's work (2024) briefly describes the concepts of the energy trilemma, where Energy Security pertains to the capability to ensure the availability, accessibility, reliability, and sustainability of energy sources. Energy Equity examines access to affordable and reliable energy for both domestic and commercial use. Sustainable Environmental Development assesses a country's progress in minimizing and preventing environmental damage and the effects of climate change. The Social Context, a novel sub-indicator, encompasses variables that evaluate social aspects such as poverty, income distribution, access to essential services, and social protection of the populace. Each sub-indicator is generated through Principal Component Analysis (PCA), employed to create the components that best capture the effects of the variable set (Silva et al., 2015). The four sub-indicators are subsequently amalgamated into a composite indicator, scaled from 0 to 100, using a simple aggregation function that assigns equal weights to each theme.

Results

Broadly, the index indicates stability throughout the analysed period, with a 2020 deterioration partly due to the pandemic crisis. Uruguay and Paraguay rank the highest on the overall index, while Brazil and Honduras are among the lowest. The Energy Security sub-indicator reveals that many countries continue to rely heavily on the export of oil and derivatives. In Bolivia, for instance, gas production is a crucial energy vector, yet the low fossil fuel prices are a factor that makes the transition difficult. In Paraguay, the export of electrical energy is significant, but the high dependence on hydroelectric plants weakens the system due to intense fluctuations in water regimes. This vulnerability is shared across several countries, as most of the primary sources of electrical energy are hydroelectric reservoirs.

Evaluating Energy Equity, there is progress in energy access due to public policies directed towards this end. However, the indicator of access to modern energy for cooking reveals disparities between urban and rural areas, indicating that a segment of the population lacks access to electricity or doesn't use it. The use of biomass has decreased in the timespan, reaching a plateau across all analysed countries, reflecting both cultural factors and pre- existing social inequality.

In the Social Context, the disparity between rural and urban areas is a significant highlight. The Gini index tends to be higher in rural areas. Uruguay and Argentina stand out as the best providers of essential services for sanitation and water. Concurrently, Brazil and Argentina have high levels of social transfers as a proportion of GDP, which help to mitigate energy poverty.

Conclusions

The indicator reveals that, despite efforts, there has been little progress in the aggregated index during the available period. The intense inequality results in the rapid adoption of new technologies, but these are limited to a small segment of the population with purchasing power. Uruguay, Paraguay, and Bolivia show better standings, while Brazil and Argentina display lower performances.
The analysis of the sub-indices indicates that energy security is compromised, primarily due to an energy matrix heavily dependent on non-renewable energies. The reliance on water sources for power generation is a vulnerability of the electrical systems. Thus, diversification of energy sources is crucial for enhancing energy security.
Policies aimed at universalizing access to energy show positive outcomes, but low-income populations face challenges in consuming more electricity. In Bolivia, for example, the policy of frozen fossil fuel prices hinders the development of economically viable solutions for the energy transition. Income disparity between urban and rural regions also impedes the transition, as in rural areas biomass can enhance energy security for families without access to electricity. Income transfer programs may alleviate energy poverty, enabling families below the poverty line to enjoy more technology and electrical energy. These preliminary results from the research indicate that the energy transition in Latin America must consider aspects related to energy poverty, at the risk of exacerbating existing social inequalities.

References

Lazaro, L. L. B., & Soares, R. S. (2024). The energy quadrilemma challenges—Insights from the decentralized energy transition in Brazil. *Energy Research & Social Science*, *113*, 103533. https://doi.org/10.1016/j.erss.2024.103533

OECD/JRC (Ed.). (2008). *Handbook on constructing composite indicators: Methodology and user guide*.OECD. https://knowledge4policy.ec.europa.eu/sites/default/files/jrc47008_handbook_final.pdf

Silva, M. C. D., Silva, J. D. G. D., & Borges, E. F. (2015). Análises de Componentes Principais para Elaborar índices de Desempenho No Setor Público (Principal Component Analysis to Develop Performance Indexes in the Public Sector). *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2828289

WEC, & Wyman, O. (2023). *World Energy Trilemma Framework*. World Energy Council. https://www.worldenergy.org/assets/downloads/World_Energy_Trilemma_Index_2022.pdf?v=1707998024

Alessandra Motz, Andrea Tenconi, Leonardo Gottardi, Roberto Bianchini, Barbara Antonioli Mantegazzini

GAS AT THE SUNSET? PERSISTENT AND TRANSIENT IMPACTS OF THE CRISIS ON THE ITALIAN GAS DEMAND

Alessandra Motz, Institute for Economic Research, Università della Svizzera italiana, Via Buffi 10, 6900, Lugano, Switzerland
Andrea Tenconi, ref. ricerche, Via Aurelio Saffi 12, 20144, Milan, Italy
Leonardo Gottardi, ref. ricerche, Via Aurelio Saffi 12, 20144, Milan, Italy
Roberto Bianchini, ref. ricerche, Via Aurelio Saffi 12, 20144, Milan, Italy
Barbara Antonioli Mantegazzini Institute for Economic Research, Università della Svizzera italiana, Via Buffi 10, 6900, Lugano, Switzerland

Overview

After a prolonged slump in both demand, and prices, autumn 2021 began with an unexpected and steady growth of wholesale prices for natural gas in Europe. The upward trend continued throughout the winter and further exacerbated after the Russian invasion of Ukraine. Unprecedented price peaks were observed in spring and summer 2022, with an astonishing spike above 300 EUR/MWh for TTF in August 2022, and a fast decrease to much lower, but still relatively high price levels over the colder months, thanks to the high level of storage inventories. Throughout 2023 natural gas prices in Europe traced back, but still remained mostly above the levels observed in the five years before the war.
Despite several measures introduced in most European countries to protect end consumers from high gas prices, at least part of this price signal was passed to the retail segment, with different magnitude and timing depending on the supply contracts signed by each consumer. At the same time, most European governments promoted energy-saving measures and launched information campaigns emphasizing that every cubic meter saved was crucial for the security of the national energy supply. They also implemented supply diversification strategies, such as increasing the volumes of LNG from the US.
Price signals and campaigns for saving energy, together with mild weather, lead to a significant decrease in energy and gas consumption in Europe. For natural gas, the European Union exceeded the 15% target set for winter 2022/2023, hitting a 18% decrease with respect to the five-year average. While the EU policy makers hope for a similar result for winter 2023/2024, it is unclear what share of this demand reduction is going to last over the next years, witnessing a structural change in natural gas consumption, and what is going to bounce back to pre-crisis levels, net of the impact of changing weather and economic conditions.
We focus on the case of Italy and assess the reduction in natural gas demand following the energy crisis. We divide Italian gas demand into three segments: gas-fired power generation, gas-intensive manufacturing, and households and small and medium-sized enterprises (SMEs). The aim of our study is to measure actual gas savings in these three segments, accounting for the impact of weather conditions and economic dynamics, and to evaluate if and to what extent this demand reduction is likely to persist over the long term.

Methods

After the appropriate statistical checks, we apply ordinary least square regressions to the following data series:

- Monthly data published by the Italian gas transmission system operator, Snam Rete gas, for withdrawals of gas-fired power generation, gas-intensive manufacturing, and households and SMEs;
- Monthly data for heating degree days computed based on Eikon Refinitiv data for average daily temperatures in some Italian macro-regions;
- Monthly data for industrial production published by Istat.

We test several specifications including a time trend and two dummies, one for the Covid-related restrictions, and one for the gas crisis. The dummy variable representing the gas crisis is our variable of interest, as it allows us to estimate, ceteris paribus, the impact of the gas crisis for each sector and month.
For the time being, we do not include gas prices in the model. This decision is connected on the one hand to the difficulties in correctly addressing endogeneity, on the other hand to the risk of incurring into measurement errors due to the heterogeneous ways in which wholesale gas prices impact the actual price paid by end customers.

Results

Our preliminary results identify three different trends for each sector included in the analysis starting from February 2022:

- For households and SMEs, the energy crisis led to significant gas savings between October 2022 and March 2023, with demand reductions often above 1 billion cubic meter (Bcm) per month, and lower but still significant savings between October and December 2023. We found instead no impact of the gas crisis between April and September in both 2022, and 2023. As a term of comparison, the yearly demand of this segment in 2019 was around 32 Bcm.
- For gas-intensive manufactories, the energy crisis induced significant gas savings starting from February 2022 and until December 2023, with demand reductions hovering around 0.2 Bcm/month, compared with a yearly demand around 14 Bcm in 2019. The impact of the energy crisis for this consumption segment hit its record between September 2022 and February 2023, with monthly savings well above 250 million cubic meters per month.
- For gas-fired generation the gas crisis induced a mixed reaction, with only some months recording significant demand reductions, and a stronger, but still erratic trend from September 2023 onwards. Monthly savings in the second half of 2023 average 0.3 Bcm/month, compared to a yearly demand around 25 Bcm in 2019. The dynamics observed in this sector clearly reflects the fact that gas-fired generation managed to cover its higher production costs through higher electricity prices, thanks to the drought that hit Italy and Europe and the temporary decrease of nuclear productions in France in 2022.
- All in all, our preliminary results suggest that the gas crisis yielded a demand reduction of around 13 Bcm between February 2022 and December 2023, with the strongest impact between October 2022 and March 2023, when gas demand was around 8 Bcm lower than expected.

Conclusions

We place our analysis within the literature concerning the structural changes in energy demand possibly induced by energy crises. Our preliminary results suggest that the crisis might have induced a structural change among households and SMEs, especially in the heating season, and among gas-intensive manufactories. There is instead no evidence of a similar trend for gas-fired generation. The analyses we plan to conduct over the next months will focus on:
- Monitoring the persistency of these trends over time,
- Exploring what lies behind these (persistent) savings, also considering the general trend toward a shift from fossil fuels implied in the decarbonization effort in which Italy is engaged.

While recognizing the insights in the behaviour of gas consumers provided by the (few) studies focussing on the price elasticity of gas demand, or on the cross-price elasticity among different energy commodities, we do not plan to focus on price elasticity of gas demand, as the magnitude of the price spikes observed during the energy crisis is such that any point estimate of price elasticity would be of minor help.

References

ACER-CEER, 2023: "European gas market trends and price drivers - 2023 Market Monitoring Report".

Borchardt K. D., 2023: "EU energy policy between emergency measures and energy transition legislation: do we need to fear for our liberalized gas market?", OIES Energy Comment.

Council Regulation (EU) 2022/1369 of 5 August 2022 on coordinated demand-reduction measures for gas.

European Commission, 2022: "Communication from the Commission to the EUropean Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - Save gas for a safe winter", COM(2022) 360 final.

Honoré A., 2022: "Demand response to high gas prices in Europe in 2021 and early 2022", OIES Energy Insight: 117.

International Energy Agengy, 2023: "Natural gas supply-demand balance of the European Union in 2023 - How to prepare for winter 2023/24".

Labandeira X., Labeaga J. M., Linares P., Lopez-Otero X., 2020: "The impacts of energy efficiency policies: Meta-analysis", Energy Policy 147, 111790, DOI: https://doi.org/10.1016/j.enpol.2020.111790

Ruhnau O., Stiewe C., Muessel J., Hirth L., 2023: "Natural gas savings in Germany during the 2022 energy crisis", Nature Energy, Volume 8, 621–628, DOI: https://doi.org/10.1038/s41560-023-01260-5

Seeliger A., 2022: "Winter is coming: Can the German industry overcome the looming gas scarcity?", OIES Energy Insight 126.

Seeliger A., 2023: "German industrial gas: Crisis averted, for now", OIES Energy Insight 137.

Roberto Cardinale

LIBERALIZATION AND THE VOLATILITY OF GAS PRICES: EXPLORING THEIR RELATION IN TIMES OF ABUNDANCE AND SCARCITY

Roberto Cardinale, The Bartlett School of Sustainable Construction, University College London,

Overview

The recent surge of natural gas prices in the EU comes against the belief emerged in recent years of the definitive advent of an era of low energy prices. While agencies and analysts are attributing the causes mainly to a temporary convergence of unfavorable factors, this article identifies long-term structural and policy factors. This is done by exploring the causal relation between liberalization reforms and trends in gas supply in three major gas markets – UK, US, and EU. Through the lens of Transaction Cost Economics, the paper finds that although liberalization is effective for reducing prices in times of gas abundance, it might cause the opposite effect in times of scarcity. This suggests that the EU policy should contemplate the coexistence of models based on both market competition and vertical integration to take advantage from low spot prices in periods of abundance and contain the surge in periods of scarcity.

Methods

The paper adopts the methodology of the comparative case study (see Collier, 1993; Dion, 2003; Flick, 2006; Yin, 2009). The selection of the cases – UK, US, EU – follows Dion's (2003) creteria, which suggest that cases should be selected based on similarities on the variables to control for and on differences in the variables under investigation. In this paper, the countries selected have all mature and large natural gas markets, while more importantly, their liberalization reforms are in a advanced stage (comparing to other relevant gas markets worldwide). The variable under investigation is how the effectiveness of liberalization reforms (associated with low domestic gas prices) changes at different levels of domestic supply, with the EU being characterised by domestic scarcity, the US by abundance, and the UK having transitioned from abundance to scarcity.

Results

The UK, US and EU cases suggest that in conditions of gas oversupply, liberalization policies can successfully achieve the objectives of enhancing market competition and reducing final prices. However, it is necessary to clearly define the causal relationship between the two key factors – abundance of gas and infrastructure in relation to liberalization policies – and their respective influence on price reduction. In fact, the abundance of gas is an essential condition for the virtuous functioning of a competitive market. Without it, there would be no room for new competitors to increase their market share at the expense of established companies by offering lower prices to consumers.

Conclusions

The current worldwide surge in natural gas prices is hitting mainly import dependent countries, first and foremost in the EU. This comes against the belief emerged in recent years of the definitive advent of an era of low energy prices, brought about by increasing market competition and diversification towards renewables. The current supply shortage seems to have caught the EU unprepared and still in a transition stage in its path towards a more competitive and green energy market, suggesting that reforming the energy sector in the EU cannot overlook one of its defining features: the persistence of a strong dependence from imports. Drawing from the experience of policy reforms adopted in the major world gas markets, the paper shows why liberalization is effective for reducing prices in periods of oversupply, while its benefits are offset in periods of shortage, such as the current one.

The paper suggests immediate actions to overcome the current crisis and long-term policy directions to pursue price affordability and energy security.

References

Collier, 1993. The Comparative Method. In A. W. Finifter, ed. *Political Science: The State of the Discipline II*. Washington D.C.: American Political Science Association.

Dion, D., 2003. Evidence and Inference in the Comparative Case Study. In *Necessary Conditions: Theory, Methodology, and Applications*. Rowman & Littlefield, pp. 95–112.

Flick, U., 2006. *An Introduction to Qualitative Research*, London; Thousand Oaks; New Delhi; Singapore: SAGE Publications.

Yin, R., 2009. *Case Study Research: Design and Methods*, Thousand Oaks, Calif.; London: SAGE Publications.

Linda Cerana, Giovanni Cappena, Marco Agostini, Arturo Lorenzoni, Stefano Moret, Francesco Baldi,

EXPLORING DECARBONIZATION STRATEGIES FOR ITALY THROUGH MACHINE LEARNING AND SOCIO-ECONOMIC ANALYSIS

Linda Cerana, Department of Industrial Engineering, University of Padua, Italy
Giovanni Cappena, Department of Industrial Engineering, University of Padua, Italy,
Marco Agostini, Department of Industrial Engineering, University of Padua, Italy,
Arturo Lorenzoni, Department of Industrial Engineering, University of Padua, Italy,
Stefano Moret, Energy & Process Systems Engineering, Department of Mechanical and Process Engineering, ETH Zürich, Switzerlan,
Francesco Baldi, ENEA, Italy

Overview

Energy scenarios play a crucial role in planning the energy transition by outlining potential pathways, risks, and opportunities for transitioning to a carbon-free energy system. However, scenario elaboration and analysis face multiple challenges, among which two are particularly relevant.
The first challenge involves the modelling tools. For a comprehensive analysis, these should allow for the representation of the entire energy system (electricity, heat, and transport sectors) with sufficient detail, while also including linkages to the economy-society and the environment. Consequently, an increasing number of modelers are combining different model structures (e.g., techno-economic bottom-up models, top-down macroeconomic models, environmental models) while trying to limit complexity and computational load.
The second challenge involves the inherent uncertainty of the model variables, including technical parameters (e.g., future availability and cost of resources, techno-economic characteristics of energy systems) and socio-economic factors (e.g., availability and cost of workforce, consumer behaviour, adoption of new policies). Uncertainty analysis can evaluate how optimal solutions are impacted by several uncertain variables. However, it generally produces a large number of plausible scenarios, which do not provide clear guidance in identifying the key steps for enabling the energy transition (Baader et al., 2023).
Considering the studies on energy scenarios for Italy in relation to these challenges, we have recognized the following research gaps:

- most studies use bottom-up techno-economic models and are deterministic (i.e., they generate a single optimal solution). Only a few have carried out simplified uncertainty analyses;
- a small number of studies include the analysis of some socio-economic effects of the development of the energy system; however, these analyses present significant limitations.

Our research aims to overcome these limitations and identify key strategies for the decarbonization of the Italian energy system by 2050, by applying uncertainty analysis and machine learning methods to scenarios elaborated through a bottom-up techno-economic model. Furthermore, to allow for the comparison of these key strategies from a socio-economic perspective, a top-down macroeconomic model is employed to assess their potential impact on sectoral value added and employment.

Methods

Our research includes three core parts.
The first part involves exploring possible energy transition scenarios for Italy using the bottom-up optimization model EnergyScope. This open-source linear programming (LP) modelling framework can optimise the design and operation of a national energy system, accounting for all energy carriers, sectors, and end-use demand types (Limpens et al., 2019). It models a single target year - as it is a snapshot model - with hourly resolution using typical days (TD), offering a good trade-off between accuracy and computational time.

Specifically, in this work, we adopted and further developed the version of EnergyScope proposed and applied to Italy by Borasio and Moret (Borasio and Moret, 2022), increasing its geographical and technological resolution.
The second part of our work involves using EnergyScope to generate a large number of energy scenarios for 2050 through a Monte Carlo uncertainty analysis, after defining the set of uncertain variables that may significantly affect the results, as well as their ranges of variations. Subsequently, the methodology based on the machine learning techniques of clustering and decision trees proposed by Baader et al. is employed to streamline the energy scenarios for Italy into a small number of storylines defined by a few critical decisions (Baader et al., 2023).
The third core part of the analysis involves evaluating the socio-economic impacts of the defined energy strategies using a macroeconomic model based on Leontief's Input-Output (IO) analysis. The main results include direct, indirect, and induced sectoral value-added and employment variations compared to today's levels. The analysis is primarily performed as a shock on the final demand of goods and services required for the deployment and operation of energy conversion technologies. Specifically, to derive the increased demand of goods and services, data is collected to define the vectors of direct technical requirements per unit of technology capacity, relating technology costs to the specific economic sectors of the Italian IO tables.

Results

Through EnergyScope, we consider the uncertainty of various variables, generating hundreds of potential scenarios that explore the options for the deep decarbonization of the Italian energy system by 2050. This is enabled by the high computational efficiency of the model, which makes it particularly suitable for uncertainty analysis while maintaining a good degree of resolution in time, space, techno-economic detail, and sector-coupling.
By applying the clustering and decision tree techniques, the large number of potential scenarios are reduced to a small number of energy transition strategies, characterized by a few key decisions. These critical decisions are highlighted, along with their consequences and the trade-offs between different strategies. For instance, a critical decision might involve choosing between a limited set of primary energy resources (e.g., bioenergy, solar, PV, nuclear). This choice might force a shift to a specific configuration of the energy system, or might leave a broader space for subsequent strategic decisions on the energy mix and infrastructure.
Finally, the obtained energy strategies are compared not only based on technical parameters and system costs but also considering the direct, indirect, and induced effects of the deployment of technologies on sectoral value added and employment.

Conclusions

The present work combines various methodologies for analysing deep decarbonization strategies for the Italian energy system. Specifically, it aims to provide clearer guidance to policymakers in identifying the key techno-economic decisions that may enable the energy transition, highlighting the consequences and trade-offs of different strategies, and providing elements to assess technical options from a socio-economic perspective.
Key questions addressed include: What technologies and factors are critical for the energy transition? Which decisions will necessarily affect subsequent choices? How will different strategies impact import/exports of energy vectors or goods and services directly or indirectly related to the energy transition? Which domestic industries will need to expand their production capacity and/or employ more workforce to sustain the transition?
Furthermore, the easier interpretability of the resulting few key transition strategies and their consequences makes them more accessible to the public, potentially enhancing the acceptance of energy policies or, ideally, fostering higher public engagement to proactively support the energy transition.
Finally, further work will be required to overcome the intrinsic limitations of the two adopted models. This may involve complementing EnergyScope with another modelling framework that allows for optimizing the entire transition pathway to the target year.

Additionally, other methodologies could be considered to address the weaknesses of input-output analysis, such as its static representation of the economy and assumptions of constant return to scale and perfect elasticity, and to incorporate consumer behaviour. Lastly, the current methodology framework does not account for feedback effects between the economic and the technical models, which would require a higher level of integration between the two.

References

J. Baader, S. Moret, W. Wiesemann, I. Staffell, and A. Bardow, "Streamlining Energy Transition Scenarios to Key Policy Decisions," Nov. 2023, https://paperswithcode.com/paper/streamlining-energy-transition-scenarios-to .

G. Limpens, S. Moret, H. Jeanmart, and F. Maréchal, "EnergyScope TD: A novel open-source model for regional energy systems," Applied Energy, vol. 255, p. 113729, Dec. 2019, doi: 10.1016/j.apenergy.2019.113729.

M. Borasio and S. Moret, "Deep decarbonisation of regional energy systems: A novel modelling approach and its application to the Italian energy transition," Renewable and Sustainable Energy Reviews, vol. 153, p. 111730, Jan. 2022, doi: 10.1016/j.rser.2021.111730.

Dai-Song Wang, Lu-Tao Zhao

DYNAMIC KNOWLEDGE GRAPH CONSTRUCTION FOR OIL MARKET RISK MANAGEMENT

Dai-Song Wang, School of Management, Beijing Institute of Technology, Center for Energy and Environmental Policy Research, Beijing Institute of Technology ,Beijing, China
Lu-Tao Zhao, School of Management, Beijing Institute of Technology, Center for Energy and Environmental Policy Research, Beijing Institute of Technology ,Beijing, China,

Abstract:

The crude oil market is characterized by numerous sources of risk events. The complex mechanisms often lead to significant fluctuations in oil prices and related indices, causing market instability. In view of this, we construct an event-driven, multi-level, time-varying domain knowledge graph model (EMT-KG) that can identify and manage oil market risks. Firstly, using large language models, we extract and analyze various of heterogeneous network information to identify and extract key entities and relationships. Secondly, based on knowledge graph theories, we characterize the primary influencing factors and their interconnections within the oil market across various time windows.

The dynamics relationships are represented through a multi-layer structure of “entity-event-risk”. Finally, the graph neural network methods are applied for detailed time-based analysis and dynamic event prediction in order to uncover the patterns of event evolution and risk transmission in the oil market based on historical event data.

The empirical analysis results based on oil market-related historical data confirm the effectiveness of the framework, proving that the temporal adaptability, dynamic expressiveness, and advanced performance of EMT-KG offer a novel perspective for oil market decision-makers.

Keywords: Oil market, Knowledge graph, Risk identification, Risk management

A SOFT-LINK TIMES ITALIA-PLEXOS APPROACH TO DEVELOP ITALIAN TRANSITION PATHWAY SCENARIOS

Agostini Marco, Consorzio RFX, University of Padua, CRF, Italy
Umberto Giuliani, Consorzio RFX, Italy
Francesco Gracceva, ENEA, Italy
Chiara Bustreo, Consorzio RFX, Italy
Bruno Baldissara, ENEA, Italy
Vittoria Battaglia, ENEA, Italy
Livio De Chicchis, ENEA, Italy
Giuseppe Zollino, University of Padua, Department of Industrial Engineering, Italy

Overview

In the pursuit for a decarbonized energy future by mid of the century, energy scenarios serve as invaluable tools to navigate the complexities of the energy transition. Among these, "transition pathway scenarios" hold particular value, providing insights into the long-term impacts of energy policy choices by modeling potential system evolutions over several decades. However, the computational complexity of these models often necessitates simplifications that can compromise their accuracy and reliability. Technology-rich models of the whole energy system are among the most frequent tools used within both the research community and the policy arena . They are useful tools to assess a range of possible energy futures and to investigate technical and economic impacts of alternative strategies over very long term horizons. However, the very high levels of intermittent RES envisaged for the future pose significant challenges on system operation and planning, but the representation of RES in long-term energy system models "needs careful attention, as intermittent RES come with a number of specific characteristics, making them different from conventional dispatchable generation." [1]. Indeed, these models "struggle to take into account of short term variations in the power system associated with increased variable renewable energy penetration", due to their limitations in terms of temporal resolution and technical detail to characterize the power system. As such, they "can oversimplify the ability of power systems to accommodate variable renewables" [2].

To address these limitations, we propose a soft-link methodology that integrates the multi-year analysis capabilities of TIMES Italy with the detailed technical analysis of PLEXOS. This methodology enables a comprehensive assessment of decarbonization pathways, considering both long-term system dynamics and detailed technical constraints, by carrying out a detailed hourly power dispatch analysis of the power system configuration resulting from TIMES scenarios. We demonstrate the application of this methodology to explorative scenarios extending to the second half of the century, analyzing the evolution of the Italian energy system. A sensitivity analysis is conducted to assess the potential role of low-emission generation technologies, including biomass, variable renewable sources, nuclear technology, CCUS and hydrogen. The proposed soft-link methodology offers a valuable tool for policymakers and energy planners, providing robust insights into the feasibility and effectiveness of decarbonization strategies. By integrating different modeling approaches this methodology bridges the gap between long-term vision and technical implementation, enabling informed decision-making for a sustainable energy future.

Methods

The proposed methodology employs a soft-link approach to integrate the strengths of TIMES Italy and PLEXOS, enabling a comprehensive assessment of long-term decarbonization pathways for the Italian energy system. TIMES Italy [3] is as a partial equilibrium, technology-rich optimization model, specifically designed to develop scenarios for alternative transition pathways towards the decarbonization of the national energy system. Operating at a low time granularity, TIMES Italy captures the evolution of the energy system as a whole, considering the intricate interactions, mutual influences, and dependencies between electricity and gas markets and infrastructures. A key strength of TIMES lies in its comprehensive modeling capabilities, encompassing the entire energy system from resource extraction to end-use demand across various sectors, including industry, residential, commercial, and transportation.

While TIMES-Italy optimizes the transition process of the energy system by defining milestone years, it does not perform an hourly analysis of the system within individual years. Instead, it aggregates the yearly 8760 hours into 12 timeslices. Moreover, it does not capture the operational constraints which characterize the functioning of the power system, e.g. ramp rates and minimum up/down time. This approach reduces computational burden but doesn't allow the estimation of short/medium-term storage requirements and specific network transport and unit commitment constraints. PLEXOS [4], on the other hand, is a commercial, detailed software tool capable of simulating the operation of the energy system with high temporal and technical granularity. It also possesses optimization capabilities for short- and medium-term system operation.

This enables the estimation of both hourly storage system operation and the evaluation of power exchanges between different market zones as well as adhering to the unit commitment constraints. The soft-link approach leverages the unique strengths of both TIMES Italy and PLEXOS to achieve a comprehensive analysis. Initially, TIMES Italy is employed to develop long-term decarbonization scenarios. These scenarios are then subjected to technical validation within the PLEXOS framework, ensuring their feasibility and adherence to real-world network constraints. This iterative soft-link approach enables a robust assessment of long-term decarbonization pathways, bridging the gap between long-term vision and technical implementation.

Results

The proposed methodology yields explorative long-term scenarios for Italy, spanning from 2025 to 2050, encompassing the entire energy system from resource extraction and imports to the fulfillment of end-use demand. The primary objective of the optimization process is cost minimization, subject to the constraint of achieving net-zero emissions by 2050 and additional constraints on the maximum and minimum renewable generation potentials for each timestep of the transition. These scenarios are further evaluated from a technical feasibility standpoint, with a focus on storage requirements for integrating non-programmable renewable sources and the potential for installing firm baseload generation with nuclear and CCUS technologies. To convey insights into the key technologies and resources critical to the transition, a sensitivity analysis is conducted using what-if scenarios. Five main variables are identified to explore the principal aspects influencing the transition: non-programmable renewable potential, biomass resource availability, degree of deployment of the hydrogen value chain, CCUS technology utilization, nuclear technology availability. These variables are not solely determined by technical availability estimates (e.g., biomass availability) but also depend on specific energy policy decisions and social impact considerations. Therefore, the what-if sensitivity analysis aims to provide policymakers with a series of clear and understandable scenarios that highlight the impact of individual policy choices on the transition process. The sensitivity analysis is structured into seven what-if scenarios:

- One optimistic scenario: all variables are set to their most optimistic levels (maximum availability and minimum resource cost).
- One conservative scenario: all variables are set to their most conservative levels (minimum availability and maximum resource cost).
- Five mixed scenarios: in each of these scenarios, one variable is set to its conservative level, while the remaining four variables are set to their optimistic levels.

These scenarios provide valuable insights into the robustness and flexibility of the transition pathways under different assumptions, enabling policymakers to make informed decisions that support a sustainable and cost-effective energy future for Italy. By analyzing these scenarios with both TIMES and PLEXOS this work provides an assessment of: a) the actual technically feasibility of each scenario; b) the technical challenges implied by each of them; c) the additional costs required for granting power system security under each configuration of the systrem.

Conclusions

This study presents a soft-link methodology integrating TIMES Italy and PLEXOS to develop robust and long-term decarbonization pathways for the Italian electricity generation system.

By leveraging the strengths of both models, this approach achieves a balance between comprehensive system modeling and detailed technical analysis. The methodology was applied to explorative scenarios extending to 2050, considering various factors like net-zero emission targets, renewable energy potential, and technology availability.
The what-if sensitivity analysis aims to reveal the significant potential of low-emission generation technologies, such as biomass, variable renewable sources, and potentially nuclear power or CCUS, in achieving a decarbonized future for Italy. The analysis also highlights the critical role of policy decisions in shaping the transition pathway. By providing clear and understandable scenarios, the soft-link methodology enables policymakers to assess the impact of different choices on the feasibility and cost-effectiveness of decarbonization strategies.

References

[1] Delarue, E. and Morris, J., Renewables Intermittency: Operational Limits and Implications for Long-Term Energy System Models, MIT Joint Program on the Science and Policy of Global Change, 2015
[2] Collins S. et al., Adding value to EU energy policy analysis using a multi-model approach with an EU-28 electricity dispatch model, Energy, 2017
[3] Cingolani et al., Riscrivere il futuro. La transizione ecologica equa ed accessibile, Solferino, 2023.
[4] Plexos, Energy Exemplar, https://www.energyexemplar.com/plexos

Diaz-Chavez Rocio, Yara Evans

SOCIO-ECONOMIC ASSESSMENT OF CCUS FOR THE EXPANSION OF THE CIRCULAR BIOECONOMY, THE COOCE PROJECT

Rocio A Diaz-Chavez; Centre for Environmental Policy, Imperial College London,
Yara Evans, Centre for Environmental Policy, Imperial College London

The exploitation of CO_2 capture, utilisation and storage technologies (CCUS) in industrial applications face significant challenges due to the high investment cost and the fierce international competition in the sectors concerned. Nonetheless, it is widely known that these industrial sectors currently account for 20% of global CO_2 emissions, and according to the 2-degree scenario of the Paris agreement, they should represent half of the stored CO_2 by 2050. In this frame, relevant sectors with high CO_2 emissions are for example steel, iron and cement making, biofuel production and waste incineration plants, oil refining, gas processing, hydrogen production.
The main objective of CooCE is to develop, demonstrate and validate a diverse portfolio of novel and flexible biotechnological processes for sustainable valorisation and long-term storage of CO_2-rich emissions tailored to local demands. The CooCE concept includes the use of efficient and sustainable anaerobic and aerobic biological processes for the conversion of CO_2 into a) clean biofuels allowing flexible on-site hybrid energy storage, and b) valuable chemical building blocks, namely biosuccinic acid (bioSA) and high-volume added value biopolymers for the production of bioplastics. The project's sustainability assessment (environmental, and socio-economic perspectives), includes the analysis of these activities on decarbonisation, thereby contributing to the creation of sustainable value chains in the energy and CO_2 intensive industrial sectors. The project also aims at linking the activities with circular economy by using waste and residues into the chemical pathways. The project is funded by each partner's country (UK, Italy, Greece, Denmark) supporting ACT which is an international initiative to establish CO_2 capture, utilisation and storage (CCUS) as a tool to combat global warming.
This paper draws on empirical data to examine the understandings and perspectives of different socio-economic criteria and interest groups of a proposed CCUS concept that entails capturing carbon for transforming into bioproducts. A mixed-methods approach was employed to analyse the socio-economic criteria through a hotspots risk analysis, social life cycle assessment and the engagement with to gauge their understanding of diverse facets of a CCUS concept oriented towards the circular bioeconomy. The analysis shows that stakeholders views, opinions and perspectives on feedstocks, conversion technologies, and intermediate and end products sometimes converge, sometimes diverge. Equally, perceptions often agree but also disagree about the role and scope of policy and interventions by the state and responses by the market. The analysis also explores the links between the demographics of research participants and their views on a selection of topics discussed (e.g., gender, age, education, etc).
More generally, the results show that there is often disagreement amongst stakeholders about the role and scope of CCUS in lowering carbon emissions to mitigate global climate change. Thus, greater alignment of ideas and perspectives amongst stakeholders may be needed to drive the development of CCUS to help both expand the circular bioeconomy and achieve Net Zero targets within proposed timescales. The results also highlight the need for wider engagement of society with the concepts of CCUS and the bioeconomy, including through continuous campaigning to enhance awareness and knowledge.

Keywords: CCUS, stakeholder, advanced biofuels, social life cycle assessment, sustainability, circular bioeconomy

Clément Baumann, Roberto Barrella, José Carlos Romero

UNVEILING ENERGY POVERTY IN SOUTHERN EUROPE: INDICATORS, VULNERABILITY FACTORS, AND POLICY IMPLICATIONS

Clément Baumann, ICAI School of Engineering, Universidad Pontificia Comillas, Alberto Aguilera, 25, 28015 Madrid, Spain
Roberto Barrella, Chair of Energy and Poverty & Institute for Research in Technology (IIT), ICAI School of Engineering, Comillas Pontifical University, Alberto Aguilera, 25, 28015 Madrid, Spain.
José Carlos Romero, Chair of Energy and Poverty & Institute for Research in Technology (IIT), ICAI School of Engineering, Comillas Pontifical University, Alberto Aguilera, 25, 28015 Madrid, Spain.

Overview

Energy poverty refers to a household's inability to meet its basic energy needs in an adequate and affordable manner. It often results from a combination of financial constraints, energy-inefficient housing, high energy prices and unfavorable socio-economic factors. The Covid-19 global health crisis and, more recently, the energy crisis have significantly exacerbated this issue in the EU. For instance, the share of European households unable to keep their homes adequately warm grew from 6.9% in 2019 to 10.6% in 2023. These crises have highlighted the fragility of the EU's energy systems and urged decision-makers to adopt a more proactive approach to mitigating their socio-economic effects. The growing urgency of understanding energy poverty in Europe highlights the need for its measurement and the identification of the vulnerability factors in different European countries.

Methods

To adequately measure energy poverty, which is a multi-dimensional issue, in Spain, Italy and France, a measurement tool calculating several indicators to capture different forms of energy poverty has been developed. The four main indicators identified by the Energy Poverty Advisory Hub (EPAH) have been used: the share of the population having arrears on utility bills, the share of the population unable to keep their home adequately warm, the share of the population having a high share of energy expenditure in income (2M), and the share of the population having a low absolute energy expenditure (M/2). Additionally, a fifth indicator has been computed: the share of the population living in a dwelling with leaks, dampness and rot. To compute these indicators, we used the data from the national Household Budget Surveys (HBS) and the Statistics on Income and Living Conditions (SILC), which are conducted on a periodical basis.
Additionally, to identify the characteristics of those households more vulnerable to energy poverty, an econometric analysis has been performed. This model intends to explain whether a household is likely to be unable to keep its home adequately warm, based on socio-economic factors. To this extent, French data from the SILC has been used.

Results

The measurement tool developed enables the calculation of the five different energy poverty indicators under study for the case of Spain, Italy and France for the years in which the data are available. In all three countries, the situation is alarming, as the values of the indicators have all increased over the 2018-2022 period. Nevertheless, there are differences in the prevalence of different types of energy poverty. Disproportionate energy expenditure is slightly higher in Spain, while low absolute energy expenditure is more prevalent in France and Italy. The share of the population having arrears on utility bills is higher in Spain than in France (9.2% vs. 7.1% in 2022), but it increased over the 4-years period in both countries. The same indicator is lower in Italy, where it remained stable at around 5% over the period.

Both Spain and France show alarming results in the inability to keep home adequately warm, an indicator that has roughly doubled over the past 4 years, although the problem remains much more acute in Spain. Conversely, the share of the Italian population unable to keep their home adequately warm decreased between 2019 and 2020, then it has been stable in 2021 and increased in 2022. Additionally, the share of the population living in a dwelling with leaks, dampness and rot has also increased by about 50% in all three countries between 2018 and 2020.
The econometric model we developed aims to identify the households unable to keep home adequately warm, using socio-economic and demographic factors. Although this model does not clearly identify households at risk, it does identify certain risk factors. The more children a household has, the higher the probability of being unable to keep the home adequately warm it has. Additionally, households whose reference person has no higher education are more likely to be unable to keep their home adequately warm. Finally, if the reference person is inactive or unemployed, the probability of being in energy poverty also increases significantly. This model has yielded a pseudo-R-squared of 0.109.

Conclusions

Despite some disparities, France, Italy and Spain share similar trends in terms of energy poverty. This reinforces the idea that harmonized policies to tackle energy poverty at the European level could be relevant.
The households vulnerable to energy poverty remain difficult to clearly identify precisely because of the multitude of socioeconomic factors to be considered and the multiple facets of energy poverty. However, some vulnerability factors can be identified, such as a low level of education, being inactive or unemployed, or having a large family to support. These factors should help to design policies to adequately tackle energy poverty by addressing vulnerable households.

References

Antepara, I., Papada, L., Gouveia, J., Katsoulakos, N., & Kaliampakos, D. (2020, July 16). Improving Energy Poverty Measurement in Southern European Regions through Equivalization of Modeled Energy Costs . *Sustainability*.

Antunes, M., Teotónico, C., Quintal, C., & Martins, R. (2023). Energy affordability across and within 26 European countries: Insights into the prevalence and depth of problems using microeconomic data. *Energy Economics, 127*.

Baker, K., Mould, R., & Restrick, S. (2018). Rethink fuel poverty as a complex problem. *Nature Energy, 3*(8), 610-612.

Barrella, R., & Romero, J. (2023). Unveiling Hidden Energy Poverty in a Time of Crisis: A Methodological Approach for National Statistics. *Living with Energy Poverty*, pp. 41-51.

Barrella, R., Mora Rosado, S., & Romero Mora, J. (2024). *BOLETIN DE VULNERABILIDAD N°31: El* impacto de la pobreza energética en la vulnerabilidad social de la poblacion atendida por CRE en el contexto de la crisis inflacionaria. Madrid: Cruz Roja Española.

Barrella, R., Romero, J., Linares, J., Arenas, E., Asín, M., & Centeno, E. (2022, April). The dark side of energy poverty: Who is underconsuming in Spain and why? *Energy Research & Social Science, 86*.

Brabo-Catala, L., Collins, E., & Barton, B. (2024). Key Fuel Poverty Indicators and Variables: A Systemic Literature Review. *Economics of Energy, 13*(1).

Camboni, R., Corsini, A., Miniaci, R., & Valbonesi, P. (2021). Mapping fuel poverty risk at the municipal level. A small-scale analysis of Italian Energy Performance Certificate, census and survey data. *Energy Policy, 150*.

Energy Poverty Advisory Hub. (2023). *National Indicators*. Retrieved June 13, 2024, from Energy Poverty Advisory Hub: https://energy-poverty.ec.europa.eu/observing-energy-poverty/national-indicators_en

EPAH. (2022). *Energy Poverty National Indicators: Insights for a more effective measuring.*

EPAH. (2023). *Energy Poverty National Indicators: Uncovering New Possibilities for Expanded* Knowledge

Eurostat. (2021). *Methodological Guidelines and Description of EU-SILC Target Variables.*

Eurostat. (2023, September 13). *9% of EU population unable to keep home warm in 2022*. Retrieved from Eurostat: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20230911-1

International Energy Agency. (2023). *Italy 2023 Energy Policy Review.*

ISTAT. (2023, September 29). *Microdata Files*. Retrieved from ISTAT: https://www.istat.it/en/analysis-and-products/microdata-files

Koukoufikis, G., & Uihlein, A. (2022). *Energy poverty, transport poverty and living conditions- An analysis of EU data and socioeconomic indicators.*

Menyhert, B. (2023). Existing chalenges and potential improvements to energy poverty measurement. *EPAH Annual Conference.* Warsow.
Meyer, S., Laurence, H., Bart, D., Middlemiss, L., & Maréchal, K. (2018, June). Capturing the multifaceted nature of energy poverty: Lessons from Belgium. *Energy Research & Social Science, 40*, pp. 273-283.
Romero Mora, J., Barrella, R., & Centeno Hernáez, E. (2022). *Informe de Indicadores de Pobreza Energética en España 2021.*
Romero, J., Linares, P., & López, X. (2018, April). The policy implications of energy poverty indicators. *Energy Policy, 115*, pp. 98-108.
Romero, J., Linares, P., & López-Otero, X. (2017, July). The policy implications of energy poverty indicators.
Thema, J., & Vondung, F. (2020). EPOV indicator dashboard: Methodology guidebook. *Wuppertal* Institut für Klima, Umwelt, Energie GmbH.

Roula Inglesi-Lotz, Jessika Bohlmann, Victoria Graham, Livingstone Senyonga, Wizelle Kritzinger,

INSTITUTIONAL QUALITY: A HURDLE OR A CATALYST TO ELIMINATING ENERGY POVERTY IN SUB-SAHARAN AFRICA?

Roula Inglesi-Lotz, Professor, Department of Economics, University of Pretoria
Jessika Bohlmann, Ph.D., Research Specialist, Faculty of Economic and Management Sciences, University of Pretoria
Victoria Graham, Professor, Senior Director: Strategic Initiatives and Administration, University of Johannesburg,
Livingstone Senyonga, Ph.D., Senior Lecturer, Department of Energy Science and Technology, Makerere University Business SchoolWizelle Kritzinger, Research Assistant, Department of Economics, University of Pretoria

Overview

In the pursuit of sustainable development, understanding the role of institutional quality in addressing energy poverty is crucial, particularly in sub-Saharan Africa, where access to modern energy services remains a significant challenge. This research investigates the impact of institutional quality on energy poverty in sub-Saharan Africa, covering the period from 2002 to 2022. The study is closely aligned with the Sustainable Development Goals (SDGs), particularly SDG 7 ("Ensure access to affordable, reliable, sustainable and modern energy for all"), SDG 1 ("End poverty in all its forms everywhere"), and SDG 16 ("Peace, justice and strong institutions"). These goals highlight the interconnectedness of energy access, poverty alleviation, and the establishment of strong institutions.

By employing a robust econometric framework, we assess how institutional factors influence energy access and poverty across 43 countries in the region. The study aligns with existing literature (Bousnina & Gabsi, 2023; González-Bautista et al., 2024; Nguyen & Su, 2022) emphasizing the critical role institutions play in shaping policies and resource allocation to mitigate energy poverty. Energy poverty is quantified through two key indicators: access to clean cooking technologies and fuels, and access to electricity, both of which are crucial for improving quality of life and promoting sustainable development in the region. Additionally, more than one measurement for institutional quality is employed due to the nature of the factor and for robustness purposes. These six measures are the Corruption Perception Index, Regulatory Quality, Government Effectiveness, Rule of Law, Democratic Accountability, and Political Stability and Absence of Violence.

Methods

Our analysis employs the System Generalized Method of Moments (SYS-GMM) estimator, as augmented by Arellano and Bover (1995) and Blundell and Bond (1998), to address endogeneity using internal instruments from lagged levels and differences of explanatory variables. The SYS-GMM approach is particularly suited for panel data characterized by few time periods (small T) and many individuals (large N), allowing us to account for dynamic dependencies, fixed effects, and endogeneity (Roodman, 2009). Additionally, this method effectively manages the challenges of autocorrelation and heteroskedasticity within the dataset.

The regression estimation can be specified as:

$$EP_{it} = \beta_0 + \beta_1 EP_{it-1} + \beta_2 INST_{it} + \beta_3 X_{it} + \varepsilon_{it} \quad (1)$$

Where i denotes the country and t denotes the year. EP_{it} is the measure of energy poverty under consideration in the respective models, $INSTit$ is a vector containing the institutional variables, and Xit denotes the vector of control variables, namely GDP per capita, income inequality, and urbanisation. $\mathcal{E}it$ is the error term. Where appropriate, variables are transformed into their natural logarithms (ln).

Results

Our preliminary results indicate mixed effects of institutional quality on energy access. Higher levels of political stability and regulatory quality impede access to energy, suggesting potential inefficiencies or barriers within these frameworks. In contrast, stronger rule of law supports better energy access, highlighting the importance of legal frameworks in facilitating energy distribution. Economically, higher GDP per capita is associated with improved energy access, affirming the role of economic growth in reducing energy poverty. However, income inequality slightly hinders electricity access, though this effect is not robust across all models.

Conclusions

The study concludes that enhancing legal frameworks and addressing economic disparities can play a significant role in improving energy access in sub-Saharan Africa. While some institutional factors may hinder energy access, strengthening rule of law and promoting economic growth can significantly improve outcomes. Policies that reduce corruption, promote equitable economic growth, and address barriers within political and regulatory systems are crucial for improving energy access and alleviating poverty. This research offers valuable insights for policymakers and regional stakeholders, contributing to the broader discourse on sustainable energy development and the role of institutions in achieving the SDGs.

References

Arellano, M., & Bover, O. (1995). Another look at the instrumental variable estimation of error-components models. Journal of Econometrics, 68(1), 29–51. doi: https://doi.org/10.1016/0304-4076(94)01642-D

Blundell, R., & Bond, S. (1998). Initial conditions and moment restrictions in dynamic panel data models. Journal of Econometrics, 87(1), 115-143. doi: https://doi.org/10.1016/S0304-4076(98)00009-8

Bousnina, R., & Gabsi, F.B. Energy poverty, government expenditure, and institution factors in Sub-Saharan Africa countries: evidence based on a panel threshold model. Environ Sci Pollut Res 30, 65512–65526 (2023). https://doi.org/10.1007/s11356-023-27005-1

González Bautista, M. G., Zurita Moreano, E. G., Vallejo Mata, J. P., & Cejas Martinez, M. F. (2024). How Do Remittances Influence the Mitigation of Energy Poverty in Latin America? An Empirical Analysis Using a Panel Data Approach.

Economies, 12(2), 40.

Nguyen, C. P., & Su, T. D. (2022). The influences of government spending on energy poverty: Evidence from developing countries. Energy, 238(Part A). doi: https://doi.org/10.1016/j.energy.2021.121785

Roodman, D. (2009). How to do Xtabond2: An Introduction to Difference and System GMM in Stata. The Stata Journal, 9(1), 86-136. doi: https://doi.org/10.1177/1536867X0900900106

Teresa Magina, Inês Carrilho-Nunes, Margarida Catalão-Lopes,

THE ROLE OF DIGITALIZATION IN REDUCING ENERGY POVERTY

Teresa Magina, Instituto Superior Técnico, Universidade de Lisboa, Portugal
Inês Carrilho-Nunes, CEGIST - Instituto Superior Técnico, Universidade de Lisboa, Portugal
Margarida Catalão-Lopes, CEGIST - Instituto Superior Técnico, Universidade de Lisboa, Portugal

Overview

Energy plays a central role in modern society, serving as a fundamental commodity that supports various activities such as heating, lighting, and cooking. It is one of the most exchanged assets, satisfying human needs and propelling countless services (Wang et al., 2023). The global concerns surrounding the energy system bring awareness of the need to reduce energy poverty. Energy poverty is a complex and multidimensional challenge, with different assessments depending on the context of the study. For instance, for low-income countries, energy poverty involves households lacking access to modern energy for essential activities like electricity and cooking fuels. Yet, for higher-income countries, energy poverty can be described as a situation in which citizens spend most of their income on energy debts or must lower their energy consumption to a level that negatively impacts their well-being, increasing their inability to keep homes adequately warm or cold (European Commission, 2023; McCauley et al., 2019; Zhao et al., 2022).

Many individuals are experiencing energy poverty or are at risk of losing access to essential energy services due to energy price inflation, coupled with low income and the lack of efficient energy systems. As a result, the risk of losing access to crucial energy services increases (European Commission, 2022). Recent metrics reveal that global progress toward universal access to energy has been hindered. For instance, the number of people living without electricity had a global increase in 2022 for the first time in decades, topping the alarming value of approximately 775 million individuals (IEA, 2022). In addition, according to the International Energy Agency (IEA), more than two billion citizens are unable to access clean cooking appliances, falling under the energy poverty bracket (IEA, 2021). Furthermore, the Eurostat indicates that around 9.3% of European Union citizens could not properly warm their homes in 2022 (i.e., about 41 million people). As a result, countries' primary concern should be building a viable power sector.

The path to accelerate the clean and efficient energy transition is, to some extent, focused on the potential of digitalization. By promoting ubiquitous connectivity, digital technologies have been revolutionizing economies, with digitalization being accountable for having the capacity to enhance the energy network's security, sustainability, and accessibility (IEA, 2017). Indeed, digitalization emerges as a potential catalyst for a clean energy transition, with the need for alignment between the rapid pace of digitalization and energy decarbonization services (Wang et al., 2023). Usually called twin transitions, digitalization and decarbonization are often perceived with divergence in what concerns the intensity associated with their deployment. In other words, digital transitions tend to occur faster than energy transitions (Fouquet & Hippe, 2022). Building synergies and fostering connections is necessary to incorporate digitalization into the energy industry. Therefore, new perspectives on the link between digitalization and energy are needed. This article is a step in that direction, exploring the connection between digitalization and energy poverty.

Methods

Econometric models are applied using panel data from 27 European Union countries, for the period 2013 to 2021, to study the impact of the digitalization revolution on energy poverty. More specifically, affordability and thermal comfort issues are assessed, considering variables such as the population's share of arrears on utility bills and the incapacity to keep home warm, using data collected from Eurostat. In addition, the models are disaggregated to test the effects of digitalization on energy poverty for the overall population, but also separately for those below and above the threshold of poverty (i.e., those living below/above the poverty threshold set at 60% of the national median equivalised disposable income). In addition, other economic and energy-related relevant variables are considered, such as the unemployment rate, urbanization level, or electricity and gas prices.

A digitalization index based on digital factors, such as internet access, broadband subscriptions, ownership of digital devices, and usage of e-commerce, among others, is also developed, using Principal Components Analysis (PCA), to serve as a proxy for a country's digitalization level, offering a comprehensive view without multicollinearity concerns.

Results

The preliminary results reveal that digitalization can decrease the share of households with arrears on utility bills and the share of households suffering from an inability to warm homes properly. More specifically, a 1% increase in digitalization's level decreases households' arrears in utility bills by 0.056 percentage points and the incapacity to keep home warm by 0.028 percentage points.
When examining disaggregated models, the impact varies based on whether individuals are below or above the poverty threshold. For instance, the use of e-commerce, a component of digitalization, affects the incidence of arrears on utility bills for those above the poverty threshold but does not show a similar effect for those below it. This can be attributed to the limited access low-income families have to advanced digital technologies, making it difficult for them to experience or benefit from the effects of such digitalization. Regarding the incapacity to keep home warm, preliminary results suggest that individuals below the poverty threshold are the ones more positively influenced by digital technologies.

Conclusions

Digitalization offers opportunities to revolutionize the energy system through practical solutions, such as influencing consumer behaviour and integrating digital technology into economic and energy infrastructure. The policy implications vary depending on the context and the indicators used to measure energy poverty. While these findings are based on studied digital indicators, they confirm the hypothesis that the digital world can pave the way for increased energy access and inclusivity. Nevertheless, further research is necessary to take advantage of the digital revolution and maximize its potential, providing policymakers with practical guidelines to implement it while ramping up the deployment of energy-saving and equity strategies.

References

European Commission. (2023). Energy Poverty in the EU. Available at: https://energy.ec.europa.eu/topics/markets-and-consumers/energy-consumer-rights/energy-poverty-eu_en

European Commission. (2022). Digitalisation of the energy system. Available at: https://energy.ec.europa.eu/topics/energy-systems-integration/digitalisation-energy-system_en

Fouquet, R., & Hippe, R. (2022). Twin transitions of decarbonisation and digitalisation: A historical perspective on energy and information in European economies. Energy Research & Social Science, 91, 102736. https://doi.org/10.1016/J.ERSS.2022.102736

IEA. (2021). Recommendations of the Global Commission on People-Centred Clean Energy Transitions. Available at: https://iea.blob.core.windows.net/assets/07406f49-ebdb-4955-9823-69c52cce04dc/Recommendationsoftheglobalcommissiononpeople-centredcleanenergytransitions.pdf

IEA. (2022). For the first time in decades, the number of people without access to electricity is set to increase in 2022. IEA, Paris. Available at: https://www.iea.org/commentaries/for-the-first-time-in-decades-the-number-of-people-without-access-to-electricity-is-set-to-increase-in-2022

McCauley, D., Ramasar, V., Heffron, R. J., Sovacool, B. K., Mebratu, D., & Mundaca, L. (2019). Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research. Applied Energy, 233–234, 916–921. https://doi.org/10.1016/J.APENERGY.2018.10.005

Wang, B., Wang, J., Dong, K., & Dong, X. (2023). Is the digital economy conducive to the development of renewable energy in Asia? Energy Policy, 173, 113381. https://doi.org/10.1016/J.ENPOL.2022.113381

Zhao, C., Dong, X., & Dong, K. (2022). Quantifying the energy trilemma in China and assessing its nexus with smart transportation. Smart and Resilient Transportation, 4(2), 78–104. https://doi.org/10.1108/SRT- 05-2022-0008

Carlotta Masciandaro, Elisesnda Jové-Llopis, Machiel Mulder

ENERGY POVERTY PERSISTENCE: A CROSS-COUNTRY ANALYSIS WITH A FOCUS ON GENDER

Carlotta Masciandaro, Faculty of Economics and Business, University of Groningen, Groningen, The Netherlands.
Elisenda Jové-Llopis, Chair of Energy Sustainability and Barcelona Institute of Economics (IEB), University of Barcelona, Barcelona, Spain.
Machiel Mulder, Faculty of Economics and Business, University of Groningen, Groningen, The Netherlands.

Overview

Energy poverty, defined as the inability of households to meet their basic energy needs due to low income and/or low energy efficiency, is a rapidly spreading problem in developed countries. This issue is partly explained by the recent energy crisis and measures aimed at advancing the energy transition, which have contributed to higher energy costs for households. In 2019, before the health crisis and the surge in global energy prices, 6.9% of the European Union's population faced difficulties in maintaining their homes at an adequate comfort temperature (Eurostat, 2024). By 2023, this indicator had increased significantly to 10.6% (Eurostat, 2024). In a context where it is essential to transition to a more sustainable energy model without leaving anyone behind, these figures on energy poverty are extremely valuable, as they serve as a crucial diagnostic tool.
Cross-sectional energy poverty indicators report how many households or individuals are living in energy poverty in a given year. However, these indicators do not address the dynamics of energy poverty, such as changes or trends over time. A static view of who is experiencing energy poverty during a specific period provides relevant information but offers an incomplete picture of the extent of energy poverty within the population. It fails to reveal the past trajectory of household energy poverty, and therefore, does not allow us to determine whether energy poverty is a persistent (long-term) or transitory (temporary) phenomenon.

Given the significant economic and social costs associated with energy poverty (European Commission, 2023; Katoch et al., 2023; Primc et al., 2021), it is essential to consider the temporal dimension to obtain a more comprehensive understanding of the phenomenon. This approach is necessary to design precise, evidence-based policies that can effectively combat energy poverty. The academic literature has traditionally focused on identifying the drivers behind energy poverty, commonly referred to as the "triangle of drivers": low income, high energy prices, and low energy efficiency. However, much of this research relies on cross-sectional data, often neglecting the dynamics of persistence and transition in energy poverty (i.e., the probability of moving into and out of poverty). This oversight hinders the formulation and implementation of appropriate interventions tailored to different trajectories of energy poverty, whether chronic or transitory. Effective actions to address energy poverty must vary depending on its persistence.
The main objective of this study is to analyze the dynamics of energy poverty in Spain and the Netherlands, considering differences across households headed by females and males. Beyond providing an update on the current extent of energy poverty in both countries, we contribute to the existing literature and ongoing debate in several ways. First, we explore the drivers of energy poverty persistence and compare the results between two distinct countries: Spain, which has a high level of energy poverty and extensive experience in addressing it, and the Netherlands, a country with low levels of energy poverty where the experiences of vulnerable energy consumers have limited recognition in national policy. To our knowledge, this is the first study to specifically analyze Dutch households in this context. Second, to account for the multidimensional nature of energy poverty, we use various indicators. This approach allows us to identify differences and similarities in the determinants of energy poverty across different measures. Finally, we examine energy poverty as a gender-uneven phenomenon, quantifying the effects of its determinants at a national level. This gender-focused analysis highlights disparities and informs more equitable policy interventions.

Methods

To examine whether energy poverty is a chronic or transitory situation and to compare these patterns between two European countries, we utilized data from the EU Statistics on Income and Living Conditions (EU-SILC). The EU-SILC provides a sample of more than 45,000 household-level data points on energy poverty indicators and a wide variety of socioeconomic variables for the period 2005 to 2021. We applied a dynamic probit model with random effects for our analysis.
A dichotomous dependent variable (Yit) was constructed, taking the value 1 when a household is in a situation of energy poverty—based on indicators proposed by the economic literature such as inadequate temperature and arrears on utilities—and 0 when a household is not considered energy poor. Estimating dynamic panel data models poses two major challenges: handling unobserved individual effects and addressing the well-known problem of initial conditions.
To address these challenges, we assumed a random effects specification (Raymond et al., 2010; Wooldridge, 2010) and followed Wooldridge's (2003) recommendation. This involves specifying unobservable individual heterogeneity by introducing the values of explanatory variables that vary over time in each period (excluding the initial period) as regressors.

Results

After accounting for individual effects and addressing the issue of initial conditions, the preliminary results of this empirical exercise reveal several important considerations. Firstly, we confirm the presence of energy state dependence in both countries. This finding indicates that being energy poor in one period significantly increases the likelihood of remaining energy poor in the subsequent period. Our empirical results also highlight notable differences between the countries, with persistence being higher among Spanish households compared to Dutch households. Furthermore, the results underscore significant gender differences in energy poverty dynamics.

Conclusions

There is little doubt that energy poverty is an urgent problem in Europe, likely to persist in the coming years due to post-pandemic effects and the energy price increases stemming from the Ukraine crisis. This dynamic relationship highlights that the persistent energy poverty trap in Spain and the Netherlands will be challenging to resolve without comprehensive policy interventions. Emergency interventions or temporary measures (from an income perspective) are insufficient to address this issue. Therefore, it is essential to design new tools that can have a real impact in the medium and long term. For these reasons, analyzing and researching energy poverty dynamics is now more important than ever, to develop a comprehensive understanding of the magnitude and root causes of this problem, which is a crucial step towards an effective and just energy transition

References

European Commission (2023). EU Guidance on Energy Poverty. Accompanying the Document Comission Recommendation on Energy Poverty. Brussels, 20.10.2023 SWD(2023) 647 Final.

Eurostat (2024). Inability to keep home adequately warm - EU-SILC survey. https://ec.europa.eu/eurostat/databrowser/view/ILC_MDES01__custom_6719233/default/table

Katoch, O. R., Sharma, R., Parihar, S., Nawaz, A. (2023). Energy poverty and its impacts on health and education: a systematic review. International Journal of Energy Sector Management, 18(2): 411–431.

Primc, K., Dominko, M., Slabe-Erker, R. (2021). 30 years of energy and fuel poverty research: A retrospective analysis and future trends. Journal of Cleaner Production, 301: 127003.

Raymond, W., Mohnen, P., Palm, F., Schim Van Der Loeff, S. (2010). Persistence of Innovation in Dutch Manufacturing: is it spurious? The Review of Economics and Statistics, 92(3), 495–504.

Wooldridge, J. M. (2005). Simple solutions to the initial conditions problem in dynamic, nonlinear panel data models with unobserved heterogeneity. Journal of applied econometrics, 20(1), 39-54.

Wooldridge, J. M. (2010). Econometric analysis of cross section and panel data. MIT Press.

Daniele Lerede, Valeria Di Cosmo

COSTS AND RISKS OF DECARBONIZATION AND NUCLEAR POWER: A TEMOA-EUROPE- SCENARIO ANALYSIS

Daniele Lerede, Open Energy Transition & MAHTEP Group, Email: daniele.lerede@polito.it
Valeria Di Cosmo, Università degli Studi di Torino, Dipartimento di Economia e Statistica "Cognetti de Martiis", Lungo Dora Siena 100a, 10153 Torino, Italy, Email: valeria.dicosmo@unito.it

Europe has a strong dependence on fossil fuels, and natural gas in particular, despite the claimed commitments towards carbon neutrality by 2050. The REPowerEU Plan is reducing the huge amount of gas imported from Russia. Nonetheless, the main strategy to guarantee security of supply mainly envisages long-term agreements with more reliable partners for gas and a larger support to the development of renewables. At the same time, a carbon-neutral energy generation technology like nuclear fission is undergoing a substantial phase-out, and the use of fossil fuels for energy production is discouraged through the adoption of growing carbon tax levels in the form of excise duties and the Emissions Trading System.

This work presents a scenario analysis carried out using the open-software and open-framework energy system optimization model TEMOA-Europe. Taken for granted the absence of Russian gas imports starting from 2027, the examined alternative scenarios envisage:

1) a business-as-usual scenario;
2) a scenario with increasing carbon prices and constraints on nuclear capacity to simulate the current phase-out trend;
3) a scenario with increasing carbon prices and the possibility to increasingly rely on nuclear electricity;
4) a constrained net-zero emissions by 2050 scenario with nuclear power available. We evaluate emissions, energy costs, the profitability of both gas and renewable energy projects providing useful insights for the development and security of the European energy system.

Emmanuel Grand, Keyvan Rucheton, Luis Lopez, Mehdi Aïd, Grégoire Saison

VALUING THE CONTRIBUTION OF AN LNG TERMINAL TO THE NATIONAL SECURITY OF SUPPLY

Emmanuel Grand, FTI Consulting, 10 rue de Bassano 75116 Paris, France
Keyvan Rucheton, FTI Consulting, 10 rue de Bassano 75116 Paris, France
Mehdi Aïd, FTI Consulting, 10 rue de Bassano 75116 Paris, France
Grégoire Saison, FTI Consulting, 10 rue de Bassano , 75116 Paris, France

Overview

The prevailing geopolitical instability in Europe underlines the critical necessity to diversify energy supply sources through investments in energy efficiency, renewable energy, and new gas infrastructure. This context accentuates the importance of securing reliable national supply of natural gas. Yet, uncertainty surrounding long-term natural gas demand and the capital-intensive nature of natural gas assets limit private investments and may result in a failure to answer short to medium-term demand. State aid could help mitigate this market failure, as security of supply is one of the potential exemption criteria to the strict European Commission competition framework.
A systematic method to quantify the improvement in security of supply is presented and applied to an LNG terminal project in a European country, offering a transparent, fact-based approach to support potential decisions to address such market failure.

Methods

In essence, we value the economic contribution of a natural gas asset within a European country by (i) modelling key stress events over a 20-year period and multiplying (ii) the reduction in curtailed demand volume caused by the presence of the asset by (iii) the cost of natural gas disruption, which we discount to establish its present value.
(i) To this end, we develop a linear programming model for volume balancing that minimises the curtailed demand during a stress condition on a weekly basis. The model is calibrated on historical data (demand profils) and takes into account the evolution of the country's gas system (based on the country's reference planning scenario). The "stress-free" model is taken as our baseline system. We select eight independent stress events from national sources and European recommendation affecting both the supply and demand sides (among others, pipeline and storage interruptions, adverse weather conditions, increase in gas demand for export). We declined them in 15 sub-events to account for the possibility of an event having potentially multiple durations. The durations and probabilities are set by cross-checking the national sources, the European recommendations and historical data.
(ii) Each simulation is run twice with and without the LNG terminal to measure its impact in reducing the volume curtailment. We also conducted sensitivity analyses in three additional baseline conditions, anticipating a new pipeline infrastructure delay, a reduction of available volume from a given supplier and a higher domestic natural gas demand.
(iii) The cost of natural gas disruption is based on ACER-published data, giving a cost in euro per MWh of curtailed gas per sub-sector. The values are discounted following ENTSOG Cost Benefit Analysis (CBA) methodology by an annual real social discount factor of 3% per annum.
Finally, to obtain a 20-year probability-weighted value of the contribution of the LNG terminal to the country's security of supply, we select the sub-event of each stress event with the highest avoided cost value and sum the values of all events thus selected across all years.

Results

While the level of avoided curtailment varies according to the stress event modelled, our simulations show that the LNG terminal can be considered as a strategic asset to the country's security of supply, with efficiently diminishing gas curtailment when facing major stress events.

We find that pipeline interruption and sea storms are events with the most avoided curtailment volume with the presence of the LNG terminal. In 2030, the terminal allow to save up to 21TWh, in the case of a seasonal pipeline interruption (November to March), 9.7 TWh in a 2-months interruption and 3.6TWh for a 2-weeks interruption. The avoided curtailment is escalated in the sensitivities: in the case of delay in new pipeline infrastructure, the LNG terminal allows to save 70TWh in the case of a seasonal disruption in the same period. Our simulation of sea storms -affecting the country's offshore terminals for two weeks- shows that an additional LNG terminal reduces by 6TWh the curtailed volume (and up to 12TWh when modelling the sensitivity with volume shortage from an expected supplier).

The reduction in avoided curtailment volume is also observed when modelling the LNG terminal during demand side stress events: a 2-week increase in heating demand results to a minimum of 4TWh of avoided curtailment and a seven day snowstorm -limiting solar capacity- to a minimum of 2.6TWh of avoided curtailment. On the other hand, minor events such as one site storage interruption or increased gas-to-power demand due to heatwaves do not require such flexibility as the system can compensate directly.

Concerning the "monetised" contribution of the asset to the security of supply, we obtain a 20-year weighted probability of 1.2 billion euros with a maximum weigthed single-year value of 109 million euros (baseline conditions) when using the lowest likelihood for each event (between national, European and historically derived probabilities). It increases to 8.6 billion euros over 20 years (baseline conditions), with a maximum single-year value of 801 million euros when using historically derived likelihood.

Conclusion

Comparing the previous minimum 20-year weighted probability contribution of the LNG terminal of 1.2 billion euros with its planned costs, estimated at around 800 million euros, the State aid would be justified. In addition, we have designed our approach to be transparent and fact-based in order to facilitate rational public decision-making. Further research could extend this analysis by incorporating additional potential benefits, such as induced changes in gas and electricity prices or enhanced market diversification. This could be achieved by integrating our security of supply methodology within the broader ENTSOG CBA framework, which includes both monetised and non-monetised indicators.

References

ACER (2018), Study on the Estimation of the Cost of Disruption of Gas Supply in Europe

ENTSO-G (2023), Single Sector Cost Benefit Analysis (CBA) Methodology – draft

M. E. Biresselioglu and al. (2012), Modeling Turkey's future LNG supply security strategy, *Energy Policy* 46/ 144- 152

Paula Gonzalez, Shahriyar Nasirov, Jose Opazo, Claudio A. Agostini, Carlos Silva

DEVELOPERS' PERSPECTIVE ON BARRIERS AFFECTING DISTRIBUTED SOLAR PV GENERATIONS IN CHILE

Paula Gonzalez, Adolfo Ibañez University, Cile
Shahriyar Nasirov, Adolfo Ibañez University, Cile
Jose Opazo, Adolfo Ibañez University, Cile
Claudio A. Agostini, Adolfo Ibañez University, Cile
Carlos Silva, Adolfo Ibañez University, Cile

Overview

Over the last few years, the role of Non-Conventional Renewable Energies (NCRE) in the Chilean matrix has increased significanttly. The participation of NCRE in the total installed energy capacity grew from only 5% in 2014 to 30% in August 2021 (Energía Abierta, 2021). Solar PV technology is the most developed technology, corresponding to 16% of the energy matrix. However, most of this capacity comes from large-scale projects (utility scale). Despite the large resource potential of distributed solar PV generation in the country and all their benefits -emission reductions, cost reductions in electricity supply, decrease in electrical losses, improvement in service quality, and lessening transmission congestions- to date, the progress of these technologies in the country has been low. On reason for this is that distributed solar PV is currently in a development stage and facing several important obstacles.

In this context, we examine the key barriers that influence the implementation of distributed photovoltaic projects in Chile from the perspective of project developers, which is relevant as they are directly involved in the implementation of distributed generation projects. Identifying the main barriers allows to then propose policy recommendations to policy makers and other market players to encourage the deployment of distributed photovoltaic solar generation in Chile.

Methods

The methodology utilized in the paper consists of three complementary methods. First, we designed and implemented a questionnaire survey (comprising quantitative and qualitative data collection). Second, we conducted a series of semi-structured interviews (qualitative data collection only) with the project developers in Chile. Third, we analyzed the data to obtain robuts conclusions. These methods allow us not only to gather detailed and systematic information about the different barriers preventing a higher penetration of distributed solar PV generation in Chile, but also understanding better the exising limitations and analyzing them in a systematic a consistent way.

The questionnaire was designed and developed for conducting an online survey of project developers and obtain their opinions concerning the barriers affecting the distributed solar PV generation in Chile. For this purpose, a selection of potential barriers and relevant market actors were selected first. Then, a preliminary list of barriers was tested in a small pilot study to establish the extent to which the barriers found in the literature were also relevant and applicable in Chile. This was followed by the implementation of a questionnaire survey. Finally, the data collection from the online survey was complemented afterwards by face-to-face interviews from a random sample of selected developers from the survey respondents. The purpose of these interviews was to provide important insights and better understading of the investors' opinions and experiences over the barriers they have faced in the marketplace. In the last phase, the study uses a well-known methodology, based on the Technique of Order of Preference for Similarity with the Ideal Solution (TOPSIS) to identify and prioritize in a systematic and robust way the main critical barriers for the implementation of distributed photovoltaic projects.

Results

The results show that the most important barriers affecting and limiting the implementation of distribuated solar PV projects in Chile are "the structure of the network, its capacity and regulation for expansion" , "the long administrative process and the costs of connection to the network", "uncertainty due to stabilized price policy and other regulatory requirements" and "financial structuring and financing costs". Several of these barriers can be overcome with public policies that are not difficult to designed and implement as they mainly depend on directly government intervention, while others required a change in regulations that need Congress approval and then required a longer time.

Conclusions

The greater expansion of photovoltaic distributed generation in Chile can play a key role in the achievement of main energy objectives of the country established by the National Energy Policy plan, which contemplates fully decarbonizing its energy matrix and reaching 80% of electricity generation from renewable energy sources by 2050. In addition, This is why identifying the barriers that this segment currently faces is key to encouraging its further development.

References

Reindl, K. and Palm, J. (2021) Installing PV: Barriers and enablers experienced by non-residential property owners. *Renewable and Sustainable Energy Reviews.* 141, 110829. https://doi.org/10.1016/j.rser.2021.110829

Roberts M.B., Bruce, A. and MacGill, I. (2019). Opportunities and Barriers for Photovoltaics on Multi-Unit Residential Buildings: Reviewing the Australian Experience. *Renewable and Sustainable Energy Reviews.* 104, 95- 110. https://doi.org/10.1016/j.rser.2018.12.013

Osorio-Aravena J.C., de la Casa, J., Töfflinger, J.A. and Muñoz-Cerón, E. (2021) Identifying barriers and opportunities in the deployment of the residential photovoltaic prosumer segment in Chile. *Sustainable Cities and Society.* 69, 102824. https://doi.org/10.1016/j.scs.2021.102824

Nasirov S., Silva, C. and Agostini, C.A. (2015) Investors'Perspectives on Barriers to the Deployment of Renewable Energy igur in Chile. Energies. 8(5), 3794-3814. https://doi.org/10.3390/en8053794

Ionut Purica, Mircea Munteanu, Munizer Purica

COST OF ENERGY SYSTEM SECURITY: THE ROMANIAN CASE

Ionut Purica, CCDD-Consultative Council for Sustainable Development of Romania;
Mircea Munteanu, (parlamentary expert)
Munizer Purica, INCDMT-National Institute for Research and Development in Microtechnologies
- Bucharest, Romania

Abstract

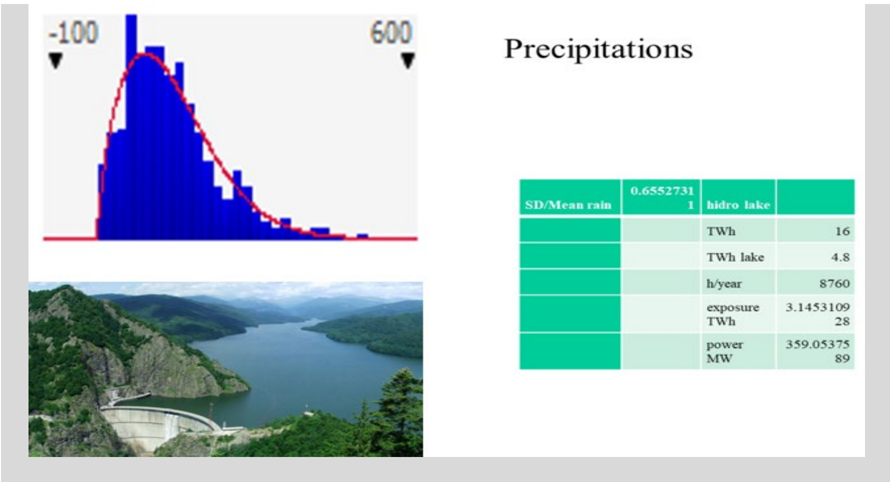
The paper analyzes the need, size and investment cost, for reserve power dictated by the volatility of hydro, photo voltaic and eolian generation, based on the dispersion of their distributions of availability determined from big data analysis.
Moreover, solutions are provided to increase gas grid safety of supply, exposed to climate change risks and city based power prosumers' efficiency.
An exemple is provided for modeling the penetration of clean technologies (PV, Eolian, Hydro, Nuclear) in the power system of Romania.

EU Green Deal

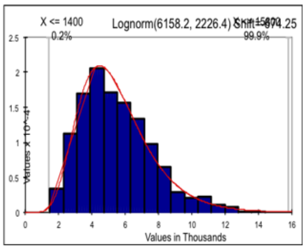
Comunism ended because it did not internalized the cost of capital;
Capitalism may end because it does not internalize the cost of environment.
The Green Deal aims at diminishing the costs to the environment by making the EU economy emission neutral at the horizon of 2050.
Action lines: - Energy - Transport - Buildings - Innovation

Elements of security

According to the Security strategy of the energy systems launched by the EU Commission in 2014 it is necessary to have a diversified portfolio of electrical energy generation technologies that ensures the coverage of situations when various types of risks manifest themselves. The same applies for gas interconnectors and for the climate change risks impact on critical infrastructures.
The standard deviation of each volatile source is giving the size of the needed reserve of power for the system.
The probability distribution are based on real data over sizeable time intervals. For instance for the Danube flow the data period is 1845-2006. For the climate change risks the data period is 1961-2011.
For Italy the gas grid risk map is based on earthquake and land slide and mechanical risk, while for Romania it is based on the climate change risks and mechanical risk.



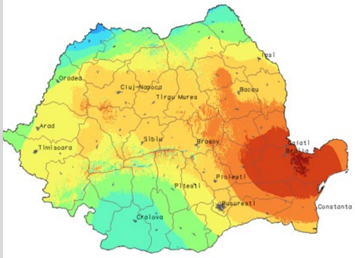
SD/Mean rain	0.6552731 1	hidro lake	
		TWh	16
		TWh lake	4.8
		h/year	8760
		exposure TWh	3.1453109 28
		power MW	359.05375 89



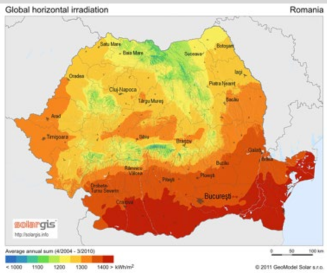
Danube

SD/Mean Danube	0.36153 4215			
		Needed security hydro run river		
		TWh	16	
		TWh run river	11.2	
		h/year	8760	
		exposure TWh	4.04918 3203	
		power MW	462.235 5254	

Wind



SD/Mean wind	0.5	wind	
		TWh	3
		TWh wind	3
		h/year	8760
		exposure TWh	1.5
		power MW	171.23287 67



Photovoltaic

SD/Mean PV	0.6	PV	
		TWh	1
		TWh PV	1
		h/year	8760
		exposure TWh	0.6
		power MW	68.493150 68

In the table below a simulation of a typical financing scheme is presented for a coal power plant of 669 MW having a total of 3000 US$/kW and a lifetime of 50 years (the monetary units in the table are given in US$ but they can be replaced with Euro without changing the values).

financing	FI equity	loc. equity	Comm.loan	Exp.loan	LT loan	Bonds	TO: $/KW	$mm i10	$mm i15	$/K\
							FI equity	0.00	0.00	
i	0.00	0.00	0.13	0.00	0.07	0.06	loc. equity	0.00	0.00	
N	8	8	5	15	15	10	Comm.loan	450.00	450.00	6
PMT	0.00	0.00	269.47	0.00	162.76	72.03	Exp.loan	0.00	0.00	
capital $/kWh	0.0720	0.8	utilization	$/kW	PMT SUM	504.26	LT loan	850.00	850.00	12
fixed op $/kWh	0.0131	40.97	$/KW	$/kW	project life	259.13	Bonds	300.00	300.00	4
var oper $/kWh	0.0011				difference:	94.60%	Total	1600.00	1600.00	23
fuel $/kWh	0.0017	0.47	$/MWh t	$/kWh inv. project life:		0.0370	cost adjustment ratio>		1.00	
TOTAL $/kWh	**0.0879**	3.64	MWh t/MWh				$mm cap	1600.00		
LIFE $/kWh>>	**0.0529**	0.0350	B10-B11				-idc	0.00		
WDR	life	PV cap	PV fix op	PV var op	PV fuel	PV kWh	-pr.conting	0.00		
0.08452	50	3012.72	1068.30	89.63	139.85	81477.64	-wk.cap	0.00		
AFUDC = allowance for funds used during construction							other adj	0.00		
YTC = years to commissioning				i = interest or return rate			net capital	1600.00		
WDR = weighted discount rate				N = years to maturity			MW	669.6		
ERROR	verifies i8 and i29			PMT = annual capital charge			$/kW	2389.49		

Capital charge unit components:	FI equity	loc. equity	Comm.loan	Exp.loan	LT loan	Bonds	TOTAL
$/kWh>>>	0.0000	0.0000	0.0385	0.0000	0.0232	0.0103	0.0720

AFUDC calc.	FI equity	loc. equity	Comm.loan	Exp.loan	LT loan	Bonds	YTC	cashflow %	
	0.00	0.00	92.81	0.00	79.51	25.39	5	0.15	All cost data $/k\
	0.00	0.00	71.15	0.00	62.92	20.15	4	0.15	
	0.00	0.00	51.91	0.00	47.34	15.20	3	0.15	
	0.00	0.00	34.82	0.00	32.73	10.54	2	0.15	
	0.00	0.00	26.19	0.00	25.35	8.18	1	0.20	
	0.00	0.00	8.22	0.00	8.18	2.65	0	0.20	
afudc/kW	0.00	0.00	285.09	0.00	256.03	82.11	623.23	1.00	1.00
$/kW <afudc	0.00	0.00	672.04	0.00	1269.41	448.03	2389.49		
$/kW w. afudc	0.00	0.00	957.13	0.00	1525.44	530.14	**3012.72**		

For WDR:	"i" weighted by PMT shares; N = 1						
	FI equity	sp. equity	Comm.loan	Exp.loan	LT loan	Bonds	TOTAL
PMT	0.00	0.00	1077.73	0.00	1625.36	561.95	3265.04

Conclusions

The results of evaluating the mitigation and adaptation measures to the risks in the energy system (considering only hydraulicity, wind and photovoltaic) lead to the need of coal capacities of at least 1000 MW.

Security to gas supply may be enhanced with North South interconnectors that link the three seas in the East of the EU. Climate change risk becomes important and an insurance policy should be considered fast.

The energy sector may not be regarded from only a commercial view point, its strategic importance as well as the social one make necessary taking into consideration non commercial costs that must be internalized in the financing scheme to reach optimal decisions.

Jens Schmugge, Hans Christian Gils, Hedda Gardian

WHAT IS THE COST OF ENERGY AUTONOMY? — ASSESSING IMPORT INDEPENDENCE FOR A MULTI-MODAL, CLIMATE-NEUTRAL EUROPEAN ENERGY SYSTEM

Jens Schmugge, German Aerospace Center (DLR), Institute of Networked Energy Systems, Curiestr. 4, 70563 Stuttgart, Germany
Hans Christian Gils, German Aerospace Center (DLR), Institute of Networked Energy Systems, Curiestr. 4, 70563 Stuttgart, Germany
Hedda Gardian, German Aerospace Center (DLR), Institute of Networked Energy Systems, Curiestr. 4, 70563 Stuttgart, Germany

Overview

As stated in the Paris Agreement, the energy systems worldwide need to be climate-neutral in the foreseeable future. In Europe, this currently results in a significant scale-up of renewable energies and a corresponding integration of the electricity, gas, heat and transport sectors for a complete decarbonisation until 2050.
Envisioned by many as the key vector for this transition to a sustainable energy system is hydrogen. The general opinion is that this is going to be accompanied by a significant amount of hydrogen imports from outside Europe.
In view of recent past developments, most notably the issues with natural gas-based energy imports that a lot of European countries faced after the start of the Ukraine war, questions concerning the energy security of the continent can be raised for such a future. This is why this contribution aims to analyse what a prospective energy autonomy of Europe would mean for its energy system. To do so, two future energy systems of Europe are compared, one that allows hydrogen imports from outside the regional scope based on cost estimates from other studies, and a second scenario with no supply with energy carriers from outside Europe. A special focus is on the comparison of infrastructure requirements and system costs for a sufficient energy supply.

Methods

A sector-integrated linear optimisation model of the European energy system is used for the analysis of the transformation to a cost-minimal and climate-neutral energy system in the target year 2050. The hourly-resolved model is built within the open-source energy system optimisation framework REMix. It includes around 100 technologies from the electricity, gas and heat sector, with a particularly high resolution of almost 50 different technologies for the latter. The regional granularity with more than 50 nodes is also high and chosen in a way that in areas with higher demand, generation and energy transfer requirements, the density of nodes is higher.
The optimisation is executed on the basis of existing power plant, electricity and natural gas grid capacities. Two scenarios are calculated: one with high hydrogen import costs and almost no resulting imports, the other with low hydrogen import costs and forced imports of cumulated 300 TWh via Mid-Eastern and Northern-African pipeline import routes.

Results

The optimisation results underline the significant ramp-up of renewables required to meet the climate neutrality goal for the target year. This is needed to substitute fossil fuels in all sectors as well as the electrification of the heat, transport and industry sectors. Hydrogen is produced in large scale across Europe to serve local demands and provide flexibility to the power system. Large-scale hydrogen caverns are an important part of the system and act as seasonal storage whereas thermal energy storage and batteries are used for short to mid-term flexibility. The option to repurpose existing natural gas infrastructure for the transmission of hydrogen is commonly used between regions with high renewable potentials and demand centres.

Our analysis indicates that an import-independent European energy system results in greater requirements to build up energy system infrastructure, most notably renewables to supply the electricity demand, electrolyser capacities to supply the evolving hydrogen demand, and seasonal and short-term storage capacities to bridge periods with fewer sun and wind hours. In our analysis, the overall system costs for the two presented systems with hydrogen-import autonomy and forced hydrogen imports differ only by an annual amount of 2 billion €. This indicates that other considerations might take precedence instead rather than pure costs.

Conclusions

Necessity for energy infrastructure changes significantly between a system with and without hydrogen imports for some technologies. Hydrogen transfers via repurposed pipelines commonly occur, whereas the construction of new dedicated hydrogen pipelines is only a rarely-chosen option.
For the assumptions made, the overall system costs of an import-independent Europe do not differ a lot from the system with large shares of hydrogen imports. With regards to energy security, it can be questioned if this measure is actually appropriate or just shifting security concerns towards imports of technologies and/or resources instead of energy carriers themselves. These also mostly come from outside Europe.

References

Wetzel et al. (2024). REMix: A GAMS-based framework for optimizing energy system models. *Journal of Open Source Software*, *9*(99), 6330. https://doi.org/10.21105/joss.06330.

Silvia Ricciuti, Christian Mari, Salvatore Manfredi, Simona Stolklin, Massimiliano Zanichielli, Francesca Giuliano

EMERGING SECURITY AND ECONOMIC CHALLENGE WITHIN RENEWABLE ENERGY COMMUNITIES: COST COMPARATIVE ANALYSIS AGAINST CYBERSECURITY ISSUES IN THE EVOLVING RECs SCENARIO

Christian Mari, Dipartimento di Ingegneria Gestionale, Politecnico di Milano, Milano, Italy,0009-0004-3893-3639
Silvia Ricciuti, Sustainable Energy, Fondazione Bruno Kessler, Trento, Italy,0000-0002-8126-6497
Salvatore Manfredi, Center for Cybersecurity, Fondazione Bruno Kessler, Email: smanfredi@fbk.eu
Simona Stoklin, CIRIAF, University of Perugia, Perugia, Italy, Email: stoklin.simona@gmail.com
Massimiliano Zanchiello, Università Sapienza, Roma, Italy, Email: massimiliano.zanchiello@gmail.com
Francesca Giuliano, Dipartimento di Economia Internazionale, delle Istituzioni e dello Sviluppo, Università Cattolica del Sacro Cuore, Milano, Italy, francesca.giuliano1@unicatt.it

Overview

In the context of the decarbonization of the energy system, the European Union promoted Directive 2018/2001/EU, also known as RED II, proposed a new legal framework for the development of renewable energy sources (RES) and, above all, to increase citizen participation in the energy transition through two new tools: collective self-consumption systems (CSC) and renewable energy communities (REC). The creation, management and optimization of these new realities of widespread energy production and consumption require the use of ICT technologies, without which the integrated production, distribution and efficient use of renewable energy would not be possible. The massive use of ICT technologies essential for the functioning of such systems brings with it the risk of threats from malicious actors, whose objectives may include undermining the stability, functioning and reliability of the community itself. This contribution aims, in the first chapter, to explain the concept of REC and, in the second chapter, to outline the cybersecurity aspects of the REC. The third chapter outlines how the implementation of cybersecurity technologies and procedures have a significant cost that faces against the revenues and savings deriving from the self-consumption of electricity.

Method

Considering the small amount of existing CERs and the quite young age of the existing ones, the main method was to review literature examples in similar context to try to predict possible future scenarios on cyber vulnerability in the context of RECs. The method is strengthened by following as case study different real newborn energy communities. The impact on cost follows typical cost analysis based on benefit and prevention. The idea is to highlight the potential security and economic challenge that will spread together with the emerging energy communities.

Results

The frameworks implemented to counter the dangers of cyber-attacks have a high cost. In fact, they require the purchase of high-performance and expensive IT systems, as well as the use of specific software that requires constant updating. At the same time, the implementation of renewable energy communities requires the implementation of complex IT and monitoring networks which, by their very nature and configuration, can be attacked by external malicious actors. However, current earnings forecasts (communities are evolving now) linked to self-consumption of electricity are poor and therefore in conflict with the costs necessary to implement adequate cyber security barriers. This suggests that sensitive areas will be created that are easily exposed to cyber-attacks and it will be necessary to arrive at a sort of trade-off between energy sales revenues and cyber security implementation costs.

Conclusions

In these new worldwide energy scenarios in which renewable energy communities (REC) are taking on an increasingly relevant role, the risk, for them, of being exposed to cyber-attacks consequently increases.

Despite the social purpose and impact on energy poverty that RECs are expected to have, the risk of malicious intent should not be underestimated. From a software and hardware point of view, there are possible strategies to prevent such risks, however the implementation of the latter requires an additional investment which could affect small/medium sized energy communities, which often have difficulties with the availability of economic resources going into contrast with the financial revenues generated by the communities which are not always so relevant. To maintain low costs and the economic sustainability of renewable energy communities, it will be necessary to shift attention from the expensive implementation of purely technological cyber prevention, based on objective security and the quality of physical cybersecurity tools, to subjective prevention where the informed, trained community's member, is placed at the center, with an active and aware role not only as active member of the community, but aware of the pitfalls arising from cyber-security issues.

References

T. Nguyen Duc, N. Quan, V. Linh, T. Vu, and G. Fujita, 'A Comprehensive Review of Cybersecurity in Inverter-Based Smart Power System Amid the Boom of Renewable Energy', IEEE Access, vol. 10, pp. 1–1, Jan. 2022, doi: 10.1109/ACCESS.2022.3163551

A. Del Pizzo, G. Montesano, C. Papa, M. Artipoli, and M. Di Napoli, '18 - Italian energy communities from a DSO's perspective', in Energy Communities, S. Löbbe, F. Sioshansi, and D. Robinson, Eds., Academic Press, 2022, pp. 303–316. doi: 10.1016/B978-0-323-91135-1.00012-2

M. Nijhuis, M. Gibescu, and J. F. G. Cobben, 'Assessment of the impacts of the renewable energy and ICT driven energy transition on distribution networks', Renew. Sustain. Energy Rev., vol. 52, pp. 1003–1014, Dec. 2015, doi: 10.1016/j.rser.2015.07.124

G. B. Gaggero, D. Piserà, P. Girdinio, F. Silvestro, and M. Marchese, 'Novel Cybersecurity Issues in Smart Energy Communities', in 2023 1st International Conference on Advanced Innovations in Smart Cities (ICAISC), Jan. 2023, pp. 1–6. doi: 10.1109/ICAISC56366.2023.10085312

Zhang, Zuopeng (Justin) ; He, Wu ; Li, Wenzhuo ; Abdous, M'Hammed, Cybersecurity awareness training programs: a cost–benefit analysis framework Wembley: Emerald Publishing Limited, Industrial management + data systems, 2021-03, Vol.121 (3), p.613-636

Lee I., Cybersecurity: Risk management framework and investment cost analysis, Elsevier Inc, Business horizons, 2021-09, Vol.64 (5), p.659-671

Johan Granberg

FUTURE ELECTRICITY GRIDS IN ENERGY ISLANDS – A SCENARIO ANALYSIS WITH CYBER SECURITY IMPLICATIONS

Johan Granberg, RISE – Research Institutes of Sweden, 412 58 Gothenburg, Sweden

Overview

The increasing integration of intermittent renewable energy sources, the impact of extreme weather events, and evolving geopolitical tensions are challenging the stability of transmission grids. In response, there is a growing trend toward developing island-capable microgrids, particularly in Sweden, where the concepts of societal resilience and total defense have gained renewed importance, echoing the strategic imperatives of the Cold War era. These microgrids, capable of operating independently from the main grid, are seen as vital for ensuring energy security and to contribute to grid stability, as well as providing resilience in the face of growing threats. Technologically, island-capable grids can range from basic reserve power systems to sophisticated configurations that allow seamless decoupling and resynchronization with the main grid.

Methods

A research project funded by the Swedish Energy Agency explored the future of energy islands and associated cyber security risks. The study employed scenario analysis, drawing on expert workshops to identify two critical variables for future energy island development: *inclusion of intermittent renewable energy sources* and *implementation of smart demand-side control systems*. A second workshop was held, inviting cyber security experts to assess the implications of the different scenarios.

Results

The horizon scan revealed that both variables are likely to increase in a 10–20-year perspective, due to cost-effectiveness, convenience, and technological advancements. However, this trend also brings heightened cyber security vulnerabilities, as previous research on smart grids have indicated. As power electronics become more prevalent and the interaction between devices increases, the potential for remote access introduces significant cyber risks. On a deregulated energy market, small municipal energy grid operators do not have internal expertise to assess or remedy these risks and will – given a low understanding of the risks – be reluctant to make the necessary investments.

Conclusions

While high investment costs have historically slowed the development of rudimentary island-capable grids into smart grids, it is now economically feasible to do so. However, the associated costs are dependent on the types of security measures that are implemented and maintained, thus giving room for savings if these risks are not properly understood. One of the primary challenges for the energy sector moving forward may be ensuring cyber resilience as these risks increase, in likelihood and in severity. Addressing cyber vulnerabilities is crucial for the sustainable and secure advancement of energy islands, particularly as they become a cornerstone of modern energy systems in Sweden and beyond.

Fulvio Fontini, Cinzia Bonaldo and Damiano Alessi

THE IMPACT OF UTILITY-SCALE RES POWER PRODUCTION ON THE ITALIAN ELECTRICITY PRICES

Overview

The study examines the impact of increased variable renewable energy sources (variable RES) on Italy's electricity system. We simulate demand and supply curves of the day-ahead market for some representative periods and we include energy produced from new solar and wind power plants to assesses the influence of these new investments in terms of prices and potential curtailments. Results indicate significant price reduction mainly in southern Italian zones. However, the northern zone, which handles the majority of Italy's electricity demand, sees fewer benefits. Limited transmis- sion capacity exacerbates this disparity, hindering power transfer from south to north. Conversely, southern zones and islands benefit from photovoltaic and wind investments by lowering prices but also causing high curtailments due to excess generation compared to demand. The study also con- siders planned transmission capacity expansions, showing price reductions in northern zones but insufficient impact in southern zones and high curtailment rates (up to 60%).

Methodology

Italy is divided into seven bidding zones: North (NORD), Centre-North (CNOR), Centre-South (CSUD), South (SUD), Calabria (CALA), Sicily (SICI), and Sardinia (SARD), a configuration influenced by the country's geographical structure. Within each zone, electricity producers and consumers engage in transactions, with limitations on transferring energy between zones. The North zone, which contains the most industrialized regions, accounts for 58% of total electricity consumption in Italy.

Energy can flow from one zone to the neighboring ones, and the maximum transferable capacity across zones is determined by TERNA (the Italian TSO). Regarding new investments in variable RES in Italy, no single dataset provides comprehensive figures. The data used in the study are sourced from the EIA repository managed by the Italian Ministry of Environment and Energy Se- curity (MASE), which tracks large-scale investments required to undergo an Environmental Impact Assessment.

Investment capacity data are converted into energy supply figures, with hourly production calcu- lated for the planned investments by multiplying plant capacities with zonal, monthly, and hourly capacity factors. To avoid randomness in primary energy source availability, the study focuses on two representative days—a Wednesday and a Sunday—of three months: March, November, and July, assuming RES plants operate at their de-rated capacity levels.

The study compares simulation results with observed power prices from actual market clearing in each zone. Supply and demand bids from Gestore Mercati Energetici (GME) for 2019 and 2022 are used to replicate the merit order dispatching and equilibrium price.

Two scenarios are constructed: the "status quo," considering existing bids, and an alternative sce- nario with added RES bids. Market coupling or splitting possibilities are considered, starting with southernmost zones (Sicily, Sardinia, Calabria, and South) due to their net energy export status and high transit constraints. Then, potential market coupling from northern zones southward is tested, since these zones are net energy importers with fewer transmission constraints. The procedure ac- counts for the topology of Italian zones, existing limits, and the location of current and new capacity.

Results

Table 1 presents median price values obtained from simulations for each zone and year. The impact of new renewable RES is notable in southern zones, where prices are driven towards zero. However, as we move northward in Italy, transmission capacity limitations become more restrictive and RES installations are fewer, resulting in a reduced impact on prices. The occurrence of price reductions to zero in some zones but not others highlights challenges in dispatching all generated RES power, particularly from the Centre-South to Centre-North and from South to Centre-South.

This is fur- ther evidenced by the curtailment figures shown in Table 2. The table details average curtailment percentages, indicating the amount of added capacity that cannot be dispatched due to insufficient transmission capacity between neighboring zones.

Table 1: Median electricity prices (e/MWh) under status quo and RES scenarios for the simulated years 2019 and 2022 across different Italian zones

zone	2019		2022	
	Stat. Quo	**RES**	**Stat. Quo**	**RES**
PUN	50.6	26.5	276.0	140.3
NORD	50.6	48.7	276.0	275.0
CNOR	50.6	48.7	276.7	275.0
CSUD	50.6	0	276.5	155.6
SUD	50.0	0	276.5	0
CALA	-	-	270.1	0
SICI	47.8	0	270.2	0
SARD	50.6	0	276.5	0

Table 2: Curtailment percentages of energy produced by new variable RES in different Italian zones for the simulated years 2019 and 2022

zone	2022	2019
SARD	85.3%	80.8%
SICI	59.4%	56.2%
CALA	19.6%	-
SUD	87.0%	83.0%
CSUD	49.3%	81.6%
CNOR	29.2%	4.5%

Conclusions

In Italy, especially in the southern zones, new variable RES investments face significant price and quantity risks due to curtailments. However, even the TSO ambitious plan will not eliminate them which implies high opportunity cost of wasting incentives for investments that shall not be able to fully exploit their production capabilities. This presents a policy dilemma: either further increase transmission grid investments or reduce the flow of investments through adjustments in incentives or the authorization process.

The figures of the foreseen investments suggest that investors are neglecting investment risks when requesting authorizations for utility-scale RES power production. The reasons are unclear, but possibilities include an investment cycle driven by bounded rationality, expectations of regulatory changes to mitigate risk, or regulatory failures in the authorization process. Regardless, the mis-alignment between investment figures, price impacts across zones and technologies, and curtailment consequences highlighted by this work must be addressed in future investment-related policies to ensure efficiency and effectiveness in promoting the energy transition.

Andrea Moglianesi, Léo Coppens, Das Partha, Duchêne François, Marenne Yves

THE IMPACT OF A DUNKELFLAUTE EVENT ON A DECARBONIZED ENERGY SYSTEM

Moglianesi Andrea, VITO, Belgium
Coppens Léo, UMONS, corresponding author
Das Partha, VITO, Belgium
Duchêne François, Royal Meteorological Institute of Belgium, Belgium
Marenne Yves, ICEDD, Belgium

Overview

Long-term system decarbonization strategies focus strongly on electrification of the end-user demand and deployment of renewable energy sources like solar and wind for power generation. Large-scale integration of these intermittent renewable energy sources raises concerns about power system adequacy. This is more relevant during the "*Dunkelflaute*" events, when the availability of solar and wind resources is simultaneously low or non-existent. It increases the need for system flexibility, which should be identified and quantified at the planning stage. In this regard, this study considers the effect of Dunkelflaute on long-term evolution of Belgian power system. A multi-region long-term energy system planning model is developed using the TIMES modelling framework to undertake multiple decarbonization scenarios for Belgium by 2050.

Methods

In the present study a widely used energy system modelling framework "TIMES" (e.g., Plazas-Niño et al., 2022 ; Coppens et al., 2022 ; Balyk et al., 2022), which was developed by IEA-ETSAP, is applied to model the Belgian energy system. To represent the impact of Dunkelflaute periods, the model includes a high temporal and spatial resolution and detailed representation of power import and export curves. This is the first energy system planning analysis carried out with the occurrence of a Dunkelflaute event as sensitivity dimension. In addition, such event is simulated with two different levels of severity, one similar to an historically recorded event, and another, more extreme one. This multi-level analysis is simultaneously cross-referenced with the availability or otherwise of a dispatchable and low-carbon electricity generation resource, the nuclear Small Modular Reactors (SMR).

Results

The *Figure 1* below shows the electricity generation mix in our 3 main scenarios: the Central, Dunkelflaute, and Dunkelflaute Extreme scenarios.

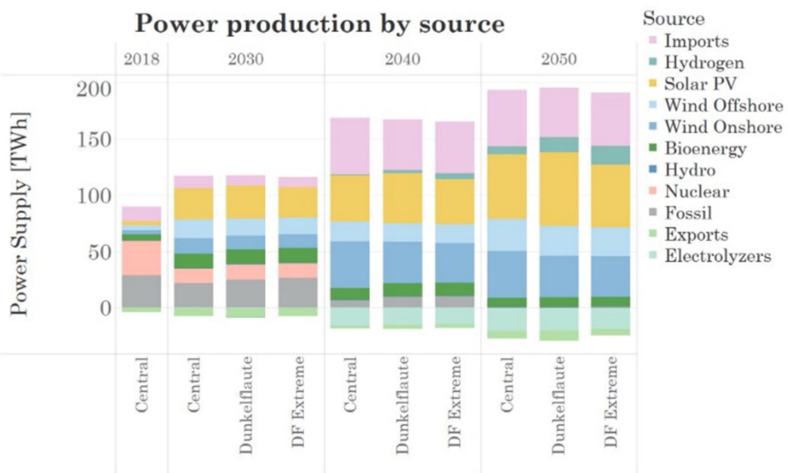


Figure 1. Power Production by Source (Central and dunkelflaute scenarios)

In terms of power production, solar PV contributes to 65 TWh in the Dunkelflaute scenario in 2050 compared to approximately 57 TWh in the Central and 55 TWh in the Dunkelflaute Extreme scenario. Wind turbines produces around 70 TWh of electricity in the central scenario. In the Dunkelflaute and Dunkelflaute Extreme scenarios, the wind power contributions are 63 and 61 TWh respectively. Hydrogen plays a crucial role to face power scarcity during the Dunkelflaute period. In 2050, total electricity production by hydrogen turbines almost doubles (13.5 TWh) in the Dunkelflaute scenario compared to the Central scenario (7 TWh) while, in the Dunkelflaute Extreme scenario, they produce almost 17 TWh of electricity in 2050. However, in all three scenarios it is used as a peaking plant, with a utilization factor between 10 and 13%. Supply of hydrogen comes from imports (66%), electrolysers (33%), and steam methane reforming with CO_2 capture (1%). In 2050, 19-21 TWh of electricity is used by the electrolyzers to produce hydrogen. Imports (26 to 30%) play a crucial role in power supply in all the three scenarios, while biomass also covers a non-negligible share (5%).

To avoid exceeding the 2-page limit, we refrain from providing further details on the results of these three scenarios. Additionally, we do not delve into the outcomes of our other scenarios, including the impact of nuclear SMR availability.

Conclusions

This study, which aims to understand the impact of considering a Dunkelflaute event on a country's energy planning, demonstrates that this impact is far from negligible. Therefore, it highlights the significant advantages that such analysis can produce, even in modelling exercises beyond the Belgian context.
Firstly, however, it is necessary to provide some context by presenting high-level results common to all scenarios. They show some of the possible pathways for Belgium to substantially reduce the carbon emissions of its energy system by 2050. Within the low-carbon scenarios analysed, electrification results to be one key driver for the decarbonization, with the power demand being more than doubled by 2050. This result underscores the need to explore strategies for decarbonizing the power sector. In this regard, renewable energy sources play a paramount role, emerging as winners across all scenarios with large-scale installations of both solar photovoltaic and wind energy (all scenarios foresee at least a quadrupling of the currently installed capacity for both by 2040). However, as wind and solar power are by nature intermittent, there is a need to study how the energy system can face a prolonged period of very low or even zero wind and solar production, commonly referred to as Dunkelflaute periods.
Secondly, it has been possible to identify the increasing capacity of low-carbon backup technology required to compensate for Dunkelflaute periods of increasing severity (Dunkelflaute scenario and Dunkelflaute Extreme scenario). In all cases, the optimal solution has been found to be the installation of hydrogen turbine plants. However, while for the scenario not characterized by Dunkelflaute, the required installed capacity almost equals (6.62 GW) the currently installed capacity of natural gas-based plants (~7 GW), for the intermediate Dunkelfaute case, this value increases by approximately 50%, and in the most extreme case, by 150%. The installation, but more importantly, the operation of such plants entails an increase in decarbonization costs compared to Central Scenario, up to 14% by 2040 and up to 23% by 2050 (in the Dunkeflaute Extreme scenario).
Thirdly, the other sensitivity dimension, namely the potential for investments in fully flexible nuclear power technology (Small Modular Reactor – SMR), significantly influences the overall energy planning strategy of the country. Indeed, in all scenarios where this option is considered, investments exceeding 16 GW of nuclear power by 2050 are projected. Nuclear power then emerges as the primary energy source, providing baseload production for most of the year and transforming the Belgian power system from net importer to net exporter.

This study allows for the study of the relationship between system cost optimality and its level of power supply security. Ultimately, it would be interesting to replicate this analysis with a broader geographical scope, such as at the regional level or even at the European level.

References

O. Balyk *et al.*, "TIM: modelling pathways to meet Ireland's long-term energy system challenges with the TIMES-Ireland Model (v1.0)," *Geosci. Model Dev.*, vol. 15, no. 12, pp. 4991–5019, Jun. 2022, doi: 10.5194/gmd-15-4991- 2022.

L. Coppens, M. Gargiulo, M. Orsini, and N. Arnould, "Achieving −55% GHG emissions in 2030 in Wallonia, Belgium: Insights from the TIMES-Wal energy system model," *Energy Policy*, vol. 164, p. 112871, May 2022, doi: 10.1016/j.enpol.2022.112871.

F. A. Plazas-Niño, N. R. Ortiz-Pimiento, and E. G. Montes-Páez, "National energy system optimization modelling for decarbonization pathways analysis: A systematic literature review," *Renewable and Sustainable Energy Reviews*, vol. 162, p. 112406, Jul. 2022, doi: 10.1016/j.rser.2022.112406.

Marina Bertolini, Pierdomenico Duttilo, Francesco Lisi
IMPACT OF GRID INNOVATIONS ON ELECTRICITY PRICE VOLATILITY IN ITALIAN ISLAND MARKETS

Marina Bertolini, Dipartimento di Scienze Statistiche e Centro Levi Cases,
Università degli Studi di Padova, Italy.
Pierdomenico Duttilo, Dipartimento di Scienze Statistiche e Centro Levi Cases,
Università degli Studi di Padova, Italy.
Francesco Lisi, Dipartimento di Scienze Statistiche e Centro Levi Cases,
Università degli Studi di Padova, Italy.

Overview

Electricity market outcomes, specifically prices and volumes, are significantly influenced by infrastructures. In Italy, electricity market zones have unique features due to interconnection levels, energy mixes, and consumption patterns, especially Sicily and Sardinia with their limited mainland connections. Sicilian prices were studied thanks to the possibility to work on a relatively isolated environment (Sapio and Spagnolo, 2016), also focussing on renewables that play a big role in specific areas (Sapio 2015). The 2016 completion of the Sorgente-Rizziconi cable enhanced the link between Sicily and the mainland, affecting day-ahead prices.
This work examines the impact of grid innovations on the volatility of zonal electricity prices in Sicily by analysing day-ahead prices and their structural components. In a wide sense, it also forecasts the effects of future grid developments on the Sardinian and Sicilian markets. Studying these island markets is crucial to understand how infrastructure affects price volatility. These findings can potentially be generalized to other markets with suitable adaptations.

Methods

The method used in the paper is a structural components analysis on day ahead electricity prices of Sicily (the methodological approach starts from the work of Bernardi and Lisi, 2020). The dataset we used is provided by GME (Gestore dei Mercati Energetici): we used the data on day ahead electricity prices in the market zone of Sicily between 2015 and 2018 and we modelled daily series for each load period.
Results (preliminary)
Preliminary results show that starting from September 2016 (the Sorgente-Rizziconi cable officially entered in force in October 2016) prices in the day ahead market changed, increasing their volatility. We also detect that renewable production is always significant for the averages of prices, while looking at volatility it is significant only during specific time slots (early in the morning and late in the evening).

Conclusions

Infrastructure heavily affect the performance of electricity markets. Since the European policy – as many policies in the world - encourages the creation of local electricity markets (Agostini et al., 2021), it is important to understand the impacts that innovations, in this case structural ones, have on market prices and on the economic environment in general: price volatility has always been linked to the evaluation of investments and the associated risk (Bertolini et al., 2018), and different level of this risk might lead to e.g. different diffusion of renewable production plant and the associated industries. This has also an impact also on several socio-economic parameters, like energy access and welfare.
Studying islanded market is strategic to understand this kind of dynamics, because the effects can be more identifiable: the more a market is connected, the harder is to identify what contributes to its functioning.
Our work, which is still in its early stages, aims to analyse the effect that infrastructural innovations have on local markets from the perspective of price volatility. Preliminary analyses conducted on the introduction of the Sorgente-Rizziconi cable show that the impact on price volatility is evident and clearly recognizable.
This type of analysis allows us to take a step forward in the field of strategic investment evaluation for infrastructures, especially by providing a new perspective for network development plans.
Future work will focus on the possibility of transferring the results of one analysis to other contexts and on extending the methodology to other markets where real-time prices are even more significant, such as ancillary services and balancing markets.

References

Bernardi M., Lisi F., 2020. “Point and Interval Forecasting of Zonal Electricity Prices and Demand Using Heteroscedastic Models: The IPEX Case”. Energies, 13, 6191

Bertolini M., D’Alpaos C., Moretto M., 2018. “Do Smart Grids boost investments in domestic PV plants? Evidence from the Italian electricity markets” Energy, Volume 149, 15 April 2018, Pages 890-902

Agostini M., Bertolini M., Coppo M., Fontini F., 2021. "The Participation of Small-Scale Variable Distributed Renewable Energy Sources to the Balancing Services Market" Energy Economics, Volume 97, May 2021, 105208

Sapio, A., 2015. “The effects of renewables in space and time: A regime switching model of the Italian power price” Energy Policy85(2015) 487–499

Sapio A., Spagnolo, 2016. “Price regimes in an energy island: Tacit collusion vs. cost and network explanations”, Energy Economics 55 (2016) 157–172

Angelo Facchini, Daniele D'Armiento; Rossana Mastrandrea, Diego Garlaschelli, Alessandro Rubino

RENEWABLE ENERGY SOURCES PLANNING AT THE REGIONAL LEVEL: A CASE STUDY IN ITALY

Angelo Facchini, IMT School for Advanced Studeis Lucca, Italy
Daniele D'Armiento, IMT School for Advanced Studeis Lucca, Italy
Rossana Mastrandrea, IMT School for Advanced Studeis Lucca, Italy
Diego Garlaschelli, IMT School for Advanced Studeis Lucca, Italy
Alessandro Rubino· University of Bari, Italy

We use a complex networks approach and portfolio theory to analyse the spatio-temporal evolution of a set of PV and wind generators distributed in the macro-region Toscana-Marche, Italy. The optimization seeks to maximize energy output while minimizing intermittency.

We use hourly data of solar radiation and wind velocity to simulate the temporal evolution of over 130 wind and PV generators distributed over the macro-region. Using a combination of portfolio theory and a clustering algorithm based on complex networks, we can define a number of generator clusters with high internal correlation and near-zero or negative inter-correlation. We also show that the identified clusters also show spatial clustering properties, as reported in Figure 1.

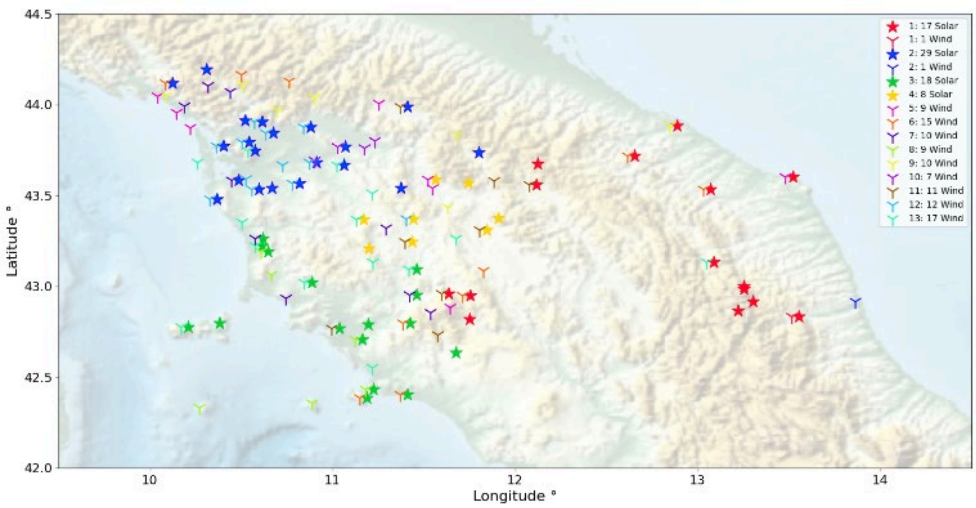


Figure 1 - Clusters identified using the complex networks approach.

Figure 1 also highlights the fact that PV and Wind generators cluster in the same geographic position but belong to different clusters, confirming the fact that PV and wind are complementary both in time and in space.

The method proposed here can provide useful insights regarding the optimal position for the installation of new generation capacity at territorial level. The resultsa can also support the regulators and decision makers when defining new areas for the development of spatially distributed renewable power generators.

Abreham Adera, Raffaele Miniaci, Luciano Lavecchia

RURAL ELECTRICITY AND CHILDREN'S EDUCATIONAL ATTAINMENT: EVIDENCE FROM ETHIOPIA ∗

Abreham Adera, University of Brescia and Italian Energy Poverty Observatory (OIPE), Italy.
Raffaele Miniaci, University of Brescia and Italian Energy Poverty Observatory (OIPE), Italy.
Luciano Lavecchia, Banca d'Italia and Italian Energy Poverty Observatory (OIPE), Italy.

Abstract

Ethiopia faces significant challenges with high school dropout and low completion rates. Concurrently the country has made remarkable strides in rural electrification. In 2000, Ethiopia's electricity generation capacity was a mere 1.7 TWh, which escalated sevenfold to 12.47 TWh by 2016. At this juncture, if electrification can effectively address the challenges of low educational attainment, these impacts should be observable in Ethiopia. However, there remains a limited understanding of how Ethiopia's progress in electrification has influenced child welfare and gender dynamics.

Therefore, this paper examines the relationship between rural electrification and child education, while also exploring the underlying mechanisms. We employ differences-in-differences as the identification strategy. Specifically, we use publicly available data from Ethiopia to assess the impact by comparing households that were not electrified in both 2011 and 2015 with households whose houses were electrified in 2015.

We find that children in electrified households experience significant gains in educational attainment. Additionally, we also find that rural electrification substantially enhances women's engagement in non-agricultural employment, which is likely the channel through which electrification positively impacts child education.

This study elucidates rural electrification's broader impacts on gender equality and child wellbeing. These insights are crucial for policymakers, emphasizing the need for holistic approaches to alleviate rural energy poverty.

Keywords: Energy poverty, Electrification, Children, Education, Women, Employment, Rural, Ethiopia
JEL Codes: I21, I39, J13, J16, J22, J24

Anna Carozzani, Chiara D'Alpaos, Michele Moretto

INVESTMENTS IN HYBRID RENEWABLE ENERGY SYSTEMS IN MOUNTAIN COMMUNITIES

Anna Carozzani, Department of Civil, Environmental and Architectural Engineering - University of Padova, via Venezia 1 – 35131 Padova, Italy
Chiara D'Alpaos, Department of Civil, Environmental and Architectural Engineering - University of Padova and Interdepartmental Centre "Giorgio Levi Cases" for Energy Economics and Technology, via Venezia 1 – 35131 Padova, Italy
Michele Moretto, Department of Economics and Management - University of Padova and Interdepartmental Centre "Giorgio Levi Cases" for Energy Economics and Technology, via del Santo 33 – 35123 Padova, Italy

Overview

In response to global imperatives for sustainable energy practices, the integration of variable energy resources (VERs) into energy systems has gained prominence. In the context of the European Union, diverse physical geographies, socio-economic conditions, and cultural characteristics influence energy supply security and the development potential of different energy technologies. Diversifying investments in the energy sector allows the exploitation of spatial and temporal complementarity of VERs. Hybrid Renewable Energy Systems (HRES), which integrate multiple renewable energy sources with potential coupling to non-renewable energy sources, can address challenges such as intermittency, grid connectivity limitations, and enhance reliability compared to traditional power systems.

Method

We propose a framework that simulates investment decisions in HRES, composed of a Small Hydropower Plant (SHP) and a Photovoltaic Power Plant (PVP) coupled with battery storage, meant to balance supply-demand dynamics of small mountain communities. Key assumptions include the collective ownership of the plants, the sharing of energy production and the use of the SHP as a baseload provider. The model incorporates economic and technical parameters to evaluate its profitability and effectiveness. This community-driven approach aims to maximizing self-consumption efficiency rather than gaining profit from energy selling, and it aligns with sustainable development goals.

Results

We determine the investment value and provide useful insights into the economic viability of the project and the optimal size and timing of investments in HRES under different scenarios. Our analysis disentangles the optimal strategy in the energy production mix from the two technologies to satisfy the energy community demand and minimize energy costs.

Conclusions

The contribution investigates the profitability of different HRES configurations and its effectiveness in promoting sustainable energy practices at the community level. In detail, we show that integrating SHP and PVP technologies with a shared battery storage, allows for the optimization of local resource utilization and the minimization of grid dependency, thereby contributing to global climate goals. The study provides policymakers and stakeholders valuable insights to foster the implementation of decentralized energy systems and accelerate the transition towards a sustainable energy sector.

References

Andreolli, F., D'Alpaos, C., & Moretto, M. (2022). Valuing investments in domestic PV-Battery Systems under uncertainty. Energy economics, 106, 105721.

Borkowski, D., Cholewa, D., & Korzeń, A. (2021). Run-of-the-river hydro-PV battery hybrid system as an energy supplier for local loads.Energies, 14(16), 5160.

Castellini, M. Di Corato, L., Moretto, M. & Vergalli, S. (2021) Energy exchange among heterogeneous prosumers under price uncertainty. Energy Economics 104, 105647.

Streimikiene, D., Siksnelyte-Butkiene, I., & Lekavicius, V. (2023). Energy diversification and security in the EU: comparative assessment in different EU regions. Economies, 11(3), 83.

Diyun Huang and Geert Deconinck

WHY UNDERLYING MARKET STRUCTURE MATTERS FOR THE IMPLEMENTATION OF CROSS-BORDER FINANCIAL TRANSMISSION RIGHTS IN EUROPE

Diyun Huang, Electa department, University of Leuven/ EnergyVille, Kasteelpark Arenberg 10, 3001, Heverlee, Belgium
Geert Deconinck, Electa department, University of Leuven/ EnergyVille, Kasteelpark Arenberg 10, 3001,Heverlee, Belgium

Overview

The development of cross-border financial transmission rights (FTRs) is instrumental for facilitating cross-border bilateral contracts in Europe. ACER has proposed the flow-based method for the allocation of cross-border long-term transmission rights [1]. However, financial transmission rights have been devised and adopted under the nodal pricing-based market structure. The financial transmission right allocation under nodal pricing is subject to the simultaneous feasibility test, which is essentially an optimization algorithm that includes nodal network conditions. The generated outcome from this optimization process can be physically feasible, if the grid typologies do not change from the time of allocation to the real-time operation.

The central question is whether the financial transmission rights can be transposed from nodal to zonal pricing. D'Aertrycke and Smeers evaluated the feasibility of transposing FTRs from a nodal pricing system to a zonal one with two proposed criteria [2]. The first criterion concerned the satisfaction of superposition and netting properties. The authors explained that the superposition and netting properties could not be fulfilled when the generation demand shift keys (GDSKs) are non-linear. The second criterion focused on the firmness of FTRs under FBMC. Their qualitative analysis demonstrated that due to the absence of GDSK in the forward market, the firmness of FTRs is unlikely to be guaranteed.

In this research, we also investigate whether firmness of cross-border financial transmission rights could be guaranteed under zonal pricing in Europe. The adopted approach is to dive into the grid modeling process of the flow-based method and analyse critical challenges to compute grid parameters such as base case and GDSKs in the long-term FTR auction. Furthermore, we investigate whether accurate bidding zone division in the long-term timeframe is a feasible solution to improve the efficiency of financial transmission right allocation under zonal pricing.

Methods

The firmness of the long-term transmission rights is defined as the physical feasibility in this research, which is different from the financial firmness referred in some literature. The physical feasibility of the allocated FTRs in the grid operation could allow the physical energy delivery for the long-term bilateral contracts across borders. The long-term in this research refers to up to 3 to 5 years prior to electricity delivery.

The inherent methodological dilemma for the flow-based model stems from the early construction of grid models by the TSOs prior to market bid submission. At the time of grid modeling, the TSOs need to forecast injection and withdrawal pattern, which is a result of the market clearing. The information asymmetry between system operator and the market players, could lead to inaccurate grid modeling and lowers the economic efficiency for system dispatch. The long-term FTRs serving as financial hedging against congestion risks only represents a fraction of the generation load portfolio from market players. In addition, the long-term timeframe also gives market players the flexibility to invest and adjust their generation and load patterns. In the long-term FTR auction, these effects amplify the information asymmetry between the TSOs and market players, compared with the day-ahead market. Consequently, it increases the uncertainties significantly for the TSOs to forecast the injection and withdrawal patterns.

Results & Conclusions

Our analysis demonstrates how the grid modelling inefficiencies as a result of information asymmetry will be exacerbated in the long-term transmission right auction, compared to day-ahead market.
In the long-term auction for financial transmission rights, forecasting the injection and withdrawal patterns will be much more difficult for the TSOs. As a result, the firmness of the allocated financial transmission rights could not be easily guaranteed as in the simultaneous feasibility test under nodal pricing. In this context, we propose a comprised solution that introduces congestion management consideration in the GDSK computation to help ensure the physical feasibility of allocated FTRs. However, this restricted grid modelling approach has implications for the cross-border trade feasible region and capacity utilizations, which in turn influence the dispatch patterns. Using a four node and five line case study to illustrate the theoretical discussion, the cross-border trade volume and dispatch outcomes are compared between the FTR allocation under nodal and zonal pricing.
The research from Felten et al. indicates that the potentially congested lines in FB model could change when the ex-post realized GDSKs deviate from the ex-ante applied values [3]. In this research, the disparity between the ex-ante and ex-post GDSKs in the case study is demonstrated by their Euclidian distance. Factors that contribute to the deviation between the ex-ante and ex-post GDSKs are linked to intrinsic flow-based methodological dilemma such as information asymmetry and the zonal market model setting. Therefore, the effective identification of congested lines for bidding zone division prior to market opening is not always feasible for the long-term financial transmission right auction.
In conclusion, this research demonstrates the limitations of flow-based method under zonal pricing to support effective implementation of cross-border financial transmission rights.

References

ACER. (2021, January 27). Long Term Flow-Based Capacity Calculation and Allocation Workshop [Power point]. Long Term Flow-Based Capacity Calculation and Allocation Workshop. https://www.acer.europa.eu/sites/default/files/events/documents/2022-01/Long%20Term%20FlowBased%20Capacity%20Calculation%20and%20Allocation%20Workshop%20Thursday%2027%20January%202021%2C%209-12h.pdf

D’Aertrycke, G., & Smeers, Y. (2013). Transmission Rights in the European Market Coupling System: An Analysis of Current Proposals. In Financial Transmission Rights: Analysis, Experiences and Prospects (Lecture Notes in Energy, 7) (p. 549). Springer.

Felten, B., Osinski, P., Felling, T., & Weber, C. (2021). The flow-based market coupling domain - Why we can’t get it right. Utilities Policy, 70, 101136. https://doi.org/10.1016/j.jup.2020.101136

Valentin Satgé

SENSITIVITY ANALYSIS OF LOAD PROFILES: IMPLICATIONS FOR RESOURCE ADEQUACY IN FUTURE POWER SYSTEM

Valentin Satgé, CEA/DES/1-Tésé, Université Paris Saclay, Gif sur Yvette, France, GAEL University of Grenoble-Alpes, France

Overview

In the context of the energy transition, accurately modeling electricity system is essential to understanding the stakes of this transition and ensuring the reliability of future power grids. For France, one key benchmark in ensuring system reliability is maintaining a loss of load duration (LOLD) lower than 3 hours per year, in average, which validate the security of the production and consumption. Resource Adequacy (RA) assessment are used to calculate the "3-hour metric". Traditional RA uses Monte Carlo method, simulations of multiple climatic years and planned/unpla nned outages. These methods effectively capture inter-annual variability by taking numerous loads and climatic values such as capacity factor for variable renewable energy sources.
However, such variations are contingent upon the underlying assumptions that shape the electricity demand profile - factors like the penetration of heat pumps or the rate of building renovations. Forecasting these profiles accurately poses significant challenges . Often, historical data is used as a proxy for future load shapes, but this approach may not fully account for the structural changes that electrification technologies introduce. A slight adjustment can significantly alter the hourly demand profile, often resulting in greater deviations than those typically observed through inter-annual variation alone. Thus, it becomes crucial to investigate how these structural shifts in demand might influence overall system adequacy, potentially in ways that are more disruptive than climatic variability.

Methods

In this study, we investigate the impact of small variations in the electricity load profile on resource adequacy criteria. To do so, a European electricity model is developed based on the French Transmission System Operator projection for 2050, utilizing the hourly dispatch simulation model AntaresSimulator. The model is designed to meet the probabilistic criterion of a maximum of 3 hours annual loss of loads. While the power system is not optimized, it is constructed to be sufficiently representative for conducting sensitivity analysis. A particular focus is made on the French power system.
Four distinct scenarios are modeled: each of them featuring different hourly electricity demand profile - yet still with the same annua) amount. The aim is to explore how tiny variations in key assumptions, such as a small modification in the adoption of electrification technologies, could reshape the hourly load. The 'reference scenario' is based on historical load data: deformation of the profile in the future by new electrification is not taken into account. In the 'winter scenario', the consumption during winter is progressively increased in 2% increments, ranging from a 2% to 12% of increase - modeling a changes in the share of electrification of heat or building renovation. The 'peakload scenario' models a 5% from 20% increase in peak demand - reflecting a greater penetration of heat pump or less intelligent electric vehicles charging. Finally, the 'summer scenario' explores the effect of rising air conditioning usage by applying similar increments to summer consumption.
The analysis aims to demonstrate that even a resource-adequate system, as seen in the reference scenario, can experience significant degradation in adequacy when slight shifts in the load profile appear.

Results

The results ofthis study reveal that even minor modification in the load profile can have a significant impact on system adequacy. An increase of 2% for the winter is sufficient to demonstrate that the system is not resource- adequate anymore. A 4% increase in winter leads to a 50% rise in the number of hours in failure, while this number reaches 120% fora 12% increase.

This study also confirms the importance of using multiple climatic year for resource adequacy assessments.
Out of the 30 climatic years studied in the modeling , only 20% of them were responsible for violating the "3-hour metric ", demonstrating that relying on a limited number of climatic years can distort the results. Using a few years could either capture only difficult or overly favorable years - leading to an oversized or undersized power system. Furthermore, the system 's sensitivity to load variations differs across years: some are only sensible to a change ofthe load during the peak hours, while some LOLD increase only with winter demand increase.
For France, summer load variations had minimal impact on the system adequacy. Yet, in southem regions, such as Italy, Spain or even the state of California, a focus during the summer period might be crucial to ensuring resource adequacy for the system.

Conclusions

This study highlights the criticai role of electricity load shapes in resource adequacy assessment. A slight change in the load profile might have significant impact on the adequacy of the system.
The results of this study could be used by anyone using a power system modeling. While this approach is particularly useful for long-term forecasting models, it may have less immediate application in current system models, where the technological shares of electrification are relatively stable. The use of multiple climatic years is generally sufficient to address inter-annual variability in these cases.
In forecasting model, questions about the electricity load are primordial and structural changes might change patterns in the consumption. While this study used historical load data - largely because such data is easily available for numerous climatic years, the ideai scenario would involve using already modified load shapes to better retlect anticipated future shifts. Even in these ideai cases, small additional changes to the load profile would stili need to be analyzed to fully understand their impact on system adequacy.
Moreover, while total annual electricity consumption is often the primary focus, the shape of the load profile - determined by assumptions about technology penetration, such as heat pumps or electric vehicles, can be just as influential. These findings emphasize the need for deeper integration of load profile studies for specific analysis of resource adequacy assessments, but also in generai forecasting model. Understanding how these variations affect system performance is essential for ensuring the security of supply.

References

B. Leibowicz et. al, (2024), « The importance of capturing power system operational details in resource adequacy assessments", Electric Power Systems Research, Volume 228
Y. Sun et. al, (2022), "Insights into methodologies and operational details of resource adequacy assessments: A case study with application to a broader flexibility framework", Applied Energy 328
O. Anderson et. al, (2024), "lmproved Decarbonization Planning through Climate Resiliency Modeling", IEEE
S. Gaure et. al, (2022), "True or not true: CO2 free electricity generation is possible", Energy 259
T. Knittel et. al, (2024), "Heating electrification in cold climates: Invest in grid flexibilities", Applied Energy 356
R. Golombek et. al, (2022), "The role of transmission and energy storage in European decarbonization towards 2050", Energy 239

Marta Moretto, Matteo Di Castelnuovo

THE MEAN REVERTING BEHAVIOUR OF ITALIAN ZONAL ENERGY PRICE: AN ANALYSIS OF THE LONG-TERM MERIT ORDER EFFECT

Matteo Di Castelnuovo, SDA Bocconi School of Management and Bocconi University, Via Roberto Sarfatti, 25, 20100 Milano MI
Marta Moretto Terribile, Bocconi University, Via Roberto Sarfatti, 25, 20100 Milano MI,

Overview

This research aims to analyze the long-term effect of the order of merit (MoE) in Italy due to renewable energy penetration (RES) during the period from 2005 to 2020.
While there are several studies that analyze MoE in the short term, there are still few that focus on the long-term effects. The reduction in the price of electricity has a long-term effect on the renewable energy investment decisions of power operators.
As the model of Acemoglu, Kakhbod, and Ozdaglar (2017) suggests, the MoE is stronger when the diversification of energy portfolios is greater. Yet, by introducing investment decisions into their model, we get that the return on investment in renewables decreases when the share of renewable energy production by individuals increases relative to the share produced by operators.
Based on this conjecture, we study how renewable energy penetration affects wholesale electricity prices in different parts of the Italian market by estimating a mean-reversion process.

Method

The analysis is based on a quantitative approach that takes into account the division of the Italian electricity market into six geographical zones (excluding the Calabria zone that was introduced in January 2021) and the use of price models based on stochastic processes. Historical zonal energy price data were collected by the Gestore dei Mercati Energetici (GME), covering the North, North-Central, South-Central, South, Sicily and Sardinia zones. Although the penetration of renewables has levelled out the PUN, the price of electricity is still quite volatile, e.g. due to seasonality, at hourly, weekly, monthly and quarterly levels. The mean-reverting method allows the identification of a long-term average price that tends to stable values. Given the long period of the quarterly time series of energy prices, both 'seasonality' and possible jumps are less important because the quarterly time series are much less variable. This makes it possible to use traditional models, as Schwartz (1997) or Pindyck (1999).

Results

The results show a clear MoE in almost all analysed zones, with a significant reduction in electricity prices, especially in those where the increase in renewable generation was greatest. To show the reduction in energy prices, both time series of each zone were analysed to compare the MoE at the zonal level, and three series (North, South, Sicily) divided into two sub-periods (2005 to 2012 and 2013 to 2020) to study the MoE temporally in the same zone. The analysis showed that in Northern and Southern Italy, as well as in Sicily, the increase in renewable energy production contributed decisively to the decrease in electricity costs. In particular, the fall in prices is more evident when comparing the two periods analysed, with a gradual reduction in long-term prices in the second phase. Although other factors, such as the fall in gas prices, influenced energy prices, the growth of renewables played a crucial role in determining a downward trend in energy prices, confirming the importance of these sources in the future of the Italian electricity market. Finally, the prices observed in 2020 appear to be an anomaly due to the COVID-19 pandemic. The normality tests on the residuals, conducted using the Jarque-Bera test, confirm that the data for all areas except Sardinia are not normally distributed due to this anomaly. Removing the year 2020, the results show that the historical data are normally distributed in all areas.

Conclusions

The first conclusions drawn from the research confirm that the growth of production from renewable sources has contributed substantially to the reduction of electricity prices in the different areas of the Italian market. In particular, the area of Sicily showed the greatest reduction in the long-term average price, due to both the high starting price and the growing production of energy from renewable sources. The mean reverting model used proved to be effective in predicting long-term price trends, confirming the presence of a clear merit order effect in all the areas analysed. Although the role of renewables was decisive, other factors, such as gas price trends and market policies, also contributed to price volatility. The research suggests that further research could focus on post-2020 developments, considering the impact of the energy crisis and changes in market structure.

References

Acemoglu, D., Kakhbod, A. and Ozdaglar, A. (2017). 'Competition in electricity markets with Renewable Energy Sources', The Energy Journal, 38(1_suppl), pp. 137–156.

ARERA (2020). 'Revisione della regolazione della bolletta 2.0 per maggiore semplicità, comprensibilità e uniformità'. Available at: https://www.arera.it/fileadmin/allegati/docs/24/136-24.pdf

Cartea, Á. & Figueroa, M.G. (2005). 'Pricing in electricity markets: A mean reverting jump diffusion model with seasonality'. Applied Mathematical Finance, 12(4), pp.313-335.

Pindyck, R. S. (1999). 'The Long-Run Evolution of Energy Prices'. The Energy Journal, 20(2), pp. 1–27.

GME (2024). 'Esiti Gas MGP'. Mercato Elettrico. Available at: https://www.mercatoelettrico.org/En/esiti/MGP-Gas/EsitiGasMGP.aspx

Sabino, P. & Cufaro Petroni, N. (2021). 'Fast pricing of energy derivatives with mean-reverting jump-diffusion processes'. Applied Mathematical Finance, 28(1), pp.1-22.

Schmeck, M.D. & Schwerin, S. (2021). 'The effect of mean-reverting processes in the pricing of options in the energy market: An arithmetic approach'. Risks, 9(5), p.100.

Marta Castellini, Chiara D'Alpaos, Fulvio Fontini, Michele Moretto

OPTIMAL INVESTMENT IN STORAGE IN A DISTRIBUTED RENEWABLE ENERGY SYSTEM

Marta Castellini, Department of Economics and Management "Marco Fanno", University of Padova, Italy; Fondazione Eni Enrico Mattei, Italy
Chiara D'Alpaos, Department of Civil, Enviromental, and Architectural Engineering- University of Padova, Italy
Fulvio Fontini, Department of Economics and Management "Marco Fanno", University of Padova, Italy;
Michele Moretto, Department of Economics and Management "Marco Fanno", University of Padova, Italy;

Overview

Renewable energy generation plays a crucial role in the energy transition. Nevertheless, as many Renewable Energy Sources (RES) are intermittent, specifically photovoltaic (PV) generation, there are often mismatches between energy production and demand. These mismatches can be partially reduced thanks to storage systems. In this paper, we investigate the decision to invest in a PV power plant coupled with a Battery Energy Storage System (BESS), namely an Energy Storage System (ESS). In our setting, the BESS is connected to the national grid and the PV plant: energy can be produced, purchased from the grid, stored, self-consumed, and fed and sold into the national grid. PV production and energy consumption loads evolve stochastically over time. In addition, BESSs are costly, and energy stored has an opportunity cost, which depends on the prices of energy purchased from the national grid and energy fed into the grid, respectively. Nonetheless, BESSs can significantly contribute to increase ESSs managerial flexibility and, in turn, ESSs value. In detail, we investigate the optimal capacity of BESSs that maximizes ESSs expected net present value. We also analyse ESSs management costs to provide insights on ESSs optimal management strategy.

Methods

The problem we address allows the identification of the optimal level for the battery such that it is minimized the expected discounted sum of the opportunity cost of keeping the energy into it plus the power purchase costs net of revenues accruing from selling excess power to the grid over a planning period that we approximate to infinity. The optimization problem is solved under the assumptions that both the cumulative distribution of PV energy produced and the cumulative distribution of the energy demanded by the end-user (i.e. the load) evolve according to an Arithmetic Brownian Motion (ABM), whereas the price of the energy purchased from the grid evolves according to a Geometric Brownian Motion (GBM), and the price received for the energy sold and fed into the grid is always lower than the price of energy purchased from the grid.

Results

When the average production is above the average demand, energy is sold to the grid, and expected management costs reduce. If the selling price of energy increases, the optimal capacity reduces and the optimal policy is to sell energy to the grid and leave as little energy as possible in the battery. Furthermore, the opportunity cost of buying energy from the grid in the future is more than offset by the benefit of selling excess energy to the grid. Conversely, if the selling price decreases, there is no advantage in selling energy. Nonetheless, the value of energy stored increases due to hedging risk related to purchasing energy from the grid. This in turn generates an increase in the capacity of the battery. When the volatilities associated to production and demand increase, the risk of incurring increased operating costs is reduced by increasing the capacity of the battery, which in turn reduces the risk of incurring a buying price higher than the selling price of energy.

Conclusions

We implement a theoretical model to assess the optimal storage capacity in a dynamic pricing environment. In detail, we disentangle the importance of integrating the technical characteristics of the battery (i.e. its minimum and maximum levels), the dynamics of RES production and energy demand with economic factors (i.e. costs and revenues) in the assessment of the storage optimal size. Our framework can be useful in the design of an optimal incentive scheme and provides valuable insights on the participation of ESS owners in the capacity market to increase of energy savings.

References

Andreolli, F., D'Alpaos, C., & Moretto, M. (2022). Valuing investments in domestic PV-Battery Systems under uncertainty. Energy economics, 106, 105721.

Castellini, M. Di Corato, L., Moretto, M. & Vergalli, S. (2021) Energy exchange among heterogeneous prosumers under price uncertainty. Energy Economics 104, 105647.

de Sisternes F.J., Jenkins J.D. & Botterud A. (2016) The value of energy storage in decarbonizing the electricity sector. Applied 175, pp. 368 – 379.

Acknowledgements. Chiara D'Alpaos, Fulvio Fontini and Michele Moretto acknolwedge the financial support of Fondazione Cariparo, within the project PROTECTO (grant n. 59586). Marta Castellini acknowledges the financial support received by the European Union - NextGeneration EU, in the framework of the GRINS - Growing Resilient, INclusive and Sustainable - project (GRINS PE00000018 – CUP C93C22005270001). The views and opinions expressed are solely those of the author and do not necessarily reflect those of the European Union, nor can the European Union be held responsible for them.

Jennifer Considine, Philipp Galkin, Carlo Andrea Bollino, Abdullah Al Dayel

STORAGE VALUATION: INVESTIGATING THE LINK BETWEEN BENCHMARK PRICING DYNAMICS AND ECONOMIC FLUCTUATIONS

Jennifer Considine, Visiting Researcher, King Abdullah Petroleum Studies and Research Center (KAPSARC). P.O. Box 88550, Riyadh 11672, Saudi Arabia.
Senior Research Fellow, University of Dundee, Centre for Energy, Petroleum & Mineral Law and Policy (CEPMLP). Dundee, Scotland, UK.
Philipp Galkin, Visiting Researcher, King Abdullah Petroleum Studies and Research Center (KAPSARC). P.O. Box 88550, Riyadh 11672, Saudi Arabia.
Carlo Andrea Bollino, Visiting Researcher, King Abdullah Petroleum Studies and Research Center (KAPSARC). P.O. Box 88550, Riyadh 11672, Saudi Arabia. University of Perugia, Perugia, Italy.
Abdullah Al Dayel, Research Associate, King Abdullah Petroleum Studies and Research Center (KAPSARC). P.O. Box 88550, Riyadh 11672, Saudi Arabia.

Highlights

- We introduce an index that captures the price movements of heavy crude oil
- The index is built upon a storage valuation spread option model
- The index can forecast a regime change in the data ahead of the break point dates
- It can be used as leading indicator for the major crude oil benchmarks

Abstract

This paper introduces a heavy oil price index and examines its links with benchmark heavy oil prices and economic fluctuations. It is built based on a revenue-based storage valuation model that ties the value of storage to the spread between the price of heavy oil purchased from competitors and the domestic spot price. That value, in turn, can be interpreted as a benchmark heavy oil price, reflecting the shadow price of storage, and can be modeled as a simple spread option. High frequency daily data is used to determine the shadow value of heavy crude oil storage at different strategic locations. The values are aggregated to derive a global heavy crude oil storage index as a benchmark for heavy oil prices. This index can be used to improve the performance of market participants in heavy crude oil trading, hedging and investments.

The index captures major price movements among the leading heavy oil and primary benchmarks and can be used to provide advanced signals for energy policy and to balance global and regional markets for heavy oil, an increasing valuable resource throughout the energy transition. Finally, the index is evaluated in terms of its potential to reflect future economic fluctuations and geopolitical risk in energy markets, as well as its forecasting potential with applications to risk management and policy.

Keywords
Heavy crude oil; price index; price forecast; oil storage; spread option.
Classification Codes C5; Q4; G1; D4

Federico Santi

LONG-DURATION ENERGY STORAGE FOR POWER SYSTEM SERVICES AND INDUSTRIAL HEAT DECARBONIZATION. TECHNOLOGY ASSESSMENT OF POWER-TO-HEAT APPLICATIONS.

Federico Santi, Proofessor **Sapienza** *U*niversity of Rome, Italy

Abstract

The article examines the energy storage needs of power systems as a function of the growing penetration of Variable Renewable Energies (VRE), in a cross-sectoral perspective of combination with the decarbonization of industrial heat through electrification.
In particular, the application of Electric Thermal Energy Storage (eTES) for power-to-heat (P2H) services in the industrial sector and flexibility and Long-Duration Energy Storage (LDES) services potentially supplied to the power systems are analyzed from a technological perspective.
An assessment of the Electric Thermal Energy Storage (eTES) technologies currently available on the market, with various degrees of technological readiness level (TRL), is carried out.

Clara Fuhrer

EFFECTS OF A SYSTEMATIC VARIATION OF LOAD PROFILES ON A CLIMATE NEUTRAL ELECTRICITY SYSTEM IN GERMANY

Clara Fuhrer, Institute of Energy Economics and Rational Energy Use, University of Stuttgart, Heßbrühlstr. 49a, 70565 Stuttgart

Overview

The current government of Germany has declared the goal of reaching climate neutrality in the year 2045. In order to achieve this goal, the energy system needs to undergo a transformation towards renewable energy generation and emission free technologies. This results in a drastic decrease in control capacity. Large shares of the electricity generation are volatile wind and solar generation and thus not adjustable to the electricity demand. The difference between the volatile renewable generation and the electricity demand is crucial when determining the storage and flexibility requirements and thus drives the system costs. In energy system analysis the electricity demand is often given by standard load profiles based on historical data. This does not account for changes resulting from new technologies such as electric vehicles and heat pumps that introduce new demands as well as potential behavioural changes due to societal changes that change the demand pattern. An example for such a behavioural change is the increase in home office as a result of the COVID-19 pandemic. The goal of my research is to analyse the effects of such changes in the electricity demand pattern on the electricity system. To gain systematic understanding of these effects a systematic variation of electricity demand pattern is proposed.

Methods

Real historical load profiles exhibit certain characteristics which can be used to obtain standard load profiles. Typical temporal clusters that show similar characteristics are working days, Saturdays and Sundays or different seasons of the year. In this work peak position, peak height, peak width and number of peaks are chosen as descriptive characteristics. For a systematic variation of these characteristics they have to be parameterised in a mathematical model.

Parametrisation of load profiles

The goal is to parameterise real historical electricity load data from the years 2015 to 2022 for Germany. In order to do so with a manageable number of parameters the profile for each year with a time resolution of 1h is aggregated into typical daily profiles for workdays, Saturdays and Sun- and holidays for each season. The differentiation into the different seasons is made because the typical daily profile for each season has different characteristics due to differences in heating demand and daylight hours. The differentiation into workdays, Saturdays, Sundays and holidays is made due to different consumer behaviour. These daily profiles are then parameterised via peak position, peak height and peak width of the two peaks. Furthermore, typical weekly profiles with a time resolution of one day for each season and a typical yearly profile with a time resolution of one week are aggregated and parameterised. The weekly profile is not part of the systematic variations and therefore is not parametrised via one ore multiple peaks but via a polynomial fit. The yearly profile is parameterised via peak position, peak height and peak width of its two peaks. The parametrisation leads to seven parameters for the daily and seven parameters for the yearly profile that are determined via a non-linear least- squares fit of the model to the data. The Levenberg-Marquardt algorithm is used for fitting.

Generation of a synthetic load profile

The obtained parametrization described above is used to generate a synthetic load profile. This is done by generating time series data in accordance with the functions parametrised by the parameters determined by the performed fit. The data generated for workdays, Saturdays and Sundays for each season is normalised with the total of the respective day obtained from the parametrised fit function for the weekly profiles for each season. The assembled data for each week is then normalised with the total of the respective week obtained from the parametrised fit of the yearly profile. The data with hourly resolution assembled in this way depicts the synthetic load profile of the respective year.

Systematic parameter variation
The parametrisation of the load curves is done with the objective of describing the data on base of the chosen characteristics, peak height, peak width and peak position, which are meant to be varied. Due to the requirement of the total load value staying the same for a better comparison of temporal changes, peak height and peak width are related. In a first parameter variation the peak height of the daily profiles is varied for both peaks in the same way e.g. both daily peaks are doubled and in a contrary way e.g. the first peak is halved and the second doubled. This is done in equal fashion for every day of the year. Furthermore, the peak heights of the yearly profile are varied. Here only an equal change of both peaks is considered due to the fact that both peaks are likely caused by the same reasons. As a second relevant parameter the positions of the peaks in the daily profile is changed to be closer together and further apart by up to four hours. All in all, only individual changes and not a combination of different variations is considered for a first test of the parameter variation.

Results

To analyse the effects of the changes in load profiles on the electricity market a test model is built with the electricity market model E2M2. The test model is a greenfield electricity market model with a zero CO_2 emission restraint in order to depict the goal of climate neutrality. The model scope is the region of Germany for one year. Invest option for generation technologies are wind onshore, wind offshore, PV, and biomass with CCS. Storage technology invest options are stationary batteries and hydraulic pump storage. The model optimises the invested capacities and the electricity generation for a given load profile by minimising the system costs. A number of key parameters such as system costs, electricity prices, CO_2 emissions, electricity generation technology mix and installed capacities per technology are analysed for the different load profiles resulting from the parameter variation. The changes of those key parameters are set in relation to the changes in the profile peaks. Furthermore, the range of considered parameter variations is analysed for changes in the system in regard to one or more of its key parameters. The goal is to identify regimes of variations for which the changes in the overall system are small and to identify tipping points. At tipping points a small change in the load profile leads to a bigger change in the system which potentially enters a different regime. By showing these effects over a wide range of parameter variations of the load profile the possible effects of future load profiles changes on the electricity system are shown.

Conclusions

The possible effects on the electricity system of changes in the electricity load profile in Germany are analysed via a systematic parameter variation. This variation is made possible by the proposed parameterisation of certain load profile characteristics such as peak position or peak height. Due to the systematic variation it is possible to show the behaviour and possible tipping points of certain key parameters in the electricity system in regard to a variation of the load profile.

Alessandro Sapio

WHOLESALE ELECTRICITY PRICE INDEX FORMULAS AND VOLATILITY

Alessandro Sapio, Parthenope University of Naples, Department of Business and Economics, via Generale Parisi 13, 80132 Napoli (Italy).

Overview

In 2023, 9 million electricity users in Italy still benefited from the maggior tutela ("enhanced protection") regime. Their end user tariffs were set by the regulatory authority and revised quarterly. Though, by July 2024, 4.5 million non-vulnerable end users have to choose a free-market retailer. End user prices will be allowed to change with a higher frequency than regulated tariffs, as they may track wholesale prices - indeed, some electricity suppliers compute end user prices as a markup on the so-called PUN-Prezzo Unico Nazionale (the wholesale price index). Consumer associations expect a strong increase in the energy bill for households, e.g +8.5% according to Federconsumatori.

Less attention is paid to a potential surge in end user price volatility. This is surprising in spite of the evidence of risk averse (Qiu et al. 2017) and loss averse (Nicolson et al. 2017) electricity users, and the exposure to shocks that affect volatility at lower frequencies (pandemics, critical minerals crisis, Ukraine war, Red Sea crisis, extreme climate events). Moreover, hedging through derivatives is inaccessible to households and SMEs, who may be lacking assets and financial literacy.

The paper explores if volatility for end users can be mitigated by changing the wholesale price index formula used by retailers. Behind this proposal lies the following insight: PUN is a weighted average of zonal wholesale electricity prices, and as such can be seen as the value of a portfolio - only that probably is a bad portfolio: zonal prices may be positively correlated and the zonal weights are not optimally set by the regulator. Therefore the paper seeks alternative weighting schemes that deliver a less volatile wholesale price index.

Method

Methodologically, the paper goes through the following steps.

First, hourly time series of IPEx zonal prices and zonal purchases between 2005 and 2019 are analysed, to assess cross-correlations between the "asset values" of the PUN "portfolio". Such a preliminary step is useful to verify if the PUN variance is larger than the variance of zonal electricity prices, or to put it another way, how far are zonal shares in national wholesale electricity demand from risk-minimising shares. Common components, such as country-wide macroeconomic shocks, broad meteorological events, and international fuel prices should induce positive correlation among zonal prices, yet negative correlation may occur due to congestion.
Second, once established that there is room for improving upon the PUN in volatility terms, the paper explores and compares three proposals:

1) variance minimisation: zonal weights solve a constrained variance minimisation problem; the constraint may allow for risk premia or risk penalties;
2) lagged demand shares: the weighting scheme relies on lagged zonal demand shares, as they may be less correlated than current zonal demand shares with current zonal prices;
3) MAVER and Time Shift: building upon a market reform proposal by Confindustria (2022), the price index would be a weighted sum of PPAs for renewables and the marginal price bid from programmable sources; the weights should solve a constrained variance minimisation problem.

Notice that the computation of variance-minimising zonal weights relies on a data sample of a certain length (e.g. one year), and therefore the same zonal weights are applied to prices in different times - unless a rolling scheme is applied. Conversely, lagged demand shares retain the frequency of change of the original time series.

Results

A first set of empirical results concerns the cross-correlation among zonal prices and among zonal purchase values. Correlations are generally positive, albeit imperfectly so and with varying magnitudes, except in 2010 and in 2014 when they were negative. This is indirect evidence that PUN was more volatile than its components, hence there is room for improving the price index towards risk mitigation.
Next, the alternative electricity price indexes are compute using historical zonal electricity prices and the newly proposed weighting schemes.

The index computed using variance minimising zonal shares shows smaller infra-annual standard deviation than the observed PUN in most years, but not in all (i.e. not in 2006, 2007, 2011, 2014). Even when the variance-minimisation weighting scheme performs better, the largest reduction in standard deviation is only 1.62%. Allowing for risk premia and penalties, efficient frontiers are computed.
Using lagged demand shares would have allowed to reduce volatility in all years except in 2014 and 2016. In some years (2012, 2013) the largest reduction in volatility is achieved through a 3- months lag, while longer lags (up to 6 months) are needed in the remaining years.

The analysis of the index based on the MAVER & Time Shift proposal is still work in progress.

Conclusions

As shown by the empirical analysis, there exist alternative weighting schemes that, had they been applied to historical IPEx data, would have mitigated wholesale electricity price volatility. Though, reductions in volatility would have been rather small and in some years, the weighting scheme based on zonal demand weights performed better.
It may sound surprising that variance-minimising zonal shares underperform zonal demand shares. Though, it is worth considering that variance-minimising zonal shares are computed for a relatively long time horizon (1 year), whereas zonal demand shares vary with a hourly frequency, possibly in response to price peaks. Also, a mean-variance based risk management may be inappropriate in the context of electricity prices.
The take-home message is that risk-averse consumers and their associations can bargain retail price-setting rules that mitigate volatility. It is left to future research to assess whether the proposals examined in this paper would be incentive-compatible with electricity suppliers.
But before that, more research is needed about a number of limitations in the present analysis: optimisation could be done on shorter time horizons; the variance minimising zonal weights could be computed through a rolling scheme; the analysis could be repeated using other risk management objectives (e.g. VaR) that are more relevant with skewed and fat-tailed electricity price data; the role of congestion patterns in affecting the relative performance of the proposed wholesale price indexes deserves to be studied.

References

Baik, Y. J., Doshi, G. (2021). An Equilibrium Analysis of Power Purchase Agreement.
De Siano, R., Sapio, A. (2022). Spatial merit order effects of renewables in the Italian power exchange. Energy Economics, 108, 105827.
Nicolson, M., Huebner, G., Shipworth, D. (2017). Are consumers willing to switch to smart time of use electricity tariffs? The importance of loss-aversion and electric vehicle ownership. Energy research social science, 23, 82-96.
Qiu, Y., Colson, G., Wetzstein, M. E. (2017). Risk preference and adverse selection for participation in time-of-use electricity pricing programs. Resource and Energy Economics, 47, 126-142.

Lorenzo Monga, Davide Della Giustina, Antonio Di Giovanni, Gornati Stefano Angelo, Bartolomeo Greco

EVOLUTION OF CONSUMPTION IN THE CITY OF MILAN

Lorenzo Monga, Lead Author, A2A Spa, Italy
Davide Della Giustina, A2A Spa, Italy
Antonio Di Giovanni, Gornati Stefano Angelo, Bartolomeo Greco, A2A Spa, Italy

Overview

Cities play a pivotal role in achieving climate neutrality by 2050, with a significant challenge being the development of solutions for heating and cooling urban areas that result in low CO_2 emissions. This trend will represent opportunity and challenge for grid operators: A2A – a multi-utility primarily operating in the norther regions of Italy – created a data-driven model to forecast urban energy consumption, distributed photovoltaic generation, and CO_2 emission trends.
The model predicts consumption fluctuations and peaks by taking into consideration historical data and socio-economic factors, enabling efficient resources allocation, network extensions planning and management. The European and Italian Energy Transition targets represent the main drivers used to obtain energy trend that allows to provide information as well as the investments needed to achieve such targets.

Method

The simulation evaluates the annual energy consumption and the distributed generation of the three primary energy vectors – heat, electricity, and natural gas – in the city of Milan and it provides a forecast of their evolution through 2050.
The model can generate various scenarios by assessing how the city's energy demand for heating and cooling, private and public transportation fleets, PV production, and other parameters will evolve in the coming years.
The prediction of future trends primarily hinges on two key factors: the building renovation rate and the heat pump installation rate. These factors are influenced by the evolving regulatory framework, including the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED), as well as governmental grants such as the known as the Super Bonus 110% and the Ecobonus.

Results

The derived scenarios indicate an overall reduction in energy demand between 22-32% in 2050 driven by more efficient building solutions and the adoption of technologies such as heat pumps, electric vehicles, and district heating.

This shift is mainly supported by:
- the increasing consumption of electricity over gas. The widespread adoption of electric technologies will boost electrical demand by 40%, while gas consumption will decrease by nearly 60%.
- district heating will play an important role as enabler of decarbonization, particularly in cities like Milan, where it can recover waste heat from data centers or local renewable energy sources, contributing over 90% of distributed energy.
- the industrial sector efforts will focus primarily on electrification, biomethane, and hydrogen utilization.

This progression is consistent with the objectives of the Energy Transition and the mandated reduction in CO_2 emissions (projected to be 80% in Milan compared to 2015 levels) as stipulated by European and National directives. Achieving the decarbonisation objectives to meet the EPBD targets in the residential sector may be particularly challenging due to the associated costs for the residents of Milan, unless an incentives scheme is implemented.

Conclusions

The model facilitates the forecasting of energy demand and CO_2 emissions trends up to the year 2050. These projections will aid in investment planning and expedite the energy transition while meeting European and Italian energy targets.
Energy companies are bound to a tariff system designed to support investments while private citizens would need government or municipal grants or tax incentives in order to reach the energy efficiency targets.

Claudia Amadei, Cesare Dosi, Francesco Jacopo Pintus

THE ROLE OF STRUCTURAL CHANGES FOR THE REDUCTION OF ENERGY INTENSITY: DOES OFFSHORING MATTER? EMPIRICAL EVIDENCE FROM OECD COUNTRIES

Claudia Amadei, Department of Economics and Management, University of Padova & Interuniversity Research Centre on Public Economics, (CRIEP).
Cesare Dosi, Francesco, Department of Economics and Management, University of Padova & Interuniversity Research Centre on Public Economics, (CRIEP)
Jacopo Pintus, Department of Economics, Ca' Foscari University of Venice & CRIEP.

Overview

Over the past decades, world energy–related carbon emissions have steadily increased, albeit at a lower rate than global GDP. To date, the relative decoupling between emissions and economic activity has been mostly driven by reductions in the energy intensity of GDP.
Reductions in the energy intensity can be either due to changes in the economic landscape, namely by structural shifts towards more or less energy-intensive activities (structural effect) or by within-sector technological improvements, that may drive down the amount of energy used per unit of activity (sectoral effect) (Metcalf, 2008; Voigt et al., 2014; Hardt et al., 2018). Although these processes both affect the measurement of national intensity performance indicators, the consequences, in terms of global emissions, can vary depending on whether structural changes are mirrored by equivalent changes in domestic consumption patterns. If that does not occur, a reduction in the amount of primary energy used per unit of GDP may simply hide an increased offshoring of energy intensive activities to other countries (the so-called pollution haven hypothesis, see Bhattacharya et al., 2020). Given that emerging economies typically employ more polluting production technologies and export lower-end products associated with higher carbon emissions, the consequences for the global burden of emissions may vary (Fan et al., 2021). Indeed, it is always the case that national "production-based" and "consumption-based" emissions diverge to an extent in an open economy, with the latter taking into account emissions embodied in imported and exported goods and services, along with the differences in the resource-intensiveness of imported productions (OECD, 2016).
The main objective of the paper is to investigate the effects on energy intensity evolution of structural changes in the economy that are not mirrored by similar variations in the sectoral composition of final demand, in a sample of 15 developed OECD countries. Given that synchronized changes are a necessary condition to meet global climate change mitigation efforts and reduce carbon emissions, our aim is to shed some light on the role of national energy intensity improvements on global decarbonization.

Methods

The sample selection is that of fifteen developed OECD economies [1], over the time period 1970-2020. Our empirical strategy is twofold. We first adapt a country-specific standard Index Decomposition Analysis (IDA) of the change in energy intensity of GDP, by including an offshoring factor. This enables the study of energy intensity's historical variations and that of their main drivers, starting from those that are identified by the Kaya Identity. Then, we estimate a Bayesian Structural Panel VAR where we proxy demand-invariant structural changes with a shock in a novel instrument given by a measure of divergence between consumption-based and production-based carbon emissions. We build a statistical index tracking the time-varying divergence between these two variables, which provides, therefore, a measure of how much emissions associated with a country's final demand differ from those associated with its production over time. Indeed, the carbon effects of a structural variation in the economy are likely characterized by a change in the discrepancy between the production-based and consumption-based emissions, allowing us to appreciate the possible role of offshoring in the achievement of environmental quality improvements.

[1] Germany, United States, Italy, Great Britain, New Zealand, Spain, Belgium, Canada, Finland, France, Norway, Japan,Netherlands, Sweden and Denmark

We then include in the Panel SVAR specification endogenous variables that allow to control for the effects of structural and sectoral effects on the evolution of national energy intensity. The demand-invariant nature of the shock is imposed in the recursive identification strategy, assuming that the shock that are evaluated cannot affect on impact the domestic demand

Results

The IDA findings support the hypothesis that in most of the OECD developed countries of our sample the offshoring of energy-intensive activities has played a quite significant role in the downward evolution of the energy intensity, and thus, carbon intensity of the economy. The role of offshoring is comparable in magnitude to that of within-sector energy efficiency improvements, supporting the hypothesis of a relevant role of this factor in the attainment of national energy efficiency for developed economies. Accordingly, from the structural Impulse Response Functions of the Panel SVAR, shocks in the carbon emission divergence measures are associated with structural changes which negatively and persistently affect energy intensity evolution. The nature of the shock as a demand-invariant structural shock is confirmed by the structural impulse responses for the proxies of structural effects from the Kaya identity included in the model. Sub-sample estimations performed to relax the cross-sectional homogeneity assumption in the estimation further suggest that offshoring plays a significant role in this mechanism, given that the effects are more persistent for economies that experienced a negative contribution of offshoring to the historical evolution of national energy intensities.

Conclusions

The key intuition of our results is that part of the decrease in some developed economies' energy intensity observed in the last decades might be attributable to structural variations caused by the offshoring of energy intensive activities, and therefore should not be claimed as environmental improvements. Indeed, as our work suggests, switching the perspective from which emissions are accounted may affect inferences on the level of energy efficiency in most developed economies. The related implications are straightforward: the two approaches to measuring emissions should always be treated as complements, to provide a complete overview of environmental degradation phenomena from a global and a far-reaching perspective. Furthermore, the role of energy intensity reductions in the decarbonization processes of many developed and emerging economies may weaken when considering the fact that consumption-based and production-based emissions diverge. This implies that, at the global level, emissions' reduction targets should also account for the role of consumption in the attainment of environmental improvements. Emissions' reduction targets posed at the consumption-based levels of emissions could then work as an implicit carbon tax.

References

Bhattacharya, M., Inekwe, J. N., and Sadorsky, P. (2020). Consumption-based and territory-based carbon emissionsintensity: Determinantsandforecastingusingclubconvergenceacrosscountries. *EnergyEconomics*, 86. 1

Fan, W., Luo, X., Yu, J., and Dai, Y. (2021). An Empirical Study of Carbon Emission Impact Factors Based on the Vector Autoregression Model. *Energies*, 14(22):7794. 1

Hardt, L., Owen, A., Brockway, B., Heun, M. K., Barrett, J., Taylor, P. G., and Foxon, T. J. (2018). Untangling the drivers of energy reduction in the UK productive sectors: Efficiency or offshoring? *Applied Energy*, 223:124–133. 1

Metcalf, G. E. (2008). An empirical analysis of energy intensity and its determinants at the state level. *The Energy Journal*, 29(3):1–26. 1

OECD (2016). OECD CO2 emissions embodied in consumption. OECD Directorate for Science, Technology and Innovation Flyer. 1

Voigt, S., Cian, E. D., Schymura, M., and Verdolini, E. (2014). Energy intensity developments in 40 major economies: Structural change or technology improvement? *Energy Economics*, 41:47–62. 1

Seikh Hayatul Haque, Niels Oliver Nagel, Ian M. Trotter, Erik Trømborg, Eirik Ogner Jåstad

THE ENERGY SYSTEM IMPACTS OF ELECTRIC HEATING IN NORTHERN EUROPE UNDER VARIABLE HISTORIC WEATHER SCENARIOS

Seikh Hayatul Haque Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway
Niels Oliver Nagel, Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway
Ian M. Trotter, Institute of Public Policy and Sustainable Development/Department of Agricultural Economics, Universidade Federal de Viçosa, Brazil
Erik Trømborg Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway
Eirik Ogner Jåstad, Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway

Overview

Today the European heating sector is heavily dominated by fossil fuels (Eurostat 2024) and electrification of heating with renewable power is a central strategy in decarbonizing the North European energy system (Wråke et al. 2021; Trotter et al. 2023). Today high loads and moderate renewable output compared to the yearly average are typically already found in the coldest months (Gallo Cassarino et al. 2018) and more direct electrification would exacerbate this situation, potentially threatening the security of supply (Eggimann et al. 2020). Simultaneously will the increased demand increase the weather-driven variability and uncertainty of both power generation and consumption, implying that greater flexibility will be required in the power system to ensure a secure and stable power supply (Staffell and Pfenninger 2018; Zeyringer et al. 2018).
This study analyzes the energy system impacts of electrification on the heating sector under varying historic weather scenarios using the Balmorel energy system model. The study includes demand, capacity investments, and power price impacts across different combinations of electrification levels in different weather years. The analysis focuses on the Nordic countries, Norway, Sweden, Finland, and Denmark, but interesting findings are found for the rest of Europe as well, through changes in import/export balance from the Nordic countries. Previous studies focusing on electric heating use a single or few weather years, which limits the robustness of the results (Gea-Bermúdez et al. 2021; Wråke et al. 2021).

Method

To scrutinize the impact of electrical heating in the Nordics under various weather conditions, we use the energy system model Balmorel (Wiese et al. 2018). The model covers the power and district heat market in Europe with a particular focus on Northern European countries. Balmorel covers production, transmission, storage, and demand as well as new investments in production capacity in the included countries. The flexibility and precise temporal resolution of the model make it ideal for investigating the influence of varying weather conditions on the heat and power sectors. In this study, the model has been further developed to include a range of weather years in order to account for normal, average, and extreme weather conditions, based on historical weather patterns for the last 40 years. The new extended portfolio of weather years includes profiles for wind, solar, hydro, and heating demand. This ensures that the historical correlation between different renewable technologies and demand remains consistent for all the weather years. The tested scenarios span different weather years, environmental policies, and demand scenarios for heating as well as industrial electricity demand.

Results

Our findings offer significant insights into the interplay between electrification and weather variability impact on the electricity demand from the district heating sector and renewable supply.

The findings focus on the performance and cost-effectiveness of the heating sector, which in turn influence electricity prices and the need for capacity investments in generation and flexibility within the energy system. The results show that higher levels of electrification generally lead to improved efficiency and reduced emissions. However, the associated costs and benefits are highly sensitive to weather conditions. For instance, dry and cold years pose significant challenges to maintaining a balance in supply and demand, indicated by high sparks in power prices. Flexibility options such as more flexible demand, transmission capacity investments, and more bioenergy in district heating could help reduce the stress on the supply and demand balance in light of "the heating transition" in the Nordics, due to reduced hydropower availability, necessitating greater reliance on alternative energy sources. Conversely, wet years enhance hydropower capacity, making high electrification scenarios more economically viable. In Norway and Sweden, where hydropower constitutes a substantial portion of the energy mix, in wet weather years, electric heating is the most economically viable solution. Finland and Denmark, with more diversified energy portfolios, show varied impacts based on the interplay between electrification levels and weather patterns.

Conclusion

The study highlights the critical need for integrating comprehensive weather data into energy system models. This integration is fundamental for accurately gauging the impacts of electrification on the Nordic district heating energy system. The results may significantly differ based on the weather years considered, therefore underscoring the significance of modeling weather uncertainties for decision-makers. Strategic investments in energy storage and grid infrastructure, coupled with enhanced flexibility from biomass-based heating, are recommended as viable approaches to alleviate the stress on the energy system. As a direction for future research, it would be beneficial to broaden the scope of the analysis to encompass the whole of Europe. Additionally, future work should delve deeper into modeling various sensitivities. This includes different policy pathways and projections moving towards the year 2050.

References:

Eggimann, S., Usher, W., Eyre, N., Hall, J. W. (2020). How weather affects energy demand variability in the transition towards sustainable heating. *Energy*, 195: 116947.https://doi.org/10.1016/j.energy.2020.116947

Eurostat. (2024). *Production of electricity and derived heat by type of fuel [nrg_bal_peh]*. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_bal_peh&lang=en (accessed: 10.06.24).

Gallo Cassarino, T., Sharp, E., Barrett, M. (2018). The impact of social and weather drivers on the historical electricity demand in Europe. *Applied Energy*, 229: 176-185.https://doi.org/10.1016/j.apenergy.2018.07.108

Gea-Bermúdez, J., Jensen, I. G., Münster, M., Koivisto, M., Kirkerud, J. G., Chen, Y.-k., Ravn, H. (2021). The role of sector coupling in the green transition: A least-cost energy system development in Northern-central Europe towards 2050. *Applied Energy*, 289: 116685. https://doi.org/10.1016/j.apenergy.2021.116685

Staffell, I., Pfenninger, S. (2018). The increasing impact of weather on electricity supply and demand. *Energy*, 145: 65-78.https://doi.org/10.1016/j.energy.2017.12.051

Trotter, I. M., Bolkesjø, T. F., Jåstad, E. O., Kirkerud, J. G. (2023). Power-to-heat will increase power system weather risk: The Nordic case. *Sustainable Energy Technologies and Assessments*, 56: 103033 https://doi.org/10.1016/j.seta.2023.103033

Wiese, F., Bramstoft, R., Koduvere, H., Pizarro Alonso, A., Balyk, O., Kirkerud, J. G., Tveten, Å. G., Bolkesjø, T. F., Münster, M., Ravn, H. (2018). Balmorel open source energy system model. *Energy Strategy Reviews*, 20: 26-34. https://doi.org/10.1016/j.esr.2018.01.003

Wråke, M., Karlsson, K., Kofoed-Wiuff, A., Folsland Bolkesjø, T., Lindroos, T. J., Hagberg, M., Bosack Simonsen, M., Unger, T., Tennbakk, B., Ogner Jåstad, E., et al. (2021). *Nordic Clean Energy Scenarios: Solutions for Carbon Neutrality*. NER, 2021:01. Oslo: Nordic Energy Research. p. 174.10.6027/NER2021-01 http://norden.diva-portal.org/smash/get/diva2:1589875/PREVIEW01.jpg

Zeyringer, M., Price, J., Fais, B., Li, P.-H., Sharp, E. (2018). Designing low-carbon power systems for Great Britain in 2050 that is robust to the spatiotemporal and inter-annual variability of weather. *Nature Energy*, 3 (5): 395-403.10.1038/s41560-018-0128-x

Carolina Bonardi Pellizzari, Cristiano Franceschinis, Tiziano Tempesta, Mara Thiene, Daniel Vecchiato

ASSESSING THE IMPACT OF ENERGY EFFICIENCY ON REAL ESTATE VALUES: A HEDONIC ANALYSIS IN PADUA, ITALY

Carolina Bonardi Pellizzari, Università degli studi di Padova, Department of Land, Environment, Agriculture and Forestry (TESAF), Viale dell'Università, 16, 35020, Legnaro (PD), Italy.
Cristiano Franceschinis, Università degli studi di Padova, Department of Land, Environment, Agriculture and Forestry (TESAF), Viale dell'Università, 16, 35020, Legnaro (PD), Italy,
Tiziano Tempesta, Università degli studi di Padova, Department of Land, Environment, Agriculture and Forestry (TESAF), Viale dell'Università, 16, 35020, Legnaro (PD), Italy,
Mara Thiene, Università degli studi di Padova, Department of Land, Environment, Agriculture and Forestry (TESAF), Viale dell'Università, 16, 35020, Legnaro (PD), Italy
Daniel Vecchiato, Università degli studi di Padova, Department of Land, Environment, Agriculture and Forestry (TESAF), Viale dell'Università, 16, 35020, Legnaro (PD), Italy,

Overview

Renewable electricity generation is growing rapidly but still falls short of meeting rising demand. The International Energy Agency (IEA) reported that after a 7% increase in 2020, renewable electricity generation was projected to rise by 8% in 2021 and over 6% in 2022. However, these gains were expected to meet only about half of the global demand growth for those years (IEA, 2021). In 2022, the EU's electricity consumption dropped by 3.5% due to high energy prices, partly triggered by Russia's invasion of Ukraine, also leading to the highest growth in power generation emissions since 2003 (IEA, 2023). Technologies and policies have been developed to improve energy efficiency and reduce consumption and emissions. In the housing sector, energy efficiency includes technologies such as solar panels, modern heating systems, efficient lighting and appliances, wall insulation, and advanced window frames (Nicolae & George-Vlad, 2015). These technologies enhance both new and older buildings, improving energy performance, comfort, and creating green jobs (Meijer et al., 2012). To measure how efficient a dwelling is in terms of energy use and allow its comparison to other dwellings, the Energy Performance Certificate (EPC), mandated by the EU's Energy Performance of Buildings Directive (EPBD) 2002/91/EC, rates the energy efficiency of buildings at sale or lease (European Commission, 2002). The EPBD directive was revised through the years including 2024 (EU/2024/1275) to accelerate building renovations and accommodate regional differences (European Parliament and Council, 2024). This initiative supports the EU's goal of carbon neutrality by 2050, as buildings account for 40% of energy consumption and 36% of energy-related emissions. (European Commission, 2021).
In recent years the literature has been pointing to a capitalization of EPC in property prices (Fregonara & Rubino, 2021). In this context, the application of hedonic models (Rosen, 1974) has proven to be a valuable tool for estimating and understanding the effects of energy efficiency on housing values. Despite several studies in the literature that use hedonic models to estimate the effects of energy efficiency on housing prices, there are still conflicting results regarding these effects. In addition, it is important to note that in Italy, most studies have relied on listing prices instead of transaction prices due to challenges in obtaining actual transaction data, potentially leading to different results. This study aims to determine the extent to which energy efficiency influences the real estate market using as study case the municipality of Padua (Northeastern Italy) by estimating hedonic models using both listing and transaction prices.

Methods

To quantify the effects of energy efficiency in property price, energy performance certificates (EPC) of apartments located in the municipality of Padua were used. Specifically, two samples were used: (i) a sample of 712 listings from February 2022 obtained through web scraping techniques developed in Python programing language applied to a famous listing website in Italy; and (ii) a sample of 222 real estate transactions that occurred between July 2022 and February 2023 accessed from the database of the Italian Revenue Agency (*Agenzia delle Entrate*). These data were then separately used in two models to estimate the effect of different energy performance classes on (i) asking prices and (ii) sales prices. The energy classes were grouped into A (best-performing), BCD, and EFG (worst-performing). In addition to EPC, two other variables commonly known to influence property price were included in the models: (i) size (total area of the apartment including garage, in m2) and (ii) zone (location of the apartment within the municipality). The models were estimated by using R Studio version 4.2.3 (R Core Team, 2023).

Results

For the sales contracts model, the results show that when compared to the intermediate class (BCD), the premium price for an apartment with the best energy performance (EPC=A) is 33.8% (p-value<0.001), while apartments with the worst performance (EPC EFG) experience a 21.8% (p-value<0.001) decrease in value. As for the listings model, the premium price for EPC=A is 40.9% (p-value<0.001) and the decrease in price for those with EPC=EFG is of 17.1% (p-value<0.001).
The other two variables included in the models were statistically significant (p-value<0.001) and presented the expected effects, and together with the EPC variables, they were able to explain 58.3% of the variation of the listing prices and 61.2% of the transaction prices.

Conclusions

Although further research is needed to validate our results, the findings of this research shed light on the interaction between sustainability and real estate valuation, providing valuable information to support urban planning and investors. The capitalization of energy efficiency in property prices seems to be higher for asking prices and is likely linked to the increased energy costs coupled with regulations for the reduction of emissions, such as the EPBD. Finally, the use of Big Data collected with the web crawling technique resulted particularly effective, enabling the rapid gathering of large samples and therefore allows to overcome the difficulty of operating with real transaction data especially in the Italian or similar context, where data are available, but of difficult accessibility.

References

Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings, 91 (2002). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32002L0091

European Commission. (2021). *Making or homes and buildings fit for a greener future*.

Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast), (2024). http://data.europa.eu/eli/dir/2024/1275/oj

Fregonara, E., & Rubino, I. (2021). Buildings' energy performance, green attributes and real estate prices: methodological perspectives from the European literature. *Aestimum*. https://doi.org/10.13128/aestim-10785

IEA. (2021). *Electricity Market Report*. I. E. Agency. https://www.iea.org/reports/electricity-market-report-july-2021

IEA. (2023). *Electricity Market Report 2023*. I. E. Agency. https://iea.blob.core.windows.net/assets/255e9cba-da84-4681-8c1f-458ca1a3d9ca/ElectricityMarketReport2023.pdf

Meijer, F., Visscher, H., Nieboer, N., & Kroese, R. (2012). Jobs Creation Through Energy Renovations of the Housing Stock. *NEUJOBS WORKING PAPER D14.2*. https://conference.iza.org/conference_files/neujobs_2014/4.pdf

Nicolae, B., & George-Vlad, B. (2015). Life cycle analysis in refurbishment of the buildings as intervention practices in energy saving. *Energy and Buildings*, *86*, 74-85. https://doi.org/10.1016/j.enbuild.2014.10.021

R Core Team. (2023). *R: A language and environment for statistical computing*. In (Version 4.2.3) https://www.R-project.org/

Rosen, S. (1974). Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition. *Journal of Political Economy*, *82*(1), 34-55. https://doi.org/10.1086/260169

Francesco Castellani

DECARBONIZATION THROUGH ELECTRIFICATION OF PUBLIC HISTORIC BUILDINGS: THE CASE STUDY OF NATIONAL GALLERY OF MODERN AND CONTEMPORARY ART IN ROME

Francesco Castellani, Sapienza University of Rome, Italy

Abstract

This work shows the methodology adopted to decarbonize - through electrification - the National Gallery of Modern and Contemporary Art in Rome, an historic building working as a museum, and also provides the achieved measured results.
The decarbonization through electrification is the most important part of the integrated approach followed by the museum; this path started in 2017, efficiency works were made in 2021 and from 2022 the National Gallery is a net-zero museum hosted in a historic building.
The monitoring of energy consumption of the first year after the works shows interesting findings: the new electricity consumption has been lower than the previous one, thanks to the efficiency of the new systems: electrification does not necessarily mean to increase the electric consumption.

Federico Rossi, Beatrice Maria Toldo, Carlo Zanchetta

INTEGRATING BMS AND BIM TO IMPROVE INTEROPERABILITY BETWEEN SIMULATION AND ENERGY MANAGEMENT ENVIRONMENTS

Federico Rossi, University of Padua, Italy
Beatrice Maria Toldo, University of Padua, , Italy
Carlo Zanchetta, University of Padua, Italy

Overview

The construction sector is responsible for about 40 percent of global energy consumption, highlighting the necessity of implementing a strategic plan to optimize resources. Currently, strategies for reducing and monitoring consumption focus on high-performance technological solutions related to energy efficiency. This approach goes beyond merely collecting building energy data; it requires a comprehensive review of the processes that lead to formulating energy performance.
Effective energy data management is crucial as it enhances the flow of input and output information. This management involves two components: a static component related to the building-systems, and a dynamic management component related to the Building Management System (BMS). BMSs typically use proprietary communication protocols (such as BACnet, Modbus and KNX), which prevent interoperability and limit the efficiency of integrated building management. Thus, it is essential to explore interoperable solutions to ensure seamless data exchange.

Methods

Energy data management must be based on the standardization and structuring of modelling processes that are essential for the simulation and standardization of building management processes via BMSs. This paper addresses existing information standards by mapping information and ensuring maximum data exchange in energy performance assessment and consumption monitoring.
The proposed methodology involves integrating technical master data from Industry Foundation Classes (IFC) database with Energy Management platforms. It is therefore suggested to use the existing IFC standard to create a data mapping from and to proprietary environments, according to the different file formats required by the platforms.

Results

Within the experimentation, the mapping of BMS components within the IFC standard ensures interoperability between different management and monitoring environments. Specifically, the proposed model demonstrates the ability to facilitate energy monitoring independently of proprietary software approaches. The standardization of input data enables the creation of benchmarks between simulation environments and management environments. By comparing data, it allows the validation of simulated energy behavior based on thermodynamics through BMSs.

Conclusions

The scope of the experimentation is the real-time data reading of sensors via input-output processes in the building management environment. Consequently, the study focuses on data acquisition. Therefore, it will be important to study the issue of interoperability related not only to BMS devices, but also to system analyses and configurations through simulation environments. The latter would allow for predictions of the building's energy behavior.

References

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X. (2020). BIM assisted Building Automation System information exchange using BACnet and IFC. *Automation in Construction*, *110*, 103049. https://doi.org/10.1016/j.autcon.2019.103049

Akponanabofa Henry Oti, Kurul, E., Cheung, F., & Tah, J. (2016). *The utilization of BMS in BIM for facility management*. https://doi.org/10.13140/RG.2.2.28538.49601

Alexandrou, K., Artopoulos, G., Gigliarelli, E., Calcerano, F., & Martinelli, L. (2021). *State of the art analysis on BIM and numerical simulation interoperability*.

Yingqi Liu, Ruiyu Feng

RESEARCH ON THE EFFECT OF POLICY IMPLEMENTATION IN TEST DEMONSTRATION ZONES ON THE COMMERCIAL OPERATION OF AUTONOMOUS DRIVING - VERIFICATION BASED ON DID MODEL

Yingqi Liu, Beijing Jiaotong University, No.3 Shangyuan Village, Haidian District, Beijing;
Ruiyu Feng, Beijing Jiaotong University, No.3 Shangyuan Village, Haidian District, Beijing;

Overview

Test demonstration zone is an indispensable link to test the application and actual operation of autonomous driving technology, and is also an important foundation for autonomous driving to gradually move towards large-scale and commercial operation from closed scenarios. With the continuous maturity of autonomous driving technology, it has become a trend of development and an inevitable choice to promote the commercial operation of autonomous driving.

Method

This paper takes the policy of constructing test demonstration zones as a quasi-natural experiment, based on the panel data of 248 prefecture-level cities in China from 2014 to 2022, and uses a multi-temporal double difference model (DID) to explore the effect of the construction of test demonstration zones on the commercial operation of autonomous driving.

Results

It is found that the construction of test demonstration zones significantly promotes the commercial operation of autonomous driving, and this positive effect has a significant sustained effect. Key technologies and application scenarios, as important components in the construction of test demonstration zones, play a positive moderating role in the process of promoting the commercial operation of autonomous driving. The mechanism test shows that the construction of test demonstration zones promotes the commercial operation of autonomous driving mainly through reducing the application cost, improving the maturity of technology and enhancing the acceptance of users. The heterogeneity test shows that the empowerment effect of the test demonstration zone construction is more significant in the eastern cities with higher degree of market development and more concentrated industrial agglomeration, and has a significant spatial spillover effect on the commercial operation of autonomous driving in cities with similar economic distance.

Conclusions

This paper provides a certain reference for achieving the commercialization of autonomous driving in China and further promoting the transformation and upgrading of the automotive industry.

References

Lee D, Hess D J. (2020) "Regulations for on-road testing of connected and automated vehicles: Assessing the potential for global safety harmonization", Transportation Research Part A: Policy and Practice, 136:85-98.

Zhang, TR; Tao, D; Qu, XD, et al. (2020) "Automated vehicle acceptance in China: Social influence and initial trust are key determinants", Transportation Research Part C-Emerging Technologies, 112:220-233.

Sindi S, Woodman R. (2021) "Implementing commercial autonomous road haulage in freight operations: An industry perspective", Transportation Research Part A-Policy and Practice,152:235-253.

Silvia Orchi, Alessandro Ruvio

THE ROLE OF ELECTRIC RAILWAY IN THE TRANSPORT DECARBONIZATION

Silvia Orchi, ENEA, Via Anguillarese 301, Rome, Italy
Alessandro Ruvio, Università La Sapienza, Rome, Italy

Overview

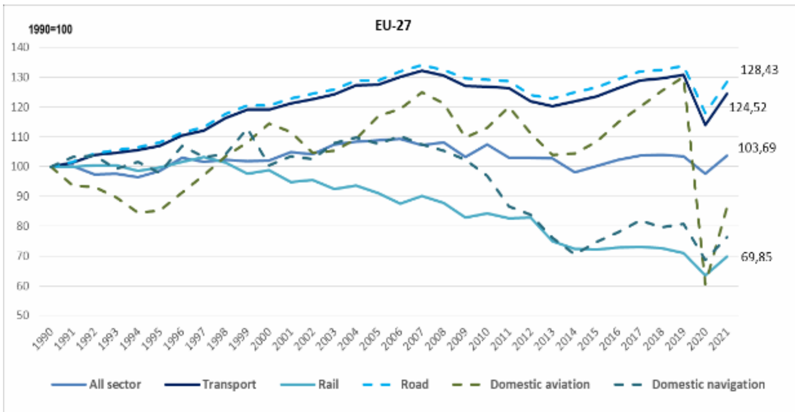
One of the main priorities of the EU and its Member States is to drastically reduce GHG emissions in compliance with the Paris agreement and to achieve the goals of climate neutrality by 2050, expressed in the European Green Deal. Transport demand is for 73% from passenger and for 37% from freight and currently accounts for about 1/4 of the EU's total GHG emissions, due to its strictly dependency on fossil fuels, it represents a challenge waiting to be solved. Several kinds of solutions exist, and from the technological point of view, electrification is one of the most promising solutions to decarbonise transport in the short term. The European Green Deal calls for a 90% reduction by 2050 compared with 1990 total emissions. The European Commission's Sustainable and Smart Mobility Strategy, published in December 2020, calls for decisive action to shift more activity towards more sustainable transport modes and identifies in the electrification of urban transport and electric railway, the elected solutions to decarbonise road transport. The paper examines the state of the art of rail technology and the recent development, its implications in transport sector with focus on railway demand from passenger and freight, final energy consumption, GHG total and specific emission and some considerations about the shift to railway from less efficient and more environmental impacting modes of transport.

Methods

The analysis of the energy demand of ends uses outlines that transport sector is responsible for more than half of global oil demand and for more than a third of global CO_2-eq emissions from fuel combustion.
Global demand for transport is growing fast and according to International Energy Agency (IEA) forecasts, given present trends, passenger and freight activity will more than double by 2050. The challenge is to decouple the social and economic progress by the increase of energy demand, CO_2-eq emissions and atmospheric pollutants.
Rail could help decouple economic growth from climate impact. From1990 to 2020, worldwide rail passengers are almost duplicated and in 2016 about 14% travelled in high-speed trains, 10% in urban electric mode, 46% in conventional electric trains and 30% in conventional diesel ones. In 2018, in the worldwide about 8% of passenger and 9% of goods travelled by rail, in the same year in EU-27 and Italy the share was 7% for passengers and 13% and 16% respectively for goods. In EU-27, from 1990 to 2021, the energy consumption in all ends uses grew by 3% while the energy consumption in transport sector grew by 24.5% manly due to the increase of private car transport and aviation, as shown in the Figure 1a. In the same period, the downward trend in final energy consumption in the railways leads, on the contrary, to a reduction of 30%.Errore. L'origine riferimento non è stata trovata. Figure 1b shows a general upwards trend in GHG emissions since 1990 for all modes of transport and, in the observed period, the increase is by 18% unlike the railway mode, whose emissions are 29% of those of 1990. Overall, GHG emissions from all sectors fall by 27%. In 2021, EU-27 transport sector, including international bunkers, is responsible for 28% of GHG emissions, of which 0,4% by rail mode (3,8 Mt CO2-eq), and represents the 27% of GHG emissions, of which 0,1% by rail mode, in Italy. In the railway industry, both onboard and stationary storage systems are now pivotal solutions for enhancing energy efficiency and enabling hybrid trains to operate without reliance on catenary systems. Storage systems allow to reduce the system's energy consumption maximizing the amount of regenerative braking and give the possibility, in the case of hybrid trains, to operate in catenary free, limiting the environmental impact and reducing costs of electrical installations. Furthermore, incorporating renewable energy sources into railway power systems presents a promising opportunity to augment electrical substations, minimizing environmental impact and reducing dependence on transmission grid.

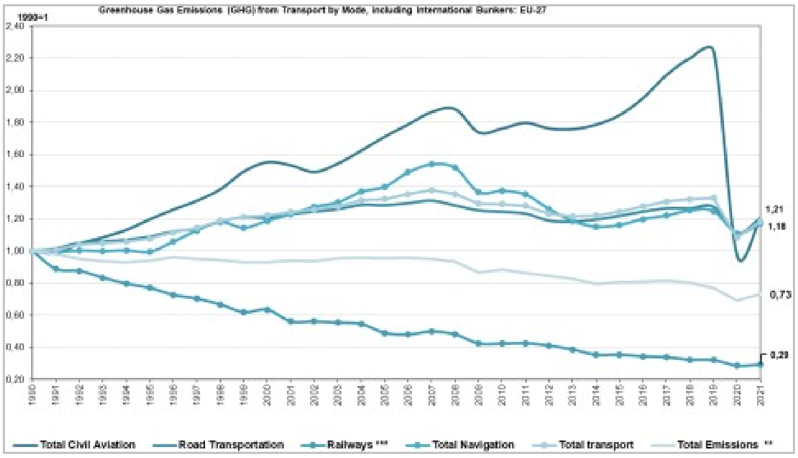
Key technologies for energy recovery include Energy Storage Systems (ESSs): flywheels, supercapacitors, electrochemical cells, and hydrogen fuel cells (HFCs), which serve as the primary alternatives. PV power plants and Wind turbines are taken into account as renewable sources.

Figure 1a: Final energy consumption evolution in EU-27 – index



Source: ENEA elaboration on Eurostat data

Figure 1b: GHG emissions evolution in EU-27 – index

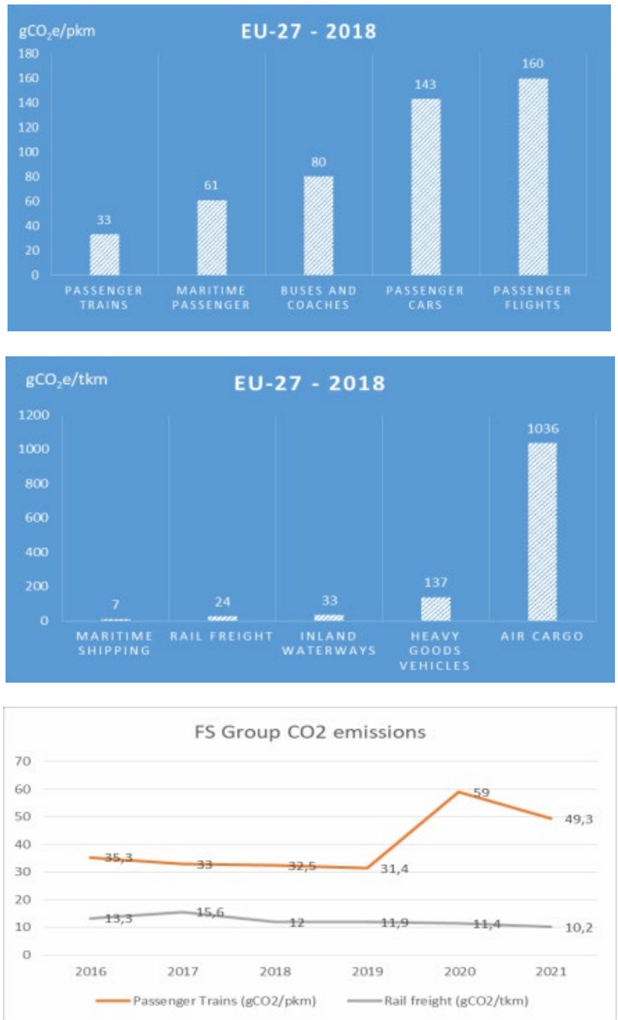


** Including International Bunkers and Indirect CO_2 but excluding LULUCF.
*** Excluding indirect emissions from electricity consumption.

Results

Rail is among the most virtuous for passenger with 33 gCO_2/p-km and for goods with 24 gCO_2/t-km (*Figure 2*). In Italy the FS group has similar values for passenger and about a half value for goods. Post covid period are affected by an intensive use of private car instead public transport, due to health safety. In pre-covid period in EU-27, the highest specific CO_2eq emissions was from air sector both for passenger and freight, followed by passenger car and heavy good vehicles.

Figure 2: WTW GHG specific emissions by mode of transport for passenger and goods



Source: www.eea.europa.eu/publications/rail-and-waterborne-transport

Rail's well-to-wheel GHG intensity improved by more than 10% between 2014 and 2018 and, according to the EEA, direct emissions from railways are projected to further decline by 22% between 2019 and 2040. A recent study by Greenpeace states that shifting all top 250 short-haul flights in Europe would result in a CO_2eq saving of around 23.4 million tons of CO_2eq per year, corresponding to 2,4% of 2021 transport GHG emissions in EU-27. The short-haul flights are a bigger emitter per passenger and per kilometre, which overall climate impact could be over 80 times worse than taking a train. Shifting from the short-haul flights (<1.500 km) to railway under six hours is a concrete possible solution to deal with transport decarbonization.

Emissions for freight transported by maritime shipping, rail and inland waterway are very low compared with those for freight transported by heavy goods vehicle (HGV). Air cargo stands out as the mode with the highest emissions by far. However, over the 2014-2018 period, air cargo saw the biggest GHG efficiency improvement (12%) followed by rail freight (11%). HGVs only showed a slight improvement of 3%. Finally, transport activity generates so-called 'external costs' that have real life consequences on society quantified in 987 bl/y in EU-27, of which railway represents 1.8%.

Conclusions

Trains are the most efficient form of passenger transport in the EU and the second best for goods transport, with specific GHG emissions that are only a fraction of most other modes. Taken together, buses and coaches are the most efficient form of road passenger transport. However, the uses of these vehicles vary significantly, which affects their emission performance. Passenger flights and cars are the least efficient forms of passenger transport and produce the highest emissions per p-km. Aviation and rail passenger transport efficiency improved by 12% and 13% respectively over the period from 2014 to 2018 with a further projected decline by 22% between 2019 and 2040 for railway. This is mainly the result of the electrification of the rail network and the declining carbon intensity of the EU's electricity mix. For aviation, the gains owe largely to the uptake of more efficient aircraft. The GHG intensity of car travel only improved marginally over the period in question. Rail travel is well matched to urban needs in a world becoming ever more urbanized. High- speed rail can serve as an alternative to short-distance air travel.
In general, conventional passenger rail and freight rail, that is already an electric mode of transport, can complement other transport modes to ensure a more efficient mobility system. Moreover, shift to rail from less efficient modes would save some million tons of CO_2eq per year, this requires the implementation of better train services that, in 2021, are worse than in 2019, in the wake of the Covid-19 pandemic and making travelling by train cheaper and easier than flying.

References

Ruvio et all, "Rail Transport", www.simte.enea.it, December 2021 Conto Nazionale dei Trasporti CNIT, 2021 Eurostat

IEA, Passenger rail transport activity by fuel type, 1995-2016, IEA, Paris CER Factsheet Sustainability

European Commission, Directorate-General for Mobility and Transport, Essen, H., Fiorello, D., El Beyrouty, K. et al., Handbook on the external costs of transport – Version 2019 – 1.1, Publications Office, 2020, https://data.europa.eu/doi/10.2832/51388 www.eea.europa.eu/publications/rail-and-waterborne-transport

Benedikt Rilling, Carsten Herbes

UNVEILING CONSUMER CHOICES FOR RENEWABLE METHANE IN PRIVATE TRANSPORTATION: A DISCRETE-CHOICE EXPERIMENT APPROACH

Benedikt Rilling: Nuertingen-Geislingen University, Institute for International Research on Sustainable Management and Renewable Energy (ISR), Neckarsteige 6-10, 727622 Nuertingen, Germany, and Heidelberg University, Institute of Political Science, Bergheimer Strasse 58, 69115 Heidelberg, German
Carsten Herbes: Nuertingen-Geislingen University, Institute for International Research on Sustainable Management and Renewable Energy (ISR), Neckarsteige 6-10, 727622 Nuertingen, Germany,

Overview

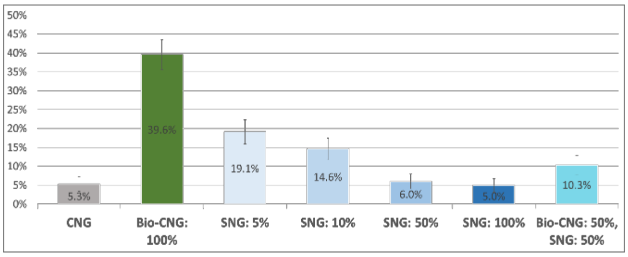
Replacing compressed natural gas (CNG) with alternative fuels can promote more sustainable transport, reduce import dependency and contribute to energy security. Renewable methane sources, like upgraded biogas (Bio-CNG) and Synthetic Natural Gas (SNG) from green hydrogen using Power-to-Gas (PtG) technology, emit significantly less CO_2 than fossil CNG. The successful adoption of renewable-based CNG alternatives depends on consumer acceptance, preferences and their willingness to use these alternatives. Existing research on consumer preferences for sustainable fuels splits into two categories: engine/vehicle choice (Beak et al., 2020; Greene et al., 2018; Yeh, 2007) and fuel choice (Linzenich et al., 2019, 2023; Tosun, 2017). Our study focuses on the latter, in detail on CNG substitutes and their specific properties, filling a gap in current research. Relevant studies on the German market found that price is the key decision factor, while emissions are less important. Furthermore, consumers favor e-fuels over biofuels and have limited knowledge about alternative fuels. Against this background we raise the following research question: How important are different attributes of renewable gas products to consumers in motorized private transportation?

Method

Our study utilizes a Discrete-Choice Experiment (DCE) conducted via an online survey to determine consumer preferences. Building on a Hierarchical Bayesian approach, we assessed these preferences using part-worth utilities on a pseudo-individual level (Hein et al., 2020; Orme, 2010; Rossi, 2014). The study design included 11 choice tasks, where participants chose between four renewable gas products and a default option (100% CNG). The products were defined by a combination of five key attributes: (1) share of renewable gas, (2) eco-labels, (3) regional production, (4) Bio-CNG origin (energy crops vs. waste), and (5) price. Each attribute had various levels (e.g., 5% SNG share, two eco-labels). These attributes and their levels were identified through extensive literature review and 23 qualitative interviews. Data collection in June 2021 resulted in 573 responses from car drivers who had considered CNG-powered vehicles. Accordingly, the results are based upon 6.303 active choices between five alternatives (see exemplary choice card above). With a Pseudo R-Squared of 0.52 and a Root Likelihood of 0.46, which is more than two times greater than the chance level of 0.2 (theoretical value for completely randomized choices between five alternatives), the model performed well (Côté et al., 2022; Hille et al., 2018).

Results

Our results indicate clear knowledge gaps for both biogas and SNG/PtG technologies, with gaps being more pronounced for the newer PtG technology compared to the more established biogas technology. With 41.5%, attribute importance scores show that the evaluation of renewable gases in the mobility sector is clearly dominated by the gas mix (i.e. the share of renewable gases), followed by the price (21.6%) and labels (20.2%). Regionality and Bio-CNG origin are clearly less important. In a fictional scenario of no price increases (see preference shares on the right) more than 5% opt for fossil CNG, 40% for one Bio-CNG product and 45% for four SNG products. This indicates that Bio-CNG is favored over SNG. This first indication is confirmed by the zero-centered part-worth utilities: Bio-CNG is clearly favored over SNG, so are lower price levels over higher. Quantity trumps quality when it comes to eco-labels: More labels were preferred to fewer labels, regardless of the label strictness.



Conclusions

Our findings validate the observations made by Linzenich et al. (2019, 2023) regarding knowledge gaps. However, we identified contrasting preferences between e-fuels and biofuels in our DCE: Our study clearly demonstrates that consumers favor biofuels, i.e. Bio-CNG over SNG, which contradicts historical public and scientific discourse, particularly concerning the food versus fuel debate. Reservations about biomass-based fuels appear to have diminished. This insight is in line with other studies: Rilling et al. (2024) for renewable gases in the heating market or Agency for Renewable Energies (2022) on a more general level, also found this shift in public perception. Current market conditions in the CNG sector in Germany (in particular legal obligations such as the greenhouse gas quota) have resulted in almost all CNG sold being Bio-CNG. Accordingly, consumer preferences are well reflected in the market supply in Germany. Marketers and policymakers should carefully consider the feasibility of introducing a relatively unknown and costly product such as SNG to the CNG market. We will delve deeper into these insights during our presentation. Our study enhances comprehension of consumer preferences for alternative fuels, thereby enabling informed political and managerial decision-making.

References

Agentur für Erneuerbare Energien. (2022). *Bioenergie: Starke gesellschaftliche Zustimmung während Energiekrise*. https://www.unendlich-viel-energie.de/bioenergie-starke-gesellschaftliche-zustimmung-waehrend-energiekrise

Beak, Y., Kim, K., Maeng, K., & Cho, Y. (2020). Is the environment-friendly factor attractive to customers when purchasing electric vehicles? Evidence from South Korea. *Business Strategy and the Environment*, *29*(3), 996–1006. https://doi.org/10.1002/bse.2412

Côté, E., Đukan, M., Pons-Seres de Brauwer, C., & Wüstenhagen, R. (2022). The price of actor diversity: Measuring project developers' willingness to accept risks in renewable energy auctions. *Energy Policy*, *163*, 112835. https://doi.org/10.1016/j.enpol.2022.112835

Greene, D., Hossain, A., Hofmann, J., Helfand, G., & Beach, R. (2018). Consumer Willingness to Pay for Vehicle Attributes: What Do We Know? *Transportation Research. Part A, Policy and Practice*, *118*, 258–279. https://doi.org/10.1016/j.tra.2018.09.013

Hein, M., Kurz, P., & Steiner, W. J. (2020). Analyzing the capabilities of the HB logit model for choice-based conjoint analysis: A simulation study. *Journal of Business Economics*, *90*(1), 1–36. https://doi.org/10.1007/s11573-019-00927-4

Hille, S. L., Curtius, H. C., & Wüstenhagen, R. (2018). Red is the new blue – The role of color, building integration and country-of-origin in homeowners' preferences for residential photovoltaics. *Energy and Buildings*, *162*, 21–31. https://doi.org/10.1016/j.enbuild.2017.11.070

Linzenich, A., Arning, K., Bongartz, D., Mitsos, A., & Ziefle, M. (2019). What fuels the adoption of alternative fuels? Examining preferences of German car drivers for fuel innovations. *Applied Energy*, *249*, 222–236. https://doi.org/10.1016/j.apenergy.2019.04.041

Linzenich, A., Bongartz, D., Arning, K., & Ziefle, M. (2023). What's in my fuel tank? Insights into beliefs and preferences for e-fuels and biofuels. *Energy, Sustainability and Society*, *13*(1), 35. https://doi.org/10.1186/s13705-023-00412-5

Orme, B. K. (2010). *Getting started with conjoint analysis: Strategies for product design and pricing research* (2. ed). Research Publ.

Rilling, B., Kurz, P., & Herbes, C. (2024). Renewable gases in the heating market: Identifying consumer preferences through a Discrete Choice Experiment. *Energy Policy*, *184*, 113857. https://doi.org/10.1016/j.enpol.2023.113857

Rossi, P. (2014). *Bayesian Non- and Semi-parametric Methods and Applications:* Princeton University Press. https://doi.org/10.1515/9781400850303

Tosun, J. (2017). The behaviour of suppliers and consumers in mandated markets: The introduction of the ethanol–petrol blend E10 in Germany. *Journal of Environmental Policy & Planning*, *20*(1), 1–15. https://doi.org/10.1080/1523908X.2017.1299624

Yeh, S. (2007). An empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles. *Energy Policy*, *35*(11), 5865–5875. https://doi.org/10.1016/j.enpol.2007.06.012

Ofir Rubin, Aviv Steren, Stav Rosenzweig

WHICH TYPE OF VEHICLE MILEAGE TAX IS THE PUBLIC MOST WILLING TO ACCEPT?

Ofir D. Rubin, Guilford Glazer Faculty of Business & Management, Ben-Gurion University of the Negev, Israel,
Aviv Steren, Guilford Glazer Faculty of Business & Management, Ben-Gurion University of the Negev, Israel,
Stav Rosenzweig, Guilford Glazer Faculty of Business & Management, Ben-Gurion University of the Negev, Israel

Overview

Electric Vehicles (EVs) are becoming increasingly popular, with their adoption projected to rise significantly in the coming years. According to the International Energy Agency (IEA), the number of EVs on the road surpassed 26 million in 2022, a 60% increase compared to the previous year (IEA, 2023). This shift towards EVs is beneficial due to their positive characteristics, such as reduced urban pollution, lower travel and operational costs, and decreased dependence on fossil fuels (Choma et al., 2020; Electric Vehicle Council, 2022). Moreover, switching from internal combustion engine (ICE) vehicles to EVs will significantly increase energy efficiency, shifting from using 12-30% fossil energy to utilizing 77% of the energy supplied by the electrical system (EPA, 2024). These benefits contribute to improved air quality, enhanced public health, and a more sustainable energy future. However, the growing prevalence of EVs also introduces several challenges. Despite their environmental advantages, EVs share many negative externalities with ICE vehicles, including traffic congestion, car accidents, and infrastructure degradation. Moreover, EVs are likely to be driven more frequently due to the rebound effect, wherein the reduced cost of driving leads to increased vehicle usage (Steren et al., 2022). This potential increase in driving highlights the need for effective mechanisms to internalize the associated externalities. Historically, the gasoline tax has served this purpose for ICE vehicles. However, this tax is ineffective for EVs as they do not use gasoline, leaving a gap in the policy framework. To address this gap, a mileage tax emerges as a potential solution to internalize the externalities associated with EVs (Davis & Sallee, 2020). A mileage tax would charge drivers based on the distance traveled, thereby aligning the cost of driving more closely with the societal costs of vehicle usage. However, implementing such a tax could slow down the adoption of EVs, as it increases the cost of their usage, potentially offsetting some of the financial benefits that currently drive their popularity. There is a growing understanding globally that it is necessary to promote mileage taxation. However, there is limited knowledge and experience in implementing mileage taxes. Several states in the US are considering this approach, with Oregon leading the way through its 'pay-per-mile' program, which charges drivers based on distance traveled instead of fuel consumption. A field experiment in Indiana found that consumers are generally unaware of the amount of tax they currently pay and do not perceive significant differences between a tax based on energy efficiency and one based on pollution levels (Duncan et al., 2020). A simulation study in Pennsylvania suggested that a mileage tax of 2.4-3.2 cents per mile would result in 50% of consumers paying the same or less than they currently do in fuel taxes (Matthews et al., 2021). These studies indicate a significant gap in the practical knowledge of vehicle taxation. Recent studies show that the effectiveness of the tax will ultimately depend on its public acceptance (Andersson et al., 2023; Duncan et al., 2020). This study aims to investigate public acceptance of a mileage tax and design a structure for such a tax that is both publicly accepted and effective in internalizing the externalities of EV usage. The goal is to develop a policy framework that mitigates the negative externalities of EVs while supporting their continued adoption, ensuring a balanced approach to sustainable transportation.

Methods

To investigate public acceptance of a mileage tax and design an effective and publicly accepted structure, we employed a Discrete Choice Experiment (DCE). Our DCE was based on random utility theory, allowing us to analyze individual preferences for mileage tax attributes.

We employed the mixed multinomial logit model instead of the multinomial logit model to account for individual heterogeneity and provide a nuanced understanding of diverse decision-making processes (Ma et al., 2019). To derive Willingness-to-Pay values, we calculated the ratio of the model coefficients to the cost coefficient. Conducted online by a professional survey company, the survey included participants from a pre-recruited panel representing the adult population of Israel, focusing on individuals who own or have permanent access to a car. Each participant was presented with six choice sets, each comprising three alternatives described by six attributes. We used a D-efficient design to create the choice sets, maximizing information and ensuring realistic attribute levels (Bliemer & Rose, 2014). A pilot study provided prior information for constructing the efficient design. The pilot study included 203 participants, resulting in 203×6×3=3,654 observations. The final survey included 24 choice sets organized into four blocks, randomly assigned to 505 respondents, resulting in 9,090 observations. The D-error in our design was 0.11.

Results

Our preliminary results indicate that participants prefer the mileage tax to be universally applied across all vehicles, rather than solely targeting EVs. Additionally, there is a clear preference for punitive measures against polluting vehicles within the tax framework – suggesting a desire to incentivize cleaner transportation choices – while we find no significant preference for providing a tax discount for energy-efficient vehicles. Respondents favored allocating tax revenues towards infrastructure improvements over pollution repair funds or state budget contributions. Residents living in peripheral areas showed a distinct preference for a mileage tax that considers the place of residence, highlighting regional equity concerns in taxation policies. However, this preference was specific to those who would benefit directly from such considerations. The cost coefficient associated with the mileage tax was negative and statistically significant. The result indicates that higher taxes deter consumers from choosing certain tax alternatives, which aligns with expectations. Finally, both a differentiated mileage tax and a fixed mileage tax per mile were viewed favorably compared to the absence of a mileage tax. This preference emphasizes support for structured and predictable tax regimes, in which EV owners also pay taxes for using their cars.

Conclusions

Our study's main contribution is highlighting public preferences for a universal mileage tax and its implications for policy design. The preference toward a universal mileage tax is important for two key reasons. First, it suggests that implementing a mileage tax exclusively on EVs, as currently promoted in prevailing public discourse, will be less publicly acceptable per se. Second, a universal tax avoids sending a negative signal that might discourage consumers from purchasing electric cars, thereby supporting the continued adoption of EVs. Moreover, the clear preference for allocating tax revenues towards infrastructure improvements highlights the importance of transparently informing the public about the intended use of tax revenues. Prioritizing the enhancement of transportation infrastructure aligns with public preferences and addresses critical areas for investment, which is essential for gaining public support and ensuring the effective implementation of the mileage tax. These insights are important for policymakers aiming to design a mileage tax that balances effectiveness with public acceptance. By considering these preferences, policymakers can support sustainable transportation while addressing the externalities associated with vehicle usage. Further details and implications will be discussed in the presentation.

References

Andersson, M., Jonsson, L., Brundell-Freij, K., & Berdica, K. (2023). Who should pay? Public acceptance of different means for funding transport infrastructure. *Transportation*, *50*(4), 1425–1448. https://doi.org/10.1007/s11116-022-10282-z

Bliemer, M. C. J., & Rose, J. M. (2014). Designing and Conducting Stated Choice Experiments. In S. Hess & A. Daly (Eds.), *Handbook of Choice Modelling*. Edward Elgar Publishing.

Choma, E. F., Evans, J. S., Hammitt, J. K., Gómez-ibáñez, J. A., & Spengler, J. D. (2020). Assessing the health impacts of electric vehicles through air pollution in the United States. *Environment International*, *144*(August), 106015. https://doi.org/10.1016/j.envint.2020.106015

Davis, L. W., & Sallee, J. M. (2020). Should Electric Vehicle Drivers Pay a Mileage Tax? *Environmental and Energy Policy and the Economy*, *1*(July), 65–94. https://doi.org/10.1086/706793

Duncan, D., Li, D., & Graham, J. D. (2020). Tax rate design and support for mileage user-fees. *Transport Policy*, *93*(April), 17–26. https://doi.org/10.1016/j.tranpol.2020.04.017

Electric Vehicle Council. (2022). *Insights into electric vehicle ownership: A survey of Tesla Owners Club Australia members in partnership with the Electric Vehicle Council*. https://electricvehiclecouncil.com.au/wp-content/uploads/2022/09/EVownerinsights.pdf

EPA. (2024). *All-Electric Vehicles*. Www.Fueleconomy.Gov. https://www.fueleconomy.gov/feg/evtech.shtml

IEA. (2023). *Global EV Outlook 2023: Catching up with climate ambitions*. https://iea.blob.core.windows.net/assets/dacf14d2-eabc-498a-8263-9f97fd5dc327/GEVO2023.pdf

Ma, S. C., Xu, J. H., & Fan, Y. (2019). Willingness to pay and preferences for alternative incentives to EV purchase subsidies: An empirical study in China. *Energy Economics*, *81*(x), 197–215. https://doi.org/10.1016/j.eneco.2019.03.012

Matthews, H. S., Fischbeck, P. S., Yuan, C., Fan, Z., Lyu, L., & Acharya, P. S. (2021). *Assessment of Prospective Mileage-Based Fee System to Replace Fuel Taxes for Passenger Vehicles in Pennsylvania*. https://ppms.cit.cmu.edu/projects/detail/297%0Ahttps://trid.trb.org/view/1636490

Steren, A., Rubin, O. D., & Rosenzweig, S. (2022). Energy-efficiency policies targeting consumers may not save energy in the long run: A rebound effect that cannot be ignored. *Energy Research & Social Science*, *90*(7), 102600. https://doi.org/10.1016/j.erss.2022.102600

Emre Avci, Oliver Woll, Marco Kunz

ENHANCING OFF-GRID ENERGY SECURITY TROUGH REVERSIBLE SOLID OXIDE CELL SYSTEMS ECONOMIC ANALYSES OF CASE STUDIES AND BUSINESS MODELS

Emre Avci, Lucerne University of Applied Sciences and Arts,
Oliver Woll, Lucerne University of Applied Sciences and Arts,
Marco Kunz, Lucerne University of Applied Sciences and Arts,

Overview

Reversible Solid Oxide Cells (RSOCs) have the potential to play a crucial role in the transition to a more secure and sustainable energy landscape, particularly in off-grid settings. This research, conducted as part of the ZEN 24/7 project, aims to explore the economic viability and integration strategies for deploying RSOCs in multi-family off-grid environments. The study investigates business models, evaluates the financial dimensions, and identifies optimal configurations to maximize the benefits of RSOCs in enhancing energy security.

Methods

The research project is structured into three primary phases, each designed to systematically explore different aspects of RSOC integration and economic feasibility:
Understanding the Current State of the Art: A comprehensive literature review and expert interviews were conducted to construct detailed RSOC models and establish a baseline for target costs. Optimizing the RSOC Models: An optimization framework was developed to evaluate system performance and economic competitiveness. This phase focused on enhancing system efficiency and economic viability by refining model performance and identifying optimal configurations for the off-grid scenarios (without electricity or gas grid or fully off-grid). Estimating Economic Viability: In this final phase, economic analyses were conducted with a specific focus on off-grid scenarios. The impact of key variables such as investment costs, interest rates, stack costs, and hydrogen prices, was thoroughly evaluated to determine the economic feasibility of RSOCs. Further potential business models for the improvement of the economic viability of RSOCs were investigated.

Results

The findings reveal that daily hydrogen production and utilization by the RSOC are nearly identical during the winter months. In the summer the RSOC is used more often for hydrogen production. A sensitivity analysis of the storage capacity shows that the optimal storage size with respect to the minimum operating cost of the energy system is not sufficient to store all the excess electricity. Therefore, PV power generation is intentionally curtailed during the summer months. This approach effectively manages seasonal fluctuations, maximizes electricity use, and ensures efficient storage and utilization of excess energy during peak production times.
Additionally, preliminary analyses of improving the business model suggest that in the scenarios connected to the electricity grid incorporating market dynamics such as intraday and day-ahead optimization, alongside the integration of battery storage systems, could further enhance the economic feasibility. These findings underscore the strategic value of RSOCs in developing more resilient, cost-effective, and sustainable energy systems for off-grid communities.
The study explored several innovative business models that could enhance the economic viability of RSOC systems in off- grid settings. Notably, the potential for hydrogen production for mobility applications emerged as a promising revenue stream. The research also identifies opportunities for ancillary services such as providing backup power for critical infrastructure or participating in demand response programs for the electricity grid connected scenarios.

Conclusions

This research highlights the significant role of RSOCs in enhancing energy security, particularly for off-grid applications. The optimized use of RSOCs in various scenarios demonstrates their ability to efficiently handle seasonal energy fluctuations, thereby reducing the need for large upfront storage investments. Additionally, the research contributes to the exploration of new business models to enhance the economic feasibility of RSOC systems and identifies key drivers to improve the business case of integrating RSOCs into the future energy system. Innovative business models, including hydrogen production for mobility and prosumer market participation underscore RSOCs' potential in enhancing energy security and sustainability in off-grid environments, paving the way for future research on large-scale implementation and policy development.

Simon Sturn, Xenia Miklin, Thomas Neier, Klara Zwickl

CARBON GIANTS: EXPLORING THE TOP 100 INDUSTRIAL CO_2 EMITTERS IN THE EU

We analyze emissions and associated damages from the top 100 industrial CO_2 emitters in the EU using data from the European Pollutant Release and Transfer Register, the EU Transaction Log, population grids, and regional information. These top emitters account for 19% of total EU CO_2 emissions, 39% of industrial CO_2 emissions, as well as a third of industrial SOx and NOx emissions, and a significant share of industrial PM10 emissions. At their current rate, the top 100 alone would exhaust the EU's carbon budget in 38.5 years. Monetized damages of these hazardous co-pollutants range from 20 to 67 billion Euros, and combined co-pollutant and climate damages amount to between 92 and 260 billion Euros. The joint climate and co-pollutant damages of a significant number of the top 100 exceed the economic value generated by the entire industry sector in their respective regions, indicating substantial under-regulation. Yet the top 100 received free EU Emissions Trading System permits for 27% of their carbon emissions in 2017. Many top pol- luters are located in densely populated regions, with 3.1% of Europe's population living within 10 kilometers of a Carbon Giant. Regions hosting a top 100 facility experience elevated exposure to air pollutants and lower life expectancy than neighboring regions. Our analysis reveals the critical importance of addressing major polluters in research and policymaking.

Keywords:

Top 100 industrial carbon emitters, co-pollutants, health and climate damages, environmental justice, geo-spatial identification

Highlights:

- Use of geo-located facility and regional data from multiple sources.
- The top 100 account for 39% of industrial and 19% of total EU CO_2 emissions.
- Carbon and co-pollutant damages of top 100 often exceed regional industry value added.
- The top 100 received free EU ETS permits for 27% of their carbon emissions in 2017.
- Regions with top 100 face higher particulate matter exposure and lower life expectancy.

Tommaso Bonini, Svetlana Ikonnikova

EUROPEAN DECARBONISATION AND REFINERIES: ANALYZING THE CONDITIONS FOR A PROFITABLE ADOPTION OF CLEAN HYDROGEN

Tommaso Bonini, Centre for Energy Markets, School of Management, Technical University of Munich, 80333 Munich, Germany
Svetlana Ikonnikova, Centre for Energy Markets, School of Management, Technical University of Munich, 80333 Munich, Germany

Overview

Natural gas, oil, and coal have historically dominated the energy consumption in Europe. Climate change has pushed the European Commission to reconsider the status quo and by setting decarbonization targets compel energy users and producers to transition to cleaner energy solutions. To achieve the imposed targets, "clean" alternatives, such as renewable energy (RE) or hydrogen, must be adopted. The choice of low carbon or net zero carbon technologies has been especially challenging for large-scale industrial consumers with high energy-intensity production, the so-called hard-to-abate sectors, who often utilize multiple energy sources and feedstock at once. The latest EU carbon emission reduction regulations, e.g., RED III, industries, including cement, chemical, heavy metal processing, must explore the use of clean substitutes across individual production processes.
The purpose of the present work is twofold. First, we offer a novel approach for industrial production analysis that allows to derive the demand and willingness to pay for cleaner energy substitutes. We demonstrate the developed methodology investigating the transition strategies for the EU oil refining sector and in doing so, analyse different channels through which decarbonisation may be achieved. Hence, the second goal of our analysis is to investigate how carbon regulations and initiatives such as the EU ETS affect and determine industrial transformations.
During our analysis, we focus on clean hydrogen as a primary fossil energy substitute and renewable energy as alternative to the grid (mix-source) electricity. Collecting the data characterizing European oil refineries, we aim at analysing a combination of fossil fuels and electricity determining sector's production possibilities. Adding costs of energy and output into the consideration, we turn to the study of the past and possible future scenarios for the sector under the carbon emission associated constraints. In sum, we present a consistent and comprehensive framework for decarbonisation strategies in an industrial sector, subject to the energy and carbon prices and constraints. To verify our approach, we perform scenario analysis and build the future projections based on the EU carbon targets.

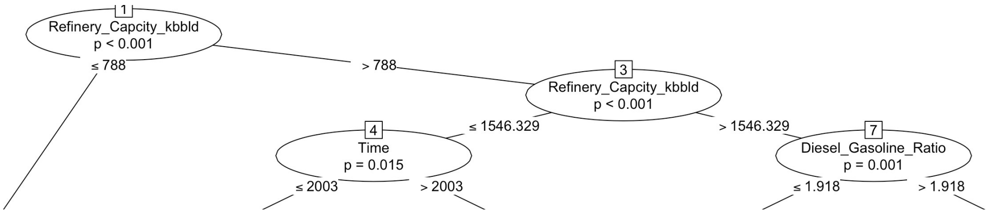
Methods

The study is developed in two interrelated parts. First, we suggest a machine-learning based approach for the industrial production analysis enabling us to derive the demand for energy, input and output price relationship, and track the carbon footprint. Second, we perform simulation to understand how the model is working in real-case scenarios. The empirical analysis is driven and linked to the theoretical model for the sector's transition to lower carbon footprint through adoption of cleaner energy. We employ the opportunity cost approach to explore how an industry may transition in an economically sustainable way. Referring to the classical producer behaviour model, we consider a profit-maximizing industrial firm with the translog production function:

$$lnY = \alpha_0 + \sum_{i=1}^{3} \alpha_i lnX_i + \frac{1}{2}\sum_{i=1}^{3}\sum_{j=1}^{3} \beta_{ij} lnX_i lnX_j$$

In which the main input factors are three, following the numeraires i and j: (1) oil, (2) natural gas, (3) electricity. According to the model, the use and the efficiency of major inputs, fossil fuels and electricity, may change driven by technological advances, the energy costs, and carbon prices. To account for that in our empirical analysis, we suggest estimating the parameters of the production function through the model-based recursive partitioning (MBRP).

The MBRP algorithm is a tree-based approach set to use split variables to identify different regimes estimating different parameters, depending on the combination of the split variables (see below). For example, as we show in the following empirical analysis, the parameters of the production function for oil refineries may vary with the capacity factor and over time:

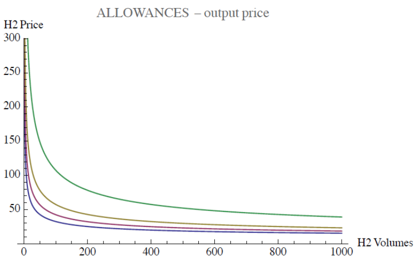


Given that we may estimate the production function and, in a similar fashion, the link between inputs, output, and possible constraint variables, we may analytically derive the demand for H2, clean electricity, and/or other energy inputs using an opportunity cost approach. Finally, in a stylized setup, we analyse how fossil fuels with the initially lower unit costs may be complemented by higher cost H2 that provides an advantage of lower emissions. Assuming the production is determined by the production function and the two major constraints, budget or non-zero profit and carbon, we would then, calculate the adoption of clean technologies and substitution of fossils as a function of (a) the output and input prices, and (b) the emission allowance or carbon cost.

Results

Inspired by the European refineries, we proceed with a series of simulations using the established theoretical framework to demonstrate the usability of our methodology and to reveal how the future market and policy dynamics may threaten or promote the adoption of hydrogen technologies. To do that, we build a database specifically focussed on oil refinery industry in Europe that relates countries (i.e., Netherlands, Belgium, Italy, France, Germany), with energy inputs (i.e., oil, natural gas, electricity) and specific parameters (i.e., refinery capacity, diesel/gasoline ratio, time). We then perform within R ecosystem the model-based recursive partitioning (MOB) seeking a logarithmic approximation of the oil refineries demand function as studied in the theoretical evaluation.
Within the theoretical part we build up the model of a profit-maximising firm. The situation of decarbonisation is represented through a two-constraint model: one which is budgetary and the other emission-related.

Afterwards we proceed by estimating the willingness to pay for clean hydrogen of the oil refineries for different scenarios and constraints. Figures below are indicative:



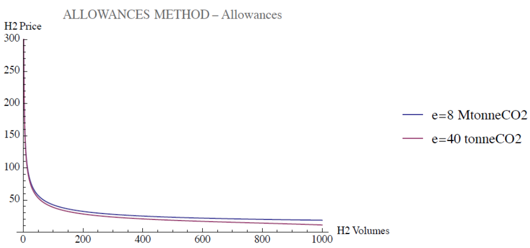
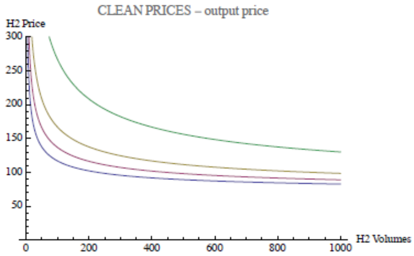


Figure 1a: Variation of the output price (left); **Figure 1b**: Variation of the emissions allowances (right)



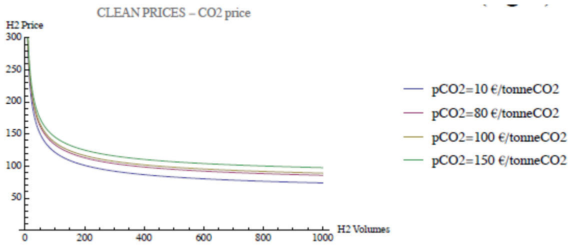


Figure 2a: Variation of the output price (left); **Figure 2b**: Variation of price of CO2 emissions (right)

Conclusions

The research indicates that establishment of a clean hydrogen market is a complex phenomenon, especially in Europe. It entails several techno-economic variables, policies and stakeholders at different levels. From national governments to European institutions and hard-to-abate companies, large and small, everyone needs more clarity to be able to navigate this situation. And there is where lies the value of the present research.

It becomes clear the role of market-maker that European oil refineries can play for clean H2 to be a viable decarbonisation alternative, pushed by three factors: (a) current usage of hydrogen in their operations, (b) high level of carbon emission, (c) good geographical positioning in the main commercial/trading routes. Oil refineries can pave the way for the establishment of clean hydrogen within hard-to-abate processes in a profit-retaining way.

Thus, adoption of clean H2 in the oil refineries is expected to have a viable business case, driven by expected tightening of emissions allowances – with a consequential increase in their price – as well as by the zero-carbon policies – e.g., Fit for 55 and its effects on the new EU cars and vans manufactured starting from 2035.

References

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The environment and directed technical change. In *American Economic Review* (Vol. 102, Issue 1, pp. 131–166). https://doi.org/10.1257/aer.102.1.131

Aleti, S., & Hochman, G. (2020). Non-Constant Elasticity of Substitution and Intermittent Renewable Energy. *Agricultural and Resource Economics Review*, *49*(2), 321–359. https://doi.org/10.1017/age.2020.7

Atkinson, S. E., & Halvorsen, R. (1976). Interfuel Substitution in Steam Electric Power Generation. *Journal of Political Economy*, *84*(5), 959–978.

Damette, O., Delacote, P., & Lo, G. Del. (2018). Households energy consumption and transition toward cleaner energy sources.

Energy Policy, *113*, 751–764. https://doi.org/10.1016/j.enpol.2017.10.060

Fuss, M. A. (1977). THE DEMAND FOR ENERGY IN CANADIAN MANUFACTURING An Example of the Estimation of Production Structures with Many Inputs*. In *Journal of Econometrics* (Vol. 5). North-Holland Publishing Company.

Griffin, J. M. (1977). Inter-Fuel Substitution Possibilities: A Translog Application to Intercountry Data. In *Review* (Vol. 18, Issue 3).

Halvorsen, R. (1977). *Energy Substitution in U.S. Manufacturing* (Vol. 59, Issue 4). https://about.jstor.org/terms

Kim, K. (2019). Elasticity of substitution of renewable energy for nuclear power: Evidence from the Korean electricity industry.

Nuclear Engineering and Technology, *51*(6), 1689–1695. https://doi.org/10.1016/j.net.2019.04.005

Newell, R. G., Jaffe, A. B., & Stavins, R. N. (1999). The Induced Innovation Hypothesis and Energy-Saving Technological Change.

The Quarterly Journal of Economics, *114*(3), 941–975. https://about.jstor.org/terms

Oxford Institute for Energy Studies. (2023). *Clean Hydrogen Roadmap: is greater realism leading to more credible paths forward?* Papageorgiou, C., Saam, M., & Schulte, P. (2013). *Elasticity of Substitution between Clean and Dirty Energy Inputs-A Macroeconomic Perspective*. http://ftp.zew.de/pub/zew-docs/dp/dp13087.pdf

Papageorgiou, C., Saam, M., & Schulte, P. (2017). Substitution between clean and dirty energy inputs: A macroeconomic perspective. *Review of Economics and Statistics*, *99*(2), 281–290. https://doi.org/10.1162/REST_a_00592

Pindyck, R. S. (1979). *Interfuel Substitution and the Industrial Demand for Energy: An International Comparison* (Vol. 61, Issue 2). https://www.jstor.org/stable/1924584

Steinbuks, J. (2010). *Interfuel Substitution and Energy Use in the UK Manufacturing Sector*. www.eprg.group.cam.ac.uk

Akira Maeda, Hiroshi Ishijima

A MODEL OF U-SHAPED RELATIONSHIP OF CORPORATE PERFORMANCE AND ESG BEHAVIOR

Akira Maeda, The University of Tokyo; 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan
Hiroshi Ishijima, Chuo University; 3-11-5 Kanda-Surugadai, Chiyoda-ku, Tokyo 101-0062, Japan

Overview

The impact of ESG (Environmental, Social and Corporate Governance) and CSR (Corporate Social Responsibility) on corporate performance has long been discussed. People are mainly interested in whether or not ESG helps improve corporate performance. There are many academic studies on this topic, but the results are not uniform: some studies show a positive relationship between the implementation of ESG activities and corporate financial and business performance indicators e.g., profit, revenue, return on assets (ROA), and return on equity (ROE). On the other hand, some studies argue that there is a negative relationship between ESG and corporate performance indicators. Whichever conclusion is reached, most of the research to date has been a discussion of whether the relationship is positive or negative, not the idea that it is essentially a mixture of both effects. The conclusion is a choice between the two.
This study is an attempt to provide a new perspective for understanding these mixed results thus far. Prior to this paper, we have proposed a hypothesis of a U-shaped relationship that can support both sides of the argument (*Figure 1*). In fact, the authors have reported on this hypothesis in several seminars and presentations (e.g. Maeda and Ishijima, 2023a; 2023b). In this paper, we report our latest findings on the theoretical analysis.

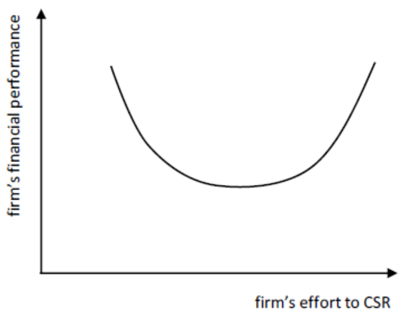


Figure 1: Conceptual diagram of a possible U-shaped relationship

Methods

We develop a theoretical model that helps explain the U-shaped curve. We use xx and yy as firm's ESG efforts and their financial performance, respectively. Let us start with considering a firm's production function with inputs of capital KK and ESG goods ZZ. Here, the ESG goods are considered as hypothetical goods that contribute to ESG. As the production function, we consider a CES function with the feature of homogeneous degree of one:

$$f(Z, K) = (\phi Z^{\rho} + (1 - \phi)K^{\rho})^{\frac{1}{\rho}}$$

where ϕ is the share parameter and ρ is a parameter that determines the elasticity of substitution between input factors. The following σ is then called the elasticity of substitution: $\sigma = \frac{1}{\rho - 1}$

Let r and v denote the rental price of the capital input and the price of the ESG input, respectively. The firm determines the allocation between capital and ESG according to the following equation:

$$\left(\frac{Z}{K}\right) = \left(\frac{\phi}{1-\phi}\right)^{-\sigma} \left(\frac{v}{r}\right)^{\sigma}$$

Due to the homogeneous degree of one nature of the production function, the higher the inputs, the higher the output, proportionally. Therefore, in order to make production independent of scale, we can divide f by K to have the following:

$$y \equiv \frac{f(Z,\,K)}{K} = \left(\phi\left(\frac{Z}{K}\right)^{\rho} + (1-\phi)\right)^{\frac{1}{\rho}} = \left(\phi x^{\rho} + (1-\phi)\right)^{\frac{1}{\rho}}$$

Here, the interpretation of ZZ/KK is originally the optimal ratio of ESG input to capital input, but here we simply consider it to be the ESG input per unit of capital input: Since the amount of capital input is also an indicator of

the size of the firm, the Z/K can be thus considered to be the ESG optimal input independent of size. Therefore, we interpret $x \equiv \frac{Z}{K}$ as an indicator of a company's ESG contribution or effort.

The interpretation of the last equation is a firm's relationship between their ESG contribution xx and their business/financial performance y. This is representing production activity of each firm. To make comparisons between firms, we introduce the following two assumptions:

Assumption 1: The larger a firm's size, the easier its financing will be.
Assumption 2: Firms with larger ESG contributions have higher elasticities of substitution between ESG goods and capital.

From assumptions 1 and 2 with detailed expressions (omitted here due to limitation of space), we obtain the following equation:

$$y = \left(\frac{2}{1 + x^{1-\frac{c}{x^{\alpha}}}}\right)^{\frac{1}{1-\frac{c}{x^{\alpha}}}} x$$

where α>0 and c>0 are constant coefficients.

Results

Equation (1) has a functional form that is difficult to treat analytically, so there is no choice but to observe the shape of the function by numerical calculation. The shape of the function is sorted out by setting α(>0) and c(>0). In fact, the shapes are observed as in Figures 2(a) and (b). As can be easily observed, the curve of Equation (1) is U-shaped, first going down and then going up.

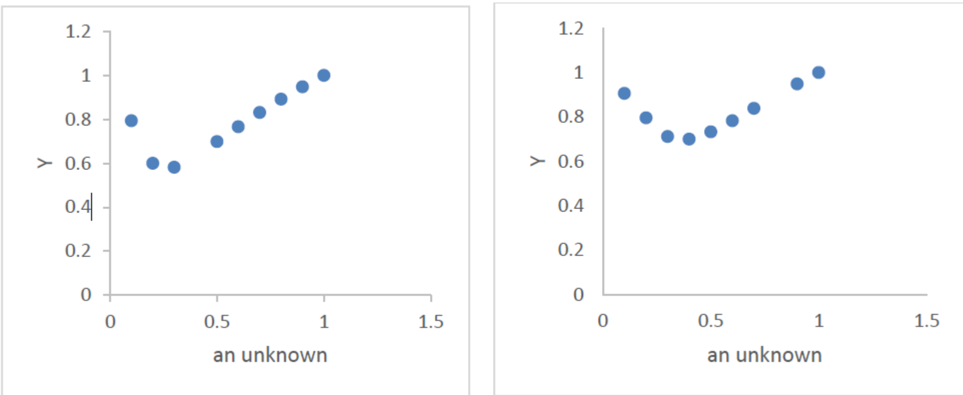


Figure 2(a): the shape of equation (1) (α=1 and c=0.4)

Figure 2(b): Shape of equation (1) (α=1 and c=0.8)

Conclusions

In this paper, we developed a theory that helps explain our hypothesis that the relationship between CSR/ESG and CFP is a U-shaped relationship. We started with CES function form, which is very common in economic analysis to determine a model that supports U-shaped curves. The model obtained here showed a shape that breaks monotonicity. In this respect, the model is quite original, and beyond CSR/ESG analysis, it has great implications for other fields, such as environmental Kuznets curves.

References

Maeda, A. and H. Ishijima (2023a). *A U-shaped Relationship Hypothesis on Corporate Financial Performance and ESG Behavior*. Presentation at 18th IAEE European Conference held at Bocconi University, Milan, 24-27 July, 2023.

Maeda, A. and H. Ishijima (2023b), "A U-Shaped Curve Hypothesis on the Relationship between Corporate ESG activity and Financial Performance," Research Institute for Mathematical Sciences, Kyoto University, Kokyuroku No.2272. pp63-67. (in Japanese)

Sabiu Bariki Sani

INTERPLAY OF FOSSIL FUEL USAGE, ENVIRONMENTAL CONCERN, AND ECONOMIC GROWTH

Sabiu Bariki Sani, Professor of Energy and Petroleum Economics, Department of Economics, Faculty of Social Sciences, University of Abuja, Nigeria.

Abstract

The global economy remains heavily dependent on fossil fuels, which are crucial for energy production, transportation and industrial processes. However, the environmental consequences of fossil fuel consumption, such as greenhouse gas emissions and ecological degradation, pose significant challenges. Balancing economic growth with environmental protection is a critical issue for policymakers worldwide. This article explores the intricate relationship between fossil fuel use, environmental sustainability, and economic development. It uses data from the International Energy Agency (IEA), the World Bank, and national statistical agencies to examine the impact of fossil fuel consumption on economic growth and environmental health.

The study employs a mixed-methods approach, integrating quantitative analysis of economic and environmental data with qualitative assessments of policy measures and technological advancements to evaluate policy measures aimed at reducing environmental harm, and discusses alternative energy sources and their potential to foster sustainable economic growth. Findings indicate that with the current global population growth and technological constraint, fossil fuel remains the most available and affordable source of energy to fuel economic growth and will continue to remain relevant within the global energy mix in spite of its effect on the environment. The study recommends de carbonization of crude oil among others to mitigate the effect of fossil fuel usage on the environment while sustaining economic growth.

Keywords: Fossil fuels, Economic growth, Environmental protection, Energy Security, Renewable energy, Sustainability, Greenhouse gas emissions

Marco Schamel

EVALUATING THE COST-COMPETITIVENESS OF DECENTRALISED GREEN FERTILIZER PRODUCTION IN SUB-SAHARAN AFRICA

Marco Schamel, Research Center on Energy Transmission and Storage (FENES) Technical University of Applied Sciences (OTH) Regensburg Seybothstrasse 2, 93053 Regensburg, Germany,

Overview

Synthetic nitrogen-based fertilizers are essential for feeding the growing world population. However, especially in the Global South, access to affordable fertilizers is instable and heavily influenced by global supply chain disruptions. Local green ammonia production can enhance supply security and significantly reduce emissions, working towards global climate neutrality. Ammonia serves as the main chemical for providing nitrogenous fertilizers and is therefore highly relevant for maintaining adequate crop yields. With Ghana as a case study, production costs for green ammonia are estimated and compared to current local nitrogen-based fertilizer prices. It shows that current cost projections for green ammonia are already within reach at current fertilizer prices. With targeted support, decentralised fertilizer production can provide a sustainable, secure and affordable supply of fertilizers to farmers in Sub-Saharan Africa, thereby improving food security and promoting climate neutrality.

Methods

Firstly, current ammonia demand for fertilizer purposes in Ghana is evaluated using several publicly available datasets. Secondly, a broad literature review is conducted to approximate costs of green ammonia production in Ghana, considering local parameters such as solar irradiation and costs of capital. Using the obtained cost estimates and demand projections, total costs are calculated to satisfy current ammonia demand, taking into account current technology data and giving insights into projected cost declines for green hydrogen equipment (e.g. electrolysers). To put these numbers into context, historical price data on ammonia is evaluated, shedding light on the price volatility due to geopolitical events and market disruption. A particular focus is furthermore placed on the differences between international supply prices on global trading hubs and domestic retail prices for fertilizers. The findings are synthesized to gain insights into the current and future cost-competitiveness of green ammonia as a feedstock for fertilizer production.

Results

Current nitrogen demand in Ghana averages about 69,000 t per annum, which equates to 84,000 t of ammonia [1] [2]. Existing literature shows a high dependency of green ammonia production costs on the local availability of renewable electricity, especially in islanded system configurations [3] [4] [5]. This finding favours countries like Ghana, which have an above-average solar energy potential [6]. However, a main challenge for solar-based energy procurement is the natural day-night intermittency of solar irradiance, leading to higher battery storage costs to satisfy minimum load requirements of the ammonia synthesis. Considering this, green ammonia production costs in Ghana are estimated to be between 950 and 1,450 USD2024 per ton of ammonia depending on the financing conditions [7]. This would lead to approximately 101 million USD of production costs to satisfy the current demand. Currently, fertilizers in Ghana are mainly imported, for example in the form of urea. Local retail prices showed high volatility, particularly since 2021, currently averaging about 600 USD/t of urea [8]. This implies an ammonia price of about 1,000 USD/t, being in the vicinity of projected green ammonia production costs and leading to total costs of 84 Mio. USD to satisfy current demand. This yields an estimated cost differential of a minimum of 17 million USD between imported nitrogenous fertilizers and locally produced green ammonia. It should be noted that the production costs do not include the conversion to storable fertilizers, local distribution, storage costs and taxes. On the other side, as renewable energy technology is set to decline further in costs, future green ammonia plants could be set up at lower costs, balancing out the potential underestimation of fertilizer production costs in this analysis [5].

Conclusions

Local green ammonia production could have transformative effects on agriculture in Sub-Saharan Africa: while leading to significant emissions savings, it could provide farmers with stable and reliable access to fertilizers, enhancing land productivity and securing food supply. Furthermore, local value creation is enhanced: by locally manufacturing a product of high value like fertilizers, Sub-Saharan African countries can capitalise on their abundant renewable energy potential, reducing the insecure and costly need for importing high-value chemicals like urea. As the analysis shows, current fertilizer prices in Sub-Saharan Africa are generally elevated compared to global benchmarks. Geopolitical disruptions like COVID-19 or the Russian invasion of Ukraine further destabilise and increase local retail prices, leading to unaffordability and supply scarcity. Local green ammonia production could reduce transport needs, mitigate carbon emissions, and ensure local price stability of fertilizers.

References

[1] International Fertilizer Association (IFA), 'IFASTAT'. Accessed: Jan. 12, 2024. [Online]. Available: https://www.ifastat.org/

[2] Food and Aggriculture Organization of The United Nations (FAO), 'FAOSTAT: Fertilizers by Nutrient'. Accessed: Sep. 16, 2024. [Online]. Available: https://www.fao.org/faostat/en/#data/RFN

[3] S. Mingolla, K. Rouwenhorst, P. Gabrielli, G. Sansavini, M. Klemun, and Z. Lu, 'Optimizing Sustainable Fertilizer Production: Techno-Economic and Environmental Assessment of Flexible Electrolytic Ammonia Production', 2024. doi: 10.2139/ssrn.4791664.

[4] M. Fasihi, R. Weiss, J. Savolainen, and C. Breyer, 'Global potential of green ammonia based on hybrid PV-wind power plants', *Appl. Energy*, vol. 294, p. 116170, Jul. 2021, doi: 10.1016/j.apenergy.2020.116170.

[5] D. Tonelli, L. Rosa, P. Gabrielli, A. Parente, and F. Contino, 'Cost-competitive decentralized ammonia fertilizer production can increase food security', *Nat. Food*, vol. 5, no. 6, pp. 469–479, May 2024, doi: 10.1038/s43016-024-00979-y.

[6] ESMAP, 'Global Photovoltaic Power Potential - Country Factsheet Ghana', World Bank, Washington, DC, 2020.

[7] R. M. Nayak-Luke and R. Bañares-Alcántara, 'Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production', *Energy Environ. Sci.*, vol. 13, no. 9, pp. 2957–2966, 2020, doi: 10.1039/D0EE01707H.

[8] AfricaFertilizer and International Fertilizer Development Center (IFDC), 'Ghana Fertilizer Prices & Market Comments: January - March 2024', 2024. [Online]. Available: https://wp.vifaakenya.org/wp-content/uploads/2024/04/Ghana-Fertilizer-Market-Comments-April-2024.pdf

António Cardoso Marques, Diogo Santos Pereira, Querubim Capimolo Lucamba

ENERGY TRANSITION AND BARRIERS FROM DOMINANT FOSSIL PLAYERS IN SADC

António Cardoso Marques, NECE, Management and Economics Department, University of Beira Interior, Portugal
Diogo Santos Pereira, NECE, Management and Economics Department, University of Beira Interior, Portugal
Querubim Capimolo Lucamba, Management and Economics Department, University of Beira Interior, Portugal

Overview

The energy transition from fossil fuels to renewable sources is crucial for reducing environmental pressures and ensuring sustainability, requiring reducing fossil fuel dependency (Heffron et al., 2021; Solomon and Krishna, 2011). According to data from SADC (2020), only 32% of rural areas in the region have access to electricity. The SADC region has a long history of reliance on coal and oil, making the transition to renewable sources a complex process. Additionally, the pursuit of environmentally sustainable energy sources can pose both a threat and an opportunity to the dominant companies in the fossil fuel sector, as well as to African countries whose economies are heavily dependent on revenues from this sector. Therefore, this study aims to analyse the barriers to energy transition in SADC, focusing on the challenges faced by the key actors in the fossil fuel-based energy sector.

Although the agreements at the international level, 1997 Quito Protocol, 2015 Paris Agreements, 2030 Agenda for Sustainable Development (UN), and United Nations Framework Convention on Climate Change (UNFCCC). Besides, the agreements at the SADC regional level SADC Energy Protocol 1996, Regional Indicative Strategic Development Plan (RISDP), South African Power Pool (SAPP), Renewable Energy and Energy Efficiency Initiative of Southern Africa (REEEP), and recently the African Charter on Renewables and Energy Efficiency 2017, continue to be key elements in accelerating the energy transition, it is notable that these programs face several barriers to achieving their objectives that go beyond political, economic and social obstacles. These barriers can be analyzed in the way companies and nations approach the energy transition discourse and the strategies they adopt in response to this scenario. In Painuly's view (2001), barriers to energy transition may be specific to a particular technology, while others may be specific to a country or region. This reality makes the energy transition in SADC a process that requires careful balancing between economic development and the need to reduce dependence on fossil fuels, in addition to promoting the growing adoption of renewable energy.

While there is an extensive body of literature on energy transition in general, this article focuses on identifying and systematizing the barriers that SADC countries face in the transition to renewable energy. This includes a detailed analysis of the major fossil fuel players and the economic interdependence of coal and oil in the region. Such a contextualized approach is scarce, as much of the research on energy transition is concentrated in more developed areas.

Methods

In this article, an exploratory qualitative research approach will be applied to triangulate the results of a survey conducted among energy specialists and some governing bodies linked to fossil fuel companies, in the SADC region with the literature review. This methodology was previously employed by Funder et al. (2021). Given the small sample size, this approach enables more profound research into the barriers to the energy transition faced by these actors. This study aims to incorporate a policy analysis of the strategies adopted by these countries' companies, examining relevant laws, reviews, and policies related to the energy transition in the SADC. These laws will be scrutinized to determine their alignment with the Sustainable Development Goals (SDGs).

Drawing from examples in countries such as South Africa, Angola, Mozambique, Botswana, Namibia, Zimbabwe, and Zambia (the major SADC countries with significant players in the fossil fuel sector, with South Africa leading in coal production and Angola in oil), this article will highlight the key barriers to the energy transition in the SADC region.

Conclusions will be drawn regarding the drivers and implications of how current programs and initiatives in SADC countries can promote the energy transition. The research will also analyze and review the existing literature related to the energy transition and its implications for the development of extractive industries, which players in the fossil fuel sector in the SADC region dominate. This study contributes to the current literature by addressing a gap concerning how fossil fuel companies can support the energy transition by using their revenues to fund renewable energy projects.

Results

The results from the consulted literature indicate that the dominant companies in the fossil fuel sector in the SADC region have significant investments in coal, oil, and gas infrastructure that still need to be fully amortized. This is exemplified by companies such as Anglo American, Glencore, Exxaro, and South32 in South Africa; Sonangol (the state-owned oil company), BP, TotalEnergies, Chevron, and ExxonMobil in Angola; and ENI, TotalEnergies, ExxonMobil, and Anadarko in Mozambique.
These companies often have strong lobbying power and influence policies and regulations to protect their interests, which are embodied in the investments made in fossil fuel infrastructure. The economic dependence on these assets hinders the transition to renewable energies, as companies are reluctant to abandon these infrastructures, continue to subsidize fossil fuels, hindering the competitiveness of renewable energy sources. One of the barriers frequently highlighted in the literature is the economic and market barrier, as renewable energy often requires high initial investments and faces market entry challenges due to the lack of adequate financial incentives.

Conclusion

The results of this research underscore the importance of addressing the barriers to energy transition in the SADC region. The findings of this article conclude that dominant fossil fuel companies in SADC still play a significant role in the region's development. Therefore, it is recommended that policymakers in these SADC countries invest more in research and renewable energy technologies, considering the energy challenges faced in the region. Policymakers must plan for decommissioning and phase-out, as these may occur sooner than expected, which could have severe consequences if reluctance persists. Finally, a key element in overcoming the barriers to energy transition lies in the need to adjust institutional and regulatory frameworks to better respond to these challenges.

References

Baker et al., (2023) Metrics for decision-making in energy justice. Annual Review of Environment and Resources, 48, 737–760. https://doi.org/10.1146/annurev-environ112621-063400

Benjamin K. Sovacool (2016) How long will it take? Conceptualizing the temporal dynamics of energy transitions, Energy Research & Social Science, 202-215 http://dx.doi.org/10.1016/j.erss.2015.12.020

M. Funder, H. Wlokas, T. Jhetam, K.H. Olsen (2021) Corporate community engagement professionals in the renewable energy industry: Dilemmas and agency at the frontline of South Africa's energy transition Energy Res Soc Sci., 81

R.J. Heffron, L. Downes, O.M. Rodriguez, D. McCauley (2021) The emergence of the 'social licence to operate'in the extractive industries? Resour. Policy., 74 (2021), Article 101272 Dec 1

Painuly, J. P. (2001). Barriers to renewable energy penetration; a framework for analysis. In *Renewable Energy* (Vol. 24). www.elsevier.nl/locate/renene

SADC. (2020). *SADC Regional Indicative Strategic Development Plan (RISDP) 2020-2030*. www.sadc.int

B.D. Solomon and K. Krishna, (2011) The coming sustainable energy transition: history, strategies, and outlook Energy Policy, 39 (11) (2011), pp. 7422-7431

Amsalu Woldie Yalew

SECTORAL AND ECONOMY-WIDE IMPLICATIONS OF REDUCING IMPLICIT SUBSIDIES TO ELECTRICITY SECTOR IN ETHIOPIA

Amsalu Woldie Yalew: Ca' Foscari University of Venice, Euro-Mediterranean Center on Climate Change (CMCC), European Institute on Economics and the Environment (EIEE), Via della Libertà, 12 - 30175 Venice (VE), Italy

Overview

Implicit and explicit subsidies for public (e.g., power and water supply) utilities are common in many developing countries. Policy changes affecting them are expected to have sectoral (e.g., changes in electricity prices and output, electricity energy supply and demand mix) and macroeconomic consequences. Indeed, the economy-wide effects would partly depend on how the government spends the revenues from reduced subsidies. This study examines the sectoral and economy-wide implications of gradually reducing the implicit subsidies to the state-owned power utilities in Ethiopia. It applies a computable general equilibrium (CGE) model with detailed representation of energy sources and demand in the country. CGE models are best suited to analyze the sectoral and economy-wide impacts of reducing subsidies as well as the alternative ways to recycle the increased revenue from reduced subsidies.

Method

The study applies a recursive dynamic CGE model called DEMETRA (JRC, 2021). The model allows flexible constant elasticity of substitution (CES) nesting of production functions and flexible CES-LES nesting of household demand systems which help to capture several features of developing economies. The production technology nest of the calibrated model for this study includes energy nests which allow imperfect substitution first between electricity from grid and off-grid sources and then, between a composite electricity, liquid fuels (petroleum and biofuels) and biomass fuels. The composite energy (of electricity, liquid fuels, and biomass fuels) is then considered as an imperfect substitute to a value-added nest which is a composite of primary factors (i.e., land, labor, and capital). Likewise, households exhibit a "fuel stacking" behavior whose energy bundle consists of fuelwood, agricultural wastes, biofuels, biogas, petroleum fuels, and electricity which are assumed to be imperfect substitutes. The model is calibrated to the 2015/2016 social accounting matrix (SAM) of Ethiopia (Mengistu et al., 2019). The SAM was adjusted to serve the core purpose of this study. First, to capture the public financing to the grid power sector investment and the resulting low electricity tariffs, "implicit" production subsidies (or negative taxes) are introduced to selected grid electricity sectors. Implicit subsidies refer to "the difference between the average revenue charged and collected at regulated prices and the revenue required to fully cover the operating costs of production and capital depreciation" (Trimble et al., 2016) which were reported to be substantial for the Ethiopian power sector (World Bank, 2019; Trimble et al., 2016). Second, the activities generating and distributing electricity services were disaggregated into 15 activities. The adjustment of the supply and use tables (SUTs) for the disaggregated electricity activities was motivated and informed by the extant literature (Cai & Arora, 2015; Peters, 2016). The total electricity output was first decomposed into generation (which is eventually further disaggregated by source – grid and off-grid, and technology– hydropower, wind, solar, diesel, etc.), and transmission and distribution (T&D) activities using information from different sources about the electricity sector in the country (EAPP, 2014; GSE & JICA, 2015; MoWIE, 2019). The demand of electricity from grid sources is distributed among industries (as intermediate input), households (as final commodity), and exports while that of off-grid sources is limited to households and selected small-scale industries (e.g., agriculture, food processing industries).
The CGE baseline scenario runs for the period of 2016 to 2030 at annual time step. It is driven by exogenous economic (IMF, 2024) and population (UNDESA, 2024) growth rates.
The policy (or experiment) scenarios involve gradually reducing the "implicit" subsidy rates to the electricity production activities by 5% every year starting from 2019 and by 60% in 2030 compared to the benchmark (2016) subsidy rates.

The year 2019 is the year in which various electricity sector reforms started to be implemented (Hassen et al., 2022; Tesfamichael et al., 2021). Such modest and gradual removal of subsidies is highly recommended to allow electricity utilities and users to adjust their production and consumption behaviors, and for their political acceptance and feasibility. Three policy scenarios, each representing a different assumption regarding government's plan to spend the savings from reducing subsidies, are considered. First, we assume the government saving remains fixed at the baseline scenario, and thus the government channels the revenues to expand the public services which include public administration, education, and health services. Second, we assume the additional revenues are used to increase government savings and thus goes to domestic savings. Third, we assume the government channels the revenues to external debt payments, and thus reduces the net financial flows from abroad to the Ethiopian government and economy.

Results

The CGE simulation results show that the impacts on real GDP are insignificant in all policy scenarios. For example, compared to the baseline scenario, real GDP in 2030 increases by 0.062% and by 0.006% in policy scenario 1 and 2 while it declines by 0.09% under policy scenario 3. Under policy scenario 1, increased revenues from reduced subsidies are spent on public services including health and education. This in return improves human capital and labor productivity according to the equations within the CGE model helping the overall economy to gain some sort of efficiency. Under policy scenario 3, however, the additional revenues are used for debt payments and hence reduces the net transfers to the government from abroad. This will also depreciate Ethiopian currency thereby reducing imports (by -0.54% in 2030) and driving up exports (by +1.23% in 2030). The notable effect of policy scenario 2 is that the increased government savings to finance domestic investment relieves the saving burden on households and enterprises. This eventually results in non-declining private households' consumption compared to a slight decline under policy scenario 1 and 3. Under all policy scenarios, grid electricity price increases (by +20%) while its supply decreases (by -10%). Part of the decline in domestic grid electricity supply is compensated by increasing grid electricity from non-subsidized sources (e.g., diesel generators, solar PVs, municipal wastes, and sugar bagasse 1 to 13%), and off-grid sources (+ 2.4%), and by reducing exports (by -28%). Most industrial and service activities tend to substitute grid electricity by off-grid electricity, and then composite electricity by petroleum fuels. Some activities such as transport services powered by electricity are severely impacted. Likewise, households' demand for electricity from grid sources declines, and is substituted by other energy sources (i.e., off-grid electricity, biomass fuels, and petroleum fuels).

Conclusions

Policies aimed at removing or reforming such subsidies to power utilities will have consequences for the rest of the economy. This study shows that the ultimate effects depend on how the government plans to spend the revenues from reduced subsidies. Although the overall impacts on real GDP could be negligible, the sign and size of the impacts vary across production activities and household groups. The insignificant aggregate impacts results are partly explained by the small share of electricity in the country's energy and macroeconomic systems. More than half of the Ethiopian households have no access to electricity. The share of the electricity sector in the national GDP is barely one percent. Yet, additional policy measures and incentives may be necessary to ensure that the shift in the power supply mix is geared towards renewable sources not into diesel-based electricity sources to stay in line with the country's ambitious Nationally Determined Contribution (NDC) to curb GHG emissions.

References

Hassen et al. (2022). "Effect of electricity price reform on households' electricity consumption in urban Ethiopia." Utilities Policy, 79, 101445.

JRC. (2021). *DEMETRA - Dynamic Equilibrium Model for Economic Development, Resources and Agriculture.* https://datam.jrc.ec.europa.eu/datam/model/DEMETRA/index.html

Trimble et al. (2016). *Financial Viability of Electricity Sectors in Sub-Saharan Africa: Quasi-Fiscal Deficits and Hidden Costs*. Policy Research Working Paper 7788, World Bank.

Marzia Sesini, Anna Cretì, Olivier Masso

UNLOCKING EUROPEAN BIOGAS AND BIOMETHANE: POLICY INSIGHTS FROM COMPARATIVE ANALYSIS

Marzia Sesini, Florence School of Regulation, Robert Schuman Center for Advanced Studies, European University Institute, Via G. Boccaccio 121, 50133 Florence, Italy;
Anna Cretì,Climate Economics Chair, Palais Brongniart, 28 place de la Bourse, 75002 Paris, France;
Université Paris Dauphine, Pl. du Maréchal de Lattre de Tassigny, 75016 Paris, France;
PSL Research University, 60 Rue Mazarine, 75006 Paris, France;
Olivier Massol, FP Energies nouvelles, 1 et 4 av. de Bois-Préau, 92852 Rueil-Malmaison, France;
IFP School, 228-232 av. Napoléon Bonaparte, 92852 Rueil-Malmaison, France;
Université Paris-Saclay, CentraleSupélec, Industrial Engineering Research Department, 3 rue Joliot-Curie, 91190 Gif-Sur-Yvette, France; Department of Economics, City, University of London, Northampton Square, London EC1V 0HB, UK.

Keywords: renewable gas; biomethane; biogas; policy mix; subsidies; comparative analysis

Overview

The European Union's 2019 Green Deal sets a goal of carbon neutrality by 2050, with electrification from renewables like wind and solar at the forefront. However, biofuels and hydrogen are vital in hard-to-decarbonize sectors. Despite this, academic research has predominantly focused on hydrogen rather than on renewable gases like biogas and biomethane. The 2022 REPowerEU Plan stresses the need for renewable gases (i.e., hydrogen and biomethane), yet scaling up biomethane faces challenges, including the need for investment, market access, grid connection, better price signals, sustainable feedstock mobilization and a unified Guarantee of Origin system across the EU.
The study evaluates European national policies supporting renewable gases, specifically biomethane and biogas, through a retrospective comparison of policies in Germany, Denmark, and Italy over a decade. The research aims to determine if renewable gases can benefit from policy frameworks similar to those that have successfully supported renewable electricity. It highlights the complex nature of supporting biogas, requiring subsidies and attention to the specific characteristics of this energy source. The study underscores the need to consider the intrinsic nature of the energy vector and incorporate demand-side subsidies. It introduces a unique database from primary sources, offering an original perspective on country-specific biogas and biomethane production, filling a gap in the detailed analysis of the relationship between support schemes and deployment for these renewable gases.
Historically, EU policies have focused more on renewable electricity than on biogas or biomethane. Nonetheless, the growing number of renewable gas plants reflects the sector's potential to contribute to the energy transition. The study identifies two main approaches in renewable energy policy literature: one emphasizes economic efficiency, while the other focuses on optimal policy design through carbon pricing and subsidies. A gap remains in understanding how multiple policy instruments interact, requiring a broader, multi-dimensional approach that goes beyond just technology. The study introduces a comprehensive framework for evaluating policy impacts on biogas and biomethane support trends, bridging the knowledge gap and assessing scheme performance in the context of public policy objectives and broader policy and economic frameworks.

Methodology

The research uses a model by Gustafsson and Anderberg as a guiding framework to evaluate biogas and biomethane policies across Europe. Through an extensive review of policy overviews, literature, and documents, an harmonized database tracking the evolution of national biogas policies between 2010 and 2019 was created, focusing on three leading biogas-producing countries: Germany, Denmark, and Italy. These countries were selected for their market maturity and diversity in production levels and feedstock types. The study excludes other developed markets like the UK and France for various reasons, including a lack of biomethane targets or specific market characteristics.
Data were gathered from both public and non-public sources to trace how these policies evolved.

The analysis explores how policy frameworks influenced biogas and biomethane development, aiming to understand the factors that contributed to successes and failures. The data collection involves an in-depth analysis of policy evolution and the creation of a harmonized database from publicly and non-publicly available sources, ensuring precision, coherence, and timeliness aligned with the study's objectives.

Results

Until the early 2000s, the biogas sector mainly relied on energy crops, high feed-in tariffs (FIT), and electricity generation through combined heat and power (CHP) units. Since then, the focus has shifted towards upgrading biogas to biomethane for grid injection, diversifying feedstocks, and reducing subsidies. This transition from FIT to feed-in premiums (FIP), and from CHP to grid injection, aims to foster a more competitive market and expand the use of renewable gases. However, market development has been uneven. Germany saw a stall between 2012 and 2014, Denmark faced a downturn after 2015, and Italy stagnated after 2013, with only a modest uptake of biomethane after the 2018 Biomethane Decree.

A comparison of the three countries shows a progression from FIT to FIP, and later to auctions and tenders, as support mechanisms for biogas and biomethane. The findings indicate that providing incentives on the supply side effectively reduces risks linked to initial investments and market establishment, as the installed capacity of biogas and biomethane responded positively to increased policy support and declined when support decreased.

However, they also underscore disparities among countries in incorporating demand and end-use considerations into their policies and the need for a strategic, long-term vision and a flexible policy ecosystem to effectively navigate the dynamic landscape of renewable gas markets. To this end, Denmark and Italy are highlighted as positive models with clear strategic visions, championing the use of biogas for waste management and transportation, showcasing the importance of aligning policies with overarching goals and adapting to changing market conditions. Additionally, the results emphasize the impact of factors such as feedstock availability, along with the geographic and economic structure of a country, on shaping the development of a market for renewable gases.

Conclusions: Lessons Learned and Implications

The study reveals a lack of comprehensive support, market perspectives, and policy frameworks, hindering the establishment of a harmonious EU-wide framework for biogas and biomethane deployment beyond electricity production. Challenges include high production costs, competition with cheaper natural gas, and weaker economic support than other renewables. To overcome these barriers, it is essential to consider the entire value chain, from production to end-use, and to introduce demand-side subsidies, adopting flexible policies to address evolving market conditions.

The comparative analysis shows that the successful deployment of biogas and biomethane depends on a holistic policy approach that integrates end-use applications, such as transportation and heating. Supply-side incentives have reduced risks and encouraged market creation, but future policies must be more flexible and responsive to market changes. Denmark and Italy illustrate the benefits of aligning policies with broader strategic goals, emphasizing the importance of waste management and transportation.

The study concludes by identifying under-researched areas, such as sustainable production, incentive structures, and the role of biogas and biomethane in the circular economy. These issues, especially in the context of the evolving energy landscape following the Ukraine conflict, require further attention to fully realize the potential of renewable gases in the EU's energy system.

Sara Giarola, Pablo Basterrechea-Roca, Nilay Shah, Yara Evans, Rocio Diaz-Chavez

ENHANCING THE CO_2 POTENTIAL AS A BIOECONOMY ENABLER

Giarola Sara, Imperial College London, UK
Pablo Basterrechea-Roca, Imperial College London, UK
Nilay Shah, Imperial College London, UK
Yara Evans, Imperial College London, UK
Rocio Diaz-Chavez, Imperial College Londo, UK

Overview

The Paris Agreement called for the strongest ever focus on reducing emissions, thus marking a step-change in international policies and national energy agendas (Hermwille et al., 2015). On this regard, the European Union (EU) has initiated an especially virtuous process compared to other nations, releasing a series of binding regulations for curbing emissions from energy and land-use compared to pre-industrial times which should make the region the first net-zero continent by 2050 (EU, 2020). However, despite the targets and the progress made so far, the EU is not on track for achieving the 1.5 ºC goal of maximum temperature increase compared to pre-industrial times. The challenges for mitigation are clearly shown by the large amount of CO_2 emissions, more than 3,200 kt in 2022 (EUROSTAT, 2022), which are calling for a dramatic curb in emissions, especially for sectors, such as industry. Enabling circularity of CO_2 can be instrumental for industries to transition away from fossils (Bains et al. 207). On the one hand, it will help industry reduce its pressure on climate change as well as on resources, since captured CO_2 can be used as a feedstock to produce chemicals and fuels (Samanta and Rajendra, 2020). On the other hand, carbon capture, use, and storage technologies (CCUS) optimized for working with biogenic CO_2 not only will reduce emissions, but also create an economic incentive to more than compensate the higher capital costs compared to incumbent technologies. Such an advantage would take place in presence of an emissions trading scheme, or a carbon tax, or a subsidy scheme.

Biomethanation, fed with biogas obtained from an anaerobic digester (AD), is the technology modelled and optimized in this study to demonstrate the feasibility of bioenergy technologies coupled with CCUS. To do so, we develop a two-layer optimization approach to estimate the life cycle cost of a biogas-fed biomethanation plant. The process is first modelled identifying the relevant process alternatives which then inform a superstructure model set to optimize the whole system, including the upstream and the downstream sides to the process. The suggested method will be used to demonstrate the criticalities of the biomethanation process and demonstrate under which conditions the process would be scalable and feasible. The analysis is robust in the way it conjugates experimental data obtained from a pilot plant operating in Greece with the process modelling and the supply chain superstructure optimization. At the system level, the process alternative selection is optimized in a supply chain where both the uptake of energy and raw materials (upstream side) and the product market conditions (downstream side) are modelled, considering a specific case study, the north-east of Greece.

Methods

We propose a two-layer optimization approach to design the integration of a biogenic source of methane (obtained from an AD plant) and a hydrogen-based biomethanation process.

In the first layer, the process is simulated and optimized from the energy point of view. In the AD section, 165.000 m3/d of wastewater is heated up to 35 ºC and then fermented. The liquid streams are then separated from the biogas, which is cleaned from impurities and sent to the biomethanation section. In the biomethanation section, a mixture of hydrogen and biogas is heated up and undergoes this reaction stoichiometry: $4H_2+CO_2 \rightarrow CH_4+2H_2O$

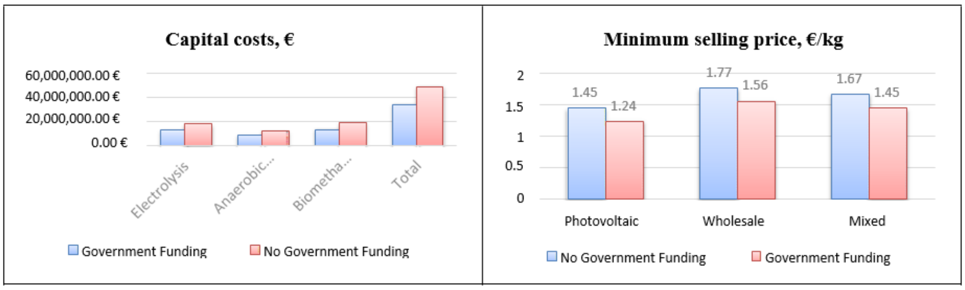
After a series of vapor-liquid separators, the biomethane can be sold. In this analysis, it is pressurized through a series of inter-refrigerated compressors and prepared for its transportation to the gas grid connection point. A final pressure of 20000 kPa is targeted for compressed truck transportation. From the initial process flowsheet, the process is optimized from the energy point of view. Three process alternatives are considered: the standalone anaerobic digester AD and the biomethanation operating after the AD. The former configuration produces electricity used for co-generation, where the excess

electricity is sold to the grid; the latter transforms the biogas into biomethane, which is injected into the natural gas grid.
In the second layer of analysis, the choice between the process alternatives is evaluated assuming a system perspective and adopting a supply chain view. Here both the process upstream and downstream are optimized assuming the policy, costs, prices, and infrastructure of the north-east of Greece. The area considered does not have a widely developed biomethane infrastructure; therefore biomethane would be first compressed and transported with trucks up to the nearest injection point

Results

From the process alternative optimized from the energy point of view, an economic analysis is carried out. In this section, relevant figures of the economic evaluation of the biomethanation process are displayed. In Figure 1, the capital costs of the project are presented displayed, both for each individual section of the plant, as well as for the overall installation. A first sensitivity analysis is performed to consider the efficacy of subsidies. These were modelled assuming that the government would support part of the capital expenditures and assumed equal to funding of 30% of the capital costs of the project. From the system point of view, a second sensitivity analysis is conducted on the quality of electricity feeding the plant. Electricity could come entirely from renewables, bought from the grid, or provided in a mixed fashion considering an 8-hour availability of renewable resources in a day and grid-electricity for the remaining hours. Results show first the relevant contribution on both capital and operating costs due to the hydrogen production, due to the high costs of electrolysis.

Figure 1: Project capital costs (left) and biomethane minimum selling price (right), both with and without government fundings.



Conclusions

With respect to the diffusion of biogas-based systems running on renewable hydrogen. governments must adopt strategies and policies that in long term would make electrolyzers available at higher efficiencies and lower capital costs. Subsidisation could be a near-term solution to reduce the capital expenditures of the technology. Subsidization would be even more important, if a full-time renewable electricity should be granted to the plant. In such a situation, storage technologies would be needed. The form of subsidization presented in this work is a partial coverage of the overnight capital expenditures. Further mechanisms would include carbon tax and biomethane price uplift.

References

Hermwille, L., Obergassel, W., Ott, H. E., & Beuermann, C. (2015). UNFCCC before and after Paris – what's necessary for an effective climate regime? *Climate Policy*, *17*(2), 150–170. https://doi.org/10.1080/14693062.2015.1115231 .

EU (2020). Long-term low greenhouse gas emission development strategy of the European Union and its Member States, available here. EUROSTAT (2022). Quarterly greenhouse gas emissions in the EU. Available here.

Bains, P., Psarras, P., Wilcox, J. (2017). CO_2 capture from the industry sector. *Progress in Energy and Combustion Science*, Volume 63, Pages 146-172, https://doi.org/10.1016/j.pecs.2017.07.001.

Samanta, S., Rajendra, S. (2020). Catalytic conversion of CO_2 to chemicals and fuels: the collective thermocatalytic/photocatalytic/electrocatalytic approach with graphitic carbon nitride. Materials Advances, Volume 1, Pages 1506-1545, http://dx.doi.org/10.1039/D0MA00293C.

Matteo Nicoli, Alessio Vai, Gianvito Colucci, Laura Savoldi

EVALUATING HOW THE AVAILABILITY OF CRITICAL RAW MATERIALS MAY AFFECT THE SECURITY OF FUTURE ENERGY SYSTEMS: A CASE STUDY FOR ITALY

Alessio Vai: Energy and Nuclear Engineer, Politecnico di Torino, Corso Duca Degli Abruzzi 24, Torino TO, Italy
Gianvito Colucci: PhD Student in Energetics, Politecnico di Torino, Corso Duca Degli Abruzzi 24, Torino TO, Italy,
Matteo Nicoli: PhD Student in Energetics, Politecnico di Torino, Corso Duca Degli Abruzzi 24, Torino TO, Italy,
Laura Savoldi: Full Professor in Nuclear Power Plants, Politecnico di Torino , Corso Duca Degli Abruzzi 24, Torino TO, Italy

Overview

The recent energy crisis underscored the need for resilient energy systems, particularly in energy-dependent regions like Italy, which imported over 4,300 PJ of natural gas and oil in 2022. This is the reason why policymakers are becoming increasingly concerned about energy security (ES). The latter is a multi-dimensional issue encompassing energy availability, accessibility, affordability, and acceptability. Additionally, the energy transition could lead to a security trade-off. Several regions are seeking greater energy independence and diversified imports, benefiting from renewable energy sources. Nevertheless, the energy transition could potentially shift the dependency towards critical raw materials (CRMs) and technologies supply chains, that presents a very high supply concentration and potential supply risk. Moreover, several reports point out possible supply-demand gaps by 2030 for raw materials that are strategic for reaching decarbonization targets. While devoted policies and studies about CRMs are increasing, a research gap emerges in evaluating how a possible limited availability of raw materials in the future may affect the security of energy systems.

Methods

This work aims to address the aforementioned gap by developing a comprehensive ES metric also including CRMs aspects, to be used in scenario analysis through energy system optimization models (ESOMs). The latter are recognized as suitable tools to support energy decision making processes. In this work, the open-source TEMOA-Italy model was used. The metric consists of seven indicators, grouped in three separate dimensions:

1. **Material supply risk (MSR).** A MSR indicator was defined for power sector, storage, and transport technologies based on established literature. It aims to evaluate the risks of materials supply chain disruption.
2. **Energy supply risk (ESR).** Three indicators were defined to account for the dependency and diversification of energy supply: Renewable energy supply (RES); Diversification of energy supply (DES); Self-sufficiency (SS).
3. **Reliability.** Three indicators were defined to account for the system robustness and resilience: Energy intensity (EI); Capacity factor (CF); Capacity credit (CC).

Once the indicators were properly linked to model outputs, they were normalized following the min-max approach and then aggregated into a single energy security index (ESI) using equal weights of 1/3 for each dimension. The ESI was used in the following scenarios:

- **Reference scenarios.** A Business as usual (BAU) scenario was used to model the minimum-cost energy system evolution according to stated policies. Then, emission constraints were set into the Net-zero emission (NZE) scenario to model the cost-optimal decarbonization.
- **Material disruption scenarios.** They account for potential materials supply shortages due to geopolitical and physical risks.

Results

The results show a significant increase of the MSR in the NZE scenario with respect to the BAU one. This is mainly due to the material consumption associated with the deployment of battery electric vehicles (BEVs) and renewable technologies in the power sector, including lithium-ion batteries (LIBs). According to the proposed metric, the higher MSR implies a decrease in overall ES, despite the reduced ESR. Indeed, the latter would contribute to improving ES thanks to the shift from fossil fuels import to the reliance on renewable energy sources available within Italy (the considered region). In scenarios modeling a disruption in the availability of CRMs imports, the total cost of the system significantly increases with respect to the optimal value associated with full availability, with the benefit of an improved ES thanks to the lower reliance on the CRMs import. The cost difference in the disruption scenarios with respect to the decarbonization one measures the economic impact associated with the implementation of possible decupling strategies from materials supplier countries or any interruption in the CRMs supply chain.

Conclusions

This work presents a metric to evaluate the security of energy system in future scenarios, accounting for risks associated with the import of CRMs. The massive penetration of BEVs and LIBs in the decarbonization scenario determines a dramatic increase in the MSR, to the detriment of overall ES. These aspects should be carefully considered by policymakers when introducing incentives or constraints aimed at a progressively higher deployment of technologies enabling emissions reduction. In perspective, studying the concurrent objectives of ES, emissions reduction, and the overall sustainability of the energy system within a multi-objective optimization framework may enrich the available tools for the analysis of future energy scenarios and provide relevant insights.

References

[1] P. Gasser, “A review on energy security indices to compare country performances” *Energy Policy*, vol. 139, Apr. 2020, doi: 10.1016/j.enpol.2020.111339.
[2] International Energy Agency (IEA), “The Role of Critical Minerals in Clean Energy Transitions – Analysis - IEA” 2021. Accessed: Nov. 29, 2023. [Online]. Available: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions
[3] European Commission, “Study on the critical raw materials for the EU 2023: final report.,” 2023.
[4] S. Carrara *et al.*, *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study*. Luxembourg: Publications Office of the European Union, 2023. doi: 10.2760/386650.
[5] M. Nicoli, F. Gracceva, D. Lerede, and L. Savoldi, “Can We Rely on Open-Source Energy System Optimization Models? The TEMOA-Italy Case Study,” *Energies (Basel)*, vol. 15, no. 18, p. 6505, Sep. 2022, doi: 10.3390/en15186505.
[6] D. Mosso, G. Colucci, D. Lerede, M. Nicoli, M. S. Piscitelli, and L. Savoldi, “How much do carbon emission reduction strategies comply with a sustainable development of the power sector?” *Energy Reports*, vol. 11, pp. 3064–3087, Jun. 2024, doi: 10.1016/J.EGYR.2024.02.056.
[7] L. Talens Peiró, N. Martin, G. Villalba Méndez, and C. Madrid-López, “Integration of raw materials indicators of energy technologies into energy system models” Appl Energy, vol. 307, p. 118150, Feb. 2022, doi: 10.1016/J.APENERGY.2021.118150.
[8] P. Bingoto, M. Foucart, M. Gusakova, T. Hundertmark, and M. Van Hoey, “The net-zero materials transition: Implications for global supply chains” 2022.

Papers

THE RELATIONSHIP BETWEEN ENERGY ACCESSIBILITY AND INCOME INEQUALITY IN LATIN AMERICA AND CARIBBEAN COUNTRIES[1]

Karen Villarroel
Instituto Superior Técnico, Universidade Lisboa, Portugal

Inês Carrilho-Nunes
CEGIST, Instituto Superior Técnico, Universidade Lisboa, Portugal

Margarida Catalão-Lopes
CEGIST, Instituto Superior Técnico, Universidade Lisboa, Portugal

Abstract

Access to modern energy services is crucial for well-being, health, and economic development, yet it remains out of reach for many marginalized communities. This article explores the relationship between access to modern energy services and income inequality within Latin America and the Caribbean (LAC), a region marked by pronounced income disparities and significant variations in energy access. Employing an econometric approach with Granger causality analysis over the years 2000 to 2019, the results suggest that enhancing access to electricity and clean cooking fuels can significantly reduce income inequality within the LAC region. However, the magnitude and direction of these effects are country-specific, underscoring the complexity of the energy-inequality nexus. Particularly, the case of Costa Rica is highlighted for its unique bidirectional causality between energy access and income inequality, fostering a virtuous cycle where development becomes endogenous. Conversely, in Bolivia, Brazil, and Honduras, this endogeneity does not occur, indicating a greater need for government policy intervention. Additionally, while increased electricity access positively affects access to clean cooking fuels in El Salvador, no direct link between energy access and income inequality is observed. Highlighting the connection between energy access and income inequality underscores the need for policy interventions specifically designed for the unique socio-economic and energy landscape of each country. These strategies must leverage energy access as a powerful means to combat income disparity effectively. While the study focuses on the LAC region, its implications extend far beyond, offering insights relevant to other middle-income nations facing similar challenges.

Keywords: Income inequality, Energy accessibility, LAC region, Granger causality

Introduction

Access to modern energy services is crucial for well-being, health, and economic development, yet it remains out of reach for many marginalized communities. This article explores the relationship between access to modern energy services and income inequality within Latin America and the Caribbean (LAC), a region marked by pronounced income disparities and significant variations in energy access. We employ an econometric approach with Granger causality testing over the years 2000 to 2019 for Bolivia, Brazil, Colombia, Costa Rica, El Salvador, and Honduras, which are included in the income ranges lower-middle and upper-middle, according to the United Nations classification. The total population of the LAC region surpassed 659 million people in 2022, and the countries selected represent almost half of this figure, around 47% (The World Bank, 2022).
The article is organized as follows. Section 2 presents a brief overview of existing literature regarding energy accessibility and income inequality. Section 3 details the methodology employed. Section 4 shows the empirical results and discusses them. Section 5 presents the conclusions, limitations, and potential perspectives for future research.

[1] This work is financed by national funds through the FCT - Foundation for Science and Technology, I.P., under the project 2022.08870.PTDC (https://doi.org/10.54499/2022.08870.PTDC). Inês Carrilho-Nunes and Margarida Catalão-Lopes gratefully acknowledge financial support from Fundação para a Ciência e a Tecnologia (FCT) through UIDB/ 00097/2020.

Literature review

This section provides a comprehensive review of existing literature, focusing on two critical areas: energy access and inequality. It begins by highlighting the global challenge of energy poverty and then explores the interplay between energy access and sustainable development, emphasizing the vital role of energy in achieving various SDGs and its impact on economic and social disparities. Furthermore, it discusses the complexities surrounding energy affordability and the multifaceted relationship between energy prices and access. Following this, the focus shifts to inequality, examining its implications on economic growth, the distribution of opportunities, and the broader social and environmental consequences. By examining these two topics, we set the stage for a deeper investigation into how energy accessibility and economic disparities are intertwined, and their collective impact on sustainable development.

Energy Access

"*About 1.2 billion people still lack access to electricity, and nearly 40 per cent of the people in the world lack access to clean cooking fuels*" (UNDP, 2018a, p. 2), which means that several people around the world are suffering from energy poverty, taking "*different forms, including a lack of access to modern energy services, a lack of reliability when services do exist, and concerns about the affordability of access*" (IEA, 2017, p. 24). In emerging countries, inadequate infrastructure and energy deprivation are also linked to energy poverty, with nations struggling with a lack of energy networks necessary for economic growth (Charlier et al., 2021).

There is a solid connection between SDG 7 (Affordable and Clean Energy) and several SDGs, including SDG 1 (No Poverty) and SDG 10 (Reduced Inequality). Furthermore, a nation that lacks access to modern energy may find it difficult or impossible to address other issues such as air pollution, low life expectancy, and scarce access to essential healthcare services (SDG 3), providing quality education (SDG 4), adapting to and mitigating climate change (SDG 11), food production and security (SDG 2), economic growth and employment (SDG 8), sustainable industrialization (SDG 9), and many others. Access to power also helps realize the idea of "Leave no one behind" because it can improve households' capacities (IEA, 2017; UNDP, 2018a), giving low-income populations better chances to raise their standard of living and leave the poverty line.

However, the price of energy can significantly influence energy access, particularly for individuals and communities with limited financial resources, impacting its affordability, availability, energy transition, and efficiency. Moreover, the relationship between energy price and access is complex and multifaceted and can vary across different regions and contexts. Other factors, such as infrastructure development, technological advancements, and policy frameworks, are also crucial in ensuring equitable and sustainable energy access (IEA, 2017; UNDP, 2018a).

Households with lower incomes tend to spend a more significant proportion of their disposable income on energy services or choose not to join grid networks. Income and equipment/appliance prices can directly contribute to energy poverty through accessibility and affordability. Indeed, lower-income populations frequently spend a disproportionate share of their income on energy, partly because energy-efficient equipment implies a higher initial investment cost. Homes with poor energy efficiency and outdated home furnishings would require people to pay more for the same energy services, which negatively impacts their quality of living and increases inequality (Oum, 2019).

Energy poverty is only a symptom of overall poverty: when households must choose between cooking, eating, and the ability to move, they are not distinguishing between energy, food, and mobility insecurity (Middlemiss, 2020). This means that energy poverty may also affect other types of poverty, as the lack of access to energy could entail being denied not only necessities like cooking and house heating, but also other components essential for both individual and societal growth, such as access to information, health care, education, and political involvement (González-Eguino, 2015).

Proving that increasing energy access can significantly affect individuals' quality of life, several findings reveal that more people with higher educational levels and longer life expectancies reside in regions with higher electrification rates. Improvements in school completion rates enable residents to obtain well-paying jobs, increasing their purchasing power and raising living standards. Furthermore, access to electricity increases the quality of medical care and lowers maternal and infant mortality, increasing life expectancy (Njiru & Letema, 2018). Therefore, improving access to energy and modern energy services is crucial to raising the quality of living and reducing energy poverty, income, gender, and other inequalities (Acheampong et al., 2021), which will be discussed in the following topics.

Inequality

Given that societies with high-income inequality experience slower economic growth and are less successful in eradicating poverty, growing inequality has been hampering progress towards the SDGs. Without the right institutions and policies, inequality produces or maintains unequal opportunities by concentrating political power among those already better off (Aiyar & Ebeke, 2020).

Despite the persistence of significant economic disparities worldwide, with a general trend of rising inequality in most developed countries since 1990, there has been a notable decrease in many Latin American nations (Figure 1). While income inequality surged during the 1990s — a decade marked by severe economic turmoil across Latin America and the Caribbean—it has been on the decline since the early 2000s. This positive trend of reducing inequality has also been observed in various countries across Africa and Asia. The Gini Coefficient varies significantly by global region. Currently, in 2020, according to the World Inequality Database (WIID, 2022), the following figures are recorded: North America=41; Europe and Central Asia=41.4; East Asia-Pacific=48.8; Latin America and the Caribbean=50.2; South Asia=51.2; Middle East and North Africa=54.2; and Sub-Saharan Africa=61.4

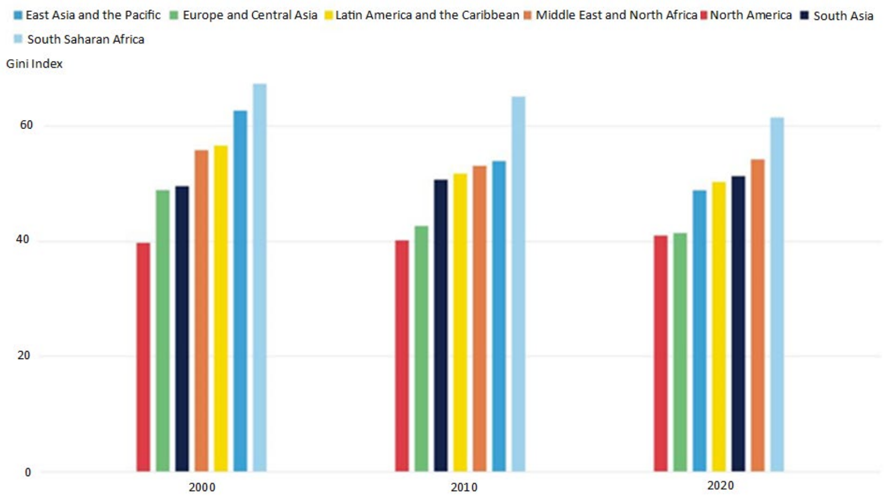


Figure 2: Gini index of previous decades by region. *Source:* WIID, 2022.

Rising income inequality significantly impacts economic growth, mainly because it reduces the capacity of the lower-income segments to invest in their skills and education. Reducing inequality is necessary to ensure equality of opportunities since people from low-income families face much weaker job prospects. Parents facing greater income inequality often led to their children having fewer equal opportunities in life (Aiyar & Ebeke, 2020). Since they represent a particularly vulnerable group, the community's lower-income members are the most affected by economic imbalances (Hassan et al., 2022).

Promoting egalitarian opportunities is not just about enhancing access to quality education, but also guaranteeing that the investment in human capital is compensated through access to productive and rewarding jobs (González-Eguino, 2015; Njiru & Letema, 2018; OECD, 2023). Economies face reduced growth in the future, as well as weaker demand today when those at the bottom of the income distribution are at a greater risk of not reaching their potential (Acheampong et al., 2021; DESA, 2020; Hassan et al., 2022).

The importance of exploring if economic inequality leads to energy poverty and environmental damage, which in turn can increase income disparity, is thus clear. To better understand this relationship, this article will focus on energy-related drivers of inequality, to investigate how energy access and other energy variables can impact income inequality, and vice-versa, seeking to answer the following research questions:

RQ1. Does access to electricity have an impact on income inequality?

RQ2. Does access to clean cooking fuels have an impact on income inequality?

RQ3. Does access to electricity impact the access to clean cooking fuels?

Methodology

The effectiveness of policy interventions and achieving SDGs depends on comprehending the complex interplay between energy access and income inequality across various socio-economic contexts. This paper uses different techniques to address these demands in different contexts, more specifically for the countries Bolivia, Brazil, Colombia, Costa Rica, El Salvador, and Honduras, which are included in the income ranges lower-middle and upper-middle, according to the United Nations classification (WIID, 2022). The total population of the LAC region surpassed 659 million people in 2022, and the countries selected represent almost half of this figure, around 47% (The World Bank, 2022). The countries' selection was dictated by data availability.

The chosen timeframe for analysis begins in 2000, as it marks the point when more comprehensive data on inequality measures and certain energy-related statistics became increasingly available for the selected countries. The cut-off year of 2019 was deliberately chosen to prevent the distorting effects of the COVID-19 pandemic on income inequality trends, as can be seen in Figure 2, with the Gini Index increasing in almost all analyzed countries in 2020. Indeed, this period represented a significant regression in development achievements, posing a challenge to efforts aimed at eradicating extreme poverty and narrowing inequalities. As a result, income inequality increased worldwide (The World Bank, 2021).

A set of relevant energy and economic data variables, chosen following the literature, was used to assess the relationship between energy access and inequality, taking into consideration other control variables. By including a diverse set of variables, we intend to comprehensively analyze income inequality from multiple angles, in a holistic approach, considering economic, social, environmental, and technological factors, with a focus on those linked with energy access.

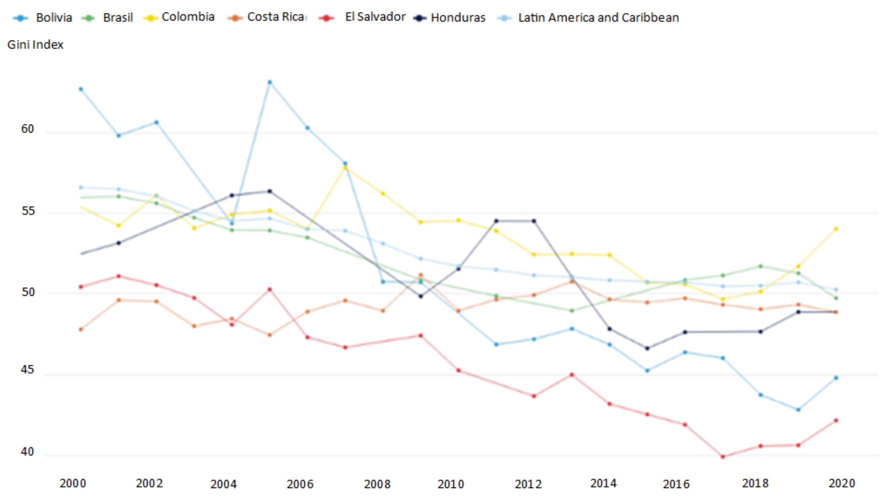


Figure 3: Gini index evolution from 2000 to 2020 by analyzed country in comparison with LAC region. *Source:* WIID, 2022.

First, the income inequality measure Gini Index was chosen, following previous works (i.e., Acheampong et al., 2021; Nguyen & Su, 2021; Zhong et al., 2020). This is a 0 to 1 or 0 to 100 measure that defines the level of income inequality of a country, with 0 representing perfect equality and 1 or 100 perfect inequality. It provides a straightforward overview of overall income or wealth inequality that is suitable when there is a need for cross-country or cross-time comparisons. This variable was collected from OECD (2023).

Regarding energy access-related variables, we consider the total population with access to electricity (variable named Electric) and the percentage of people with access to clean fuels and technology for cooking (variable named Clean cook), both collected from the World Bank, following the work of Acheampong et al. (2021) and Nguyen & Nasir (2021). These energy access variables are essential to understanding the LAC region since it is on the verge of being the first developing region in the world to attain universal access to electricity, with more than 96 percent of its population now having access to it (Barnes et al., 2018).

Other variables were also included, namely, the growth of the Gross Domestic Product (variable named GDPC) per capita, a key economic growth measure, and the urban population size (variable named Urbanpop), also collected from the World Bank.

Vector Autoregressive (VAR)-based Granger causality Wald tests will be applied to identify causal effects between variables. This approach allows the estimation of whether past values of one variable provide information that helps predict future values of another variable. While correlation analysis focuses on the magnitude and direction of the relationship, Granger causality focuses on the predictive power of one variable for another. Both tests are performed together to complement each other, although the main results are centered on the causality analysis (as in Nguyen & Nasir, 2021). This approach is essential since policy interventions should target causal factors if the goal is to address income inequality. Furthermore, Granger causality analysis considers the temporal aspect of the relationship, shedding light on the direction of causality over time, which explains its applicability in many studies (Carrilho-Nunes & Catalão-Lopes, 2022; Nguyen & Nasir, 2021; Santos & Catalão-Lopes, 2014; Sun et al., 2023).

In addition, Granger causality analysis assumes that the data is stationary, meaning that its statistical properties do not change over time (Wooldridge, 2012). Accordingly, a pre-modelling step was necessary, before applying the VAR-based Granger causality Wald test, to check the stationarity of the variables, via Fisher unit root tests with augmented Dickey-Fuller and the Phillips-Perron test methods.

The first step was to assess the plots of each country separately to identify trends. Then, the appropriate test was performed and the level of stationarity of the variables was determined. Only variables which are stationary at the same level can be tested for Granger causality (we considered series which are stationary at level [I(0)], integrated of order one [I(1)] or integrated of order two [I(2)), leading to the discard of variables with different levels of stationarity, which explains the reason why not all hypotheses could be tested in all countries.

Results and discussion

This section presents the results of the correlation analysis, and the Granger causality tests, by country, interprets them by taking their context into account and discusses their implications on policies and strategies that tackle income inequality challenges and increase clean energy accessibility.

Correlation Analysis

Table 1 presents the correlation results for the LAC region. Concerning the energy access-related variables (total population with access to electricity and percentage of people with access to clean cooking fuels and technologies), correlation analysis suggests that energy access can support a reduction in income inequality. Nonetheless, the correlation coefficient of both energy-based variables with the Gini index presents higher values in the lower-income countries, with more than 0.95 correlation in Bolivia and El Salvador and more than 0.86 in Honduras. The correlation was lower in the upper-middle-income countries Brazil and Colombia (around 0.65) and much lower in Costa Rica (0.01 for access to electricity and 0.3 for access to clean cooking fuels). These figures indicate that there is a substantial negative correlation between energy access and income inequality, which is even stronger in the poorest countries, and illustrate that it is impossible to have a one-size-fits-all strategy in the LAC region for increasing access to electricity.

Bolivia					
	Gini	Eletric	Clean cook	Urbanpop	GDPC
Gini	1.0000				
Eletric	-0.9647	1.0000			
Clean cook	-0.9551	0.9525	1.0000		
Urbanpop	-0.9480	0.9352	0.9952	1.0000	
GDPC	-0.3756	0.4967	0.4540	0.3989	1.0000

Costa Rica					
	Gini	Eletric	Clean cook	Urbanpop	GDPC
Gini	1.0000				
Eletric	-0.0129	1.0000			
Clean cook	-0.3027	0.8024	1.0000		
Urbanpop	-0.3086	0.8138	0.9987	1.0000	
GDPC	-0.2023	0.0569	-0.0738	-0.0599	1.0000

Brazil					
	Gini	Eletric	Clean cook	Urbanpop	GDPC
Gini	1.0000				
Eletric	-0.8554	1.0000			
Clean cook	-0.8255	0.9877	1.0000		
Urbanpop	-0.7395	0.9561	0.9846	1.0000	
GDPC	0.3030	-0.3657	-0.3876	-0.4060	1.0000

El Salvador					
	Gini	Eletric	Clean cook	Urbanpop	GDPC
Gini	1.0000				
Eletric	-0.9590	1.0000			
Clean cook	-0.9773	0.9877	1.0000		
Urbanpop	-0.9647	0.9811	0.9899	1.0000	
GDPC	-0.3643	0.2753	0.2889	0.2728	1.0000

Colombia					
	Gini	Eletric	Clean cook	Urbanpop	GDPC
Gini	1.0000				
Eletric	-0.6505	1.0000			
Clean cook	-0.7867	0.7316	1.0000		
Urbanpop	-0.7793	0.7333	0.9990	1.0000	
GDPC	0.3598	-0.3247	-0.0897	-0.1039	1.0000

Honduras					
	Gini	Eletric	Clean cook	Urbanpop	GDPC
Gini	1.0000				
Eletric	-0.9058	1.0000			
Clean cook	-0.8624	0.9808	1.0000		
Urbanpop	-0.8993	0.9737	0.9821	1.0000	
GDPC	0.3596	-0.0923	-0.0257	-0.0338	1.0000

Regarding the urban population, correlation analysis demonstrates a negative correlation between this variable and income inequality across each of the six countries examined. This suggests that a higher share of the population living in urban areas mitigates income inequality in the LAC region. Noteworthy, the correlation coefficient between Gini and urban population is higher in countries with less than 70% of their population living in urban areas, such as Bolivia, El Salvador, and Honduras (all low-middle-income countries, with a correlation coefficient from 0.90 to 0.97), but lower in Brazil, Colombia and Costa Rica where urbanization is more developed (upper-middle-income countries). One possible explanation is that an increase in urban population can help reduce income inequality. However, this effect is more relevant in lower-income countries with a high percentage of rural population, which could profit more from urban areas' structure and economic opportunities. Hence, to reduce income inequality, it is crucial for developing nations' Governments to actively advance rural development, enhance the well-being of rural populations, narrow the income disparity between urban and rural residents, and maintain a reasonable level of urbanization, making sure that rural areas will catch up to urban areas' rate of progress (Wang et al., 2023). Moreover, reducing income inequality in urban areas requires deliberate policies and investments in affordable housing, education, healthcare, workforce development, and social safety nets to ensure that the benefits of urbanization are shared more equitably among all residents (DESA, 2020).

As for the second control variable, GDP per capita, correlation analysis suggests a negative relationship with income inequality in some countries (Bolivia, Costa Rica, and El Salvador) but positive in others (Brazil, Colombia, and Honduras).

Granger causality analysis

Table 2 presents the results of the Granger causality testing. This analysis reinforces the idea that the impact of energy access can be different from one country to another. The test is performed on a country basis, only for the variables with equal levels of stationarity, as previously mentioned. The purpose is to evaluate the direction or absence of impact between the Gini and the energy-related variables (percentage of people with access to electricity and the percentage of people with access to clean cooking fuels and technologies), to provide adequate answers to our research questions one and two.

Then, we will test the relationship between the two energy-related variables, aiming to comprehend how access to electricity could impact access to clean cooking fuels and vice-versa, a causal effect studied, for instance, in Akter et al. (2023), and corresponding to our research question three.

Results of this analysis show that Bolivia and Costa Rica are the only countries in which access to electricity Granger causes income inequality in the sense of reducing it (RQ1). In Costa Rica, Granger causality is bidirectional, suggesting a feedback loop between these variables. Improvements in access to electricity can help reduce income inequality, but concurrently, addressing income inequality may also improve access to electricity by boosting economic capacity. These findings have important policy implications since policymakers and organizations may need to consider a two-way relationship and develop comprehensive strategies to improve access to electricity and address income disparities to create a more equitable and sustainable impact. For example, access to electricity might affect income inequality through improved education and job opportunities, while income inequality could influence access to electricity through affordability issues (Zhang et al., 2019). In Honduras also, income inequality Granger causes electricity access.

Table 2: VAR-based Granger causality Wald test results by country.

Bolivia					
Null hypothesis	χ2	Prob > χ2	Null hypothesis	χ2	Prob > χ2
Gini does not cause Electric	3.3508	0.187	Electric does not cause Gini	7.8615	0.020

Brazil					
Null hypothesis	χ2	Prob > χ2	Null hypothesis	χ2	Prob > χ2
Gini does not cause Clean cook	6.1953	0.045	Clean cook does not cause Gini	3.2248	0.199

Colombia					
Null hypothesis	χ2	Prob > χ2	Null hypothesis	χ2	Prob > χ2
Gini does not cause Clean cook	3.1371	0.208	Clean cook does not cause Gini	.17529	0.916

Costa Rica					
Null hypothesis	χ2	Prob > χ2	Null hypothesis	χ2	Prob > χ2
Gini does not cause Electric	7.0089	0.030	Electric does not cause Gini	10.429	0.005
Gini does not cause Clean cook	5.1392	0.077	Clean cook does not cause Gini	.3071	0.858
Electric does not cause Clean cook	5.5864	0.061	Clean cook does not cause Electric	.13846	0.933

El Salvador					
Null hypothesis	χ2	Prob > χ2	Null hypothesis	χ2	Prob > χ2
Electric does not cause Clean cook	44.098	0.000	Clean cook does not cause Electric	.53938	0.764

Honduras					
Null hypothesis	χ2	Prob > χ2	Null hypothesis	χ2	Prob > χ2
Gini does not cause Electric	19.386	0.000	Electric does not cause Gini	2.932	0.231
Gini does not cause Clean cook	21.506	0.000	Clean cook does not cause Gini	.21262	0.899
Electric does not cause Clean cook	16.36	0.000	Clean cook does not cause Electric	11.689	0.003

Note: The null hypothesis states that a certain variable does not Granger cause another variable within the VAR system. The null hypothesis is rejected when the p-value obtained from the Wald test (Prob > χ2) is less than the significance level of 0.1.

Table 3 summarizes these causality relations between the variables, with directionality (1) to (2):

Table 3: Summary of causality relations.

(2) / (1)	**Electricity access**	**Access to Clean cooking facilities**	**Gini Index**
Electricity access		Costa Rica, El Salvador, Honduras	Bolivia, Costa Rica
Access to Clean cooking facilities	Honduras		
Gini Index	Costa Rica, Honduras	Brazil, Costa Rica, Honduras	

In none of these countries does access to clean cooking facilities Granger cause income inequality (RQ2), but in Brazil, Costa Rica, and Honduras a reduction in income inequality Granger causes access to clean cooking facilities. In other words, variations in income inequality are responsible for changes in the availability and use of clean cooking fuels over time, possibly due to income levels influencing affordability and access to modern energy sources.

The comparatively expensive cost of clean and contemporary energy may be one of the reasons for its limited usage. If clean energy is not affordable, its economic impact will be minimal. In this scenario, policymakers and organizations may need to consider addressing income inequality as part of their strategy since policies aimed at reducing income disparities might indirectly lead to improved access to clean cooking fuels, as the previous analysis has shown for some countries. However, economic development, Government policies, and cultural factors must be considered because they may influence how income inequality affects access to clean cooking fuels and evaluate the impediments to clean energy usage. Increasing the use of clean energy after access is affordable also requires launching educational initiatives highlighting the advantages of doing so and educating people — especially women — on how to use these modern, clean energy technologies (Acheampong et al., 2021).

According to the results obtained, and focusing on RQ3, the relationship between electricity access and access to clean cooking fuels, in Costa Rica and El Salvador electricity access Granger causes the access to clean cooking fuels, while in Honduras electricity access and access to clean cooking fuels mutually Granger causes each other. In the first case, the result indicates that improvements in access to electricity are associated with improvements in access to clean cooking fuels. Policies should aim at expanding the availability of the electricity infrastructure, which may indirectly enhance access to clean cooking fuels. However, rather than concentrating only on increasing grid coverage, national governments in developing nations should also make investments to enhance the quality and dependability of energy, since the goal of providing everyone with access to clean cooking fuels may be accomplished with the support of a reliable high-quality electrical supply (Akter et al., 2023). In the second situation, policymakers and organizations need to recognize the interdependence of these variables since policies and initiatives may need to address both access to electricity and clean cooking fuels simultaneously to maximize their effectiveness, suggesting that an integrated approach to energy and infrastructure policies may be more successful. This type of project is relevant because, for example, improved access to electricity may lead to using electric stoves for cooking, thus reducing reliance on traditional biomass, which results in improved air quality and health benefits.
A project for ensuring universal access to affordable and reliable modern energy services poses significant challenges, and its success requires the development of energy policies, strategies, and action plans that support its implementation. The empirical evidence provided in this paper suggests that the impact of energy accessibility on income inequality is not only region-specific but also country-specific, implying that to profit from the benefits of energy accessibility to reduce income disparities, each country's context must be considered.

While the correlation analysis and Granger causality findings reveal the existence of a relationship in the LAC countries between increased access to clean and affordable energy on the one hand and reduced income inequality on the other, they shed light on how this relationship can be even stronger in lower-income countries, disclosing the need to address both challenges simultaneously.

Conclusion

As we navigate through an energy transition, understanding how access to energy and income inequality relate to each other becomes crucial. Indeed, facing the dual challenge of ensuring universal access to modern energy services and addressing widespread income inequality is complex but necessary for progress and an equitable transition.

This article examines how access to energy and income inequality are connected in the LAC region, showing how important modern energy is for sustainable development and reducing differences in income levels. The results suggest that enhancing access to electricity and clean cooking fuels can significantly reduce income inequality within the LAC region. However, the magnitude and direction of these effects are country-specific, underscoring the complexity of the energy-inequality nexus. Particularly, the case of Costa Rica is highlighted for its unique bidirectional causality between energy access and income inequality, fostering a virtuous cycle where development becomes endogenous. Conversely, in Bolivia, Brazil, and Honduras, this endogeneity does not occur, indicating a greater need for government policy intervention. Additionally, while increased electricity access positively affects access to clean cooking fuels in El Salvador, no direct link between energy access and income inequality is observed.

Highlighting the connection between energy access and income inequality underscores the need for policy interventions specifically designed for the unique socio-economic and energy landscape of each country. These strategies must leverage energy access as a powerful means to combat income disparity effectively. While the study focuses on the LAC region, its implications extend far beyond, offering insights relevant to other middle-income nations facing similar challenges.

References

Acheampong, A. O., Dzator, J., & Shahbaz, M. (2021). Empowering the powerless: Does access to energy improve income inequality? *Energy Economics*, *99*, 105288. https://doi.org/10.1016/j.eneco.2021.105288

Aiyar, S., & Ebeke, C. (2020). Inequality of opportunity, inequality of income and economic growth. *World Development*, *136*. https://doi.org/10.1016/j.worlddev.2020.105115

Akter, S., Mathew, N. M., & Fila, M. E. (2023). The impact of an improvement in the quality and reliability of rural residential electricity supply on clean cooking fuel adoption: Evidence from six energy poor Indian states. *World Development*, *172*. https://doi.org/10.1016/j.worlddev.2023.106366

Barnes, D. F., Samad, H., & Rivas, S. (2018). *Meeting challenges, measuring progress - The benefits of sustainable energy access in Latin America and the Caribbean*. https://doi.org/http://dx.doi.org/10.18235/0001407

Charlier, D., Legendre, B., & Ricci, O. (2021). Measuring fuel poverty in tropical territories: A latent class model. *World Development*, *140*. https://doi.org/10.1016/j.worlddev.2020.105278

DESA. (2020). The World Social Report 2020: Inequality in a rapidly changing world. In *World Social Report 2020*. United Nations. https://doi.org/10.18356/7f5d0efc-en

GEA. (2012). Global Energy Assessment: toward a sustainable future. In *Global Energy Assessment*. Cambridge University Press. https://iiasa.ac.at/projects/gea

González-Eguino, M. (2015). Energy poverty: An overview. *Renewable and Sustainable Energy Reviews*, *47*, 377–385. https://doi.org/10.1016/J.RSER.2015.03.013

Hassan, S. T., Batool, B., Zhu, B., & Khan, I. (2022). Environmental complexity of globalization, education, and income inequalities: New insights of energy poverty. *Journal of Cleaner Production*, *340*(January), 130735. https://doi.org/10.1016/j.jclepro.2022.130735

IEA. (2017). Energy access outlook 2017: From poverty to prosperity. *Https://Www.Iea.Org/Energyaccess/* , 1–143. https://www.oecd.org/publications/energy-access-outlook-2017-9789264285569-en.htm

IEA. (2022). World energy outlook. *International Energy Agency*, 524. https://www.iea.org/reports/world-energy-outlook-2022

Middlemiss, L. (2020). Energy poverty: Understanding and addressing systemic inequalities. In *Inequality and Energy: How Extremes of Wealth and Poverty in High Income Countries Affect CO2 Emissions and Access to Energy*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-817674-0.00005-9

Nguyen, C. P., & Nasir, M. A. (2021). An inquiry into the nexus between energy poverty and income inequality in the light of global evidence. *Energy Economics*, *99*, 105289. https://doi.org/10.1016/j.eneco.2021.105289

Nguyen, C. P., & Su, T. D. (2021). Does energy poverty matter for gender inequality? Global evidence. *Energy for Sustainable Development*, *64*, 35–45. https://doi.org/10.1016/j.esd.2021.07.003

Njiru, C. W., & Letema, S. C. (2018). Energy poverty and its implication on standard of living in Kirinyaga, Kenya. *Journal of Energy*, *2018*, 1–12. https://doi.org/10.1155/2018/3196567

OECD. (2023). *Inequality - Income inequality - OECD Data*. https://doi.org/10.1787/459aa7f1-en

Oum, S. (2019). Energy poverty in the Lao PDR and its impacts on education and health. *Energy Policy*, *132*(May 2019), 247–253. https://doi.org/10.1016/j.enpol.2019.05.030

The World Bank. (2022). *Population, total - Latin America & Caribbean*. https://data.worldbank.org/indicator/SP.POP.TOTL?locations=ZJ

UNDP. (2018a). Interlinkages among energy, poverty and inequalities. In *Accelerating SDG 7 Achievement: Policy Brief* (Issue 8). https://sustainabledevelopment.un.org/content/documents/17480PB8.pdf

UNDP. (2018b). *Policy brief for health and energy linkages-maximizing health benefits from the sustainable energy transition*. https://sustainabledevelopment.un.org/EnergyConference/documentation

UNDP. (2018c). *Policy Brief on the Interlinkages between Energy and Education*. https://sustainabledevelopment.un.org/content/documents/17553PB11.pdf

Wang, Q., Hu, S., Li, L., & Li, R. (2023). Accelerating urbanization serves to reduce income inequality without sacrificing energy efficiency – Evidence from the 78 countries. *Sustainable Cities and Society*, *92*, 104477. https://doi.org/10.1016/J.SCS.2023.104477

WIID. (2022). *World Income Inequality Database*. https://doi.org/https://doi.org/10.35188/UNU-WIDER/WIID-300622

Zhang, T., Shi, X., Zhang, D., & Xiao, J. (2019). Socio-economic development and electricity access in developing economies: A long-run model averaging approach. *Energy Policy*, *132*, 223–231. https://doi.org/10.1016/J.ENPOL.2019.05.031

Zhong, H., Feng, K., Sun, L., Cheng, L., & Hubacek, K. (2020). Household carbon and energy inequality in Latin American and Caribbean countries. *Journal of Environmental Management*, *273*, 110979. https://doi.org/10.1016/J.JENVMAN.2020.110979

THE ROLE OF DIGITALIZATION IN REDUCING ENERGY POVERTY

Teresa Magina
Instituto Superior Técnico, Universidade de Lisboa, Portugal, Phone: +351218417729,
Inês Carrilho-Nunes
CEGIST - Instituto Superior Técnico, Universidade de Lisboa, Portugal, Phone: +351218417729,
Margarida Catalão-Lopes
CEGIST - Instituto Superior Técnico, Universidade de Lisboa, Portugal Phone: +351218417729,

Overview

Energy plays a central role in modern society, serving as a fundamental commodity that supports various activities such as heating, lighting, and cooking. It is one of the most exchanged assets, satisfying human needs and propelling countless services (Wang et al., 2023). The global concerns surrounding the energy system bring awareness of the need to reduce energy poverty. Energy poverty is a complex and multidimensional challenge, with different assessments depending on the context of the study. For instance, for low-income countries, energy poverty involves households lacking access to modern energy for essential activities like electricity and cooking fuels. Yet, for higher-income countries, energy poverty can be described as a situation in which citizens spend most of their income on energy debts or must lower their energy consumption to a level that negatively impacts their well-being, increasing their inability to keep homes adequately warm or cold (European Commission, 2023; McCauley et al., 2019; Zhao et al., 2022).
Many individuals are experiencing energy poverty or are at risk of losing access to essential energy services due to energy price inflation, coupled with low income and the lack of efficient energy systems. As a result, the risk of losing access to crucial energy services increases (European Commission, 2022). Recent metrics reveal that global progress toward universal access to energy has been hindered. For instance, the number of people living without electricity had a global increase in 2022 for the first time in decades, topping the alarming value of approximately 775 million individuals (IEA, 2022). In addition, according to the International Energy Agency (IEA), more than two billion citizens are unable to access clean cooking appliances, falling under the energy poverty bracket (IEA, 2021). Furthermore, the Eurostat indicates that around 9.3% of European Union citizens could not properly warm their homes in 2022 (i.e., about 41 million people).
The path to accelerate the clean and efficient energy transition is, to some extent, focused on the potential of digitalization. By promoting ubiquitous connectivity, digital technologies have been revolutionizing economies, with digitalization being accountable for having the capacity to enhance the energy network's security, sustainability, and accessibility. Indeed, digitalization emerges as a potential catalyst for a clean energy transition, with the need for alignment between the rapid pace of digitalization and energy decarbonization services (Wang et al., 2023). Usually called twin transitions, digitalization and decarbonization are often perceived with divergence in what concerns the intensity associated with their deployment. In other words, digital transitions tend to occur faster than energy transitions (Fouquet & Hippe, 2022). Building synergies and fostering connections is necessary to incorporate digitalization into the energy industry. Therefore, new perspectives on the link between digitalization and energy are needed.
This article contributes to the growing body of literature on the connection between digitalization and energy poverty by offering two novel insights. First, it investigates and quantifies the relationship between digitalization and energy poverty in Europe, leveraging digital indicators from Eurostat and data from the Energy Poverty Advisory Hub (EPAH) Atlas. Specifically, it introduces innovative metrics to assess energy poverty, focusing on thermal comfort and arrears on utility bills (European Parliamentary Research Service, 2022; Johannes & Vondung, 2020). These indicators go beyond traditional measures, such as access to electricity or clean cooking, to address energy affordability and accessibility challenges prevalent in higher-income countries, where many families struggle with energy costs.

Second, the analysis examines energy poverty across total households and distinguishes between those above and below the poverty threshold. This disaggregated approach enables the design of more targeted and effective policy frameworks tailored to the specific needs of different groups, fostering sustainable energy access and affordability. The ultimate goal is to combat energy poverty while promoting inclusivity and equity. The research addresses the following questions:

RQ1: Can digitalization reduce energy poverty concerning energy affordability in Europe?

RQ2: Can digitalization reduce energy poverty concerning thermal comfort in Europe?

RQ3: How does the impact of digitalization differ across different thresholds of household poverty?

Data and Methods

To accurately measure the effect of digitalization on energy poverty and get the most holistic view of the topic, more than one measure of energy poverty is needed. The EPAH and the European Union Energy Poverty Observatory identified several primary indicators to assess the plight in Europe, namely, variables focused on energy affordability and its relationship with thermal comfort issues (European Parliamentary Research Service, 2022; Johannes & Vondung, 2020). Building upon such information and according to the data available, there are two main dependent variables in our paper – EPArrears and EPThermal, both metrics to assess Energy Poverty.

The dependent variable EPArrears considers “Arrears on Utility Bills (% country’s households)” as an indicator proxy for energy poverty, measuring the share of the population unable to pay utility bills (heat, electricity, gas, water) on time, in the 12 months prior to the survey. On the other hand, EPThermal represents the “Inability to Keep Home Adequately Warm (% country’s households)”, representing the population who declare they cannot maintain their homes at a comfortable temperature, struggling with thermal comfort issues. The two indicators chosen as dependent variables enable the analysis to understand the typology of energy poverty related to thermal comfort and affordability issues perceived in Europe. Additionally, the dependent variables are separated into groups according to the values of such metrics for different poverty levels, regarding income situation concerning the risk of poverty threshold. The division considers each country's median equivalized disposable income and is set at 60% of such value. People with an income below such a threshold are at risk of poverty and are inserted in the “below” group, while people with income values above the poverty line make the “above” group. Regarding labeling, “A60” considers households above 60% of the median equivalized income, while “B60” represents the share of households below the 60% of the median equivalized income. The division aims to study how different digitalization may affect households within the poverty line.

The models study data from 28 European countries from 2013 to 2022. The 28 countries are the following: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, and Sweden.

A group of digital metrics representing different facets of digitalization is gathered considering Individuals who ordered goods or services over the internet for private use between 3 and 12 months prior to data collection (% population), Individuals using the Internet for information about goods and services (% population), and Next-generation broadband access (%population), respectively *ebuy*, *infogs*, and *nextgen*. Additionally, following Xu et al. (2022), Principal Components Analysis (PCA) is performed to create another independent variable for the models (*pca*) to construct a Digitalization Index. The constructed variable combines three additional digital indicators, Households’ level of internet access (% population), Individuals using the Internet daily (% population), and Individuals using the Internet for online banking (%population), respectively *levelnet, netbank,* and *netdaily*. The variable *pca* is a proxy for a country's digitalization level, enabling one to study a more holistic effect of digitalization. The PCA allows for data dimensionality reduction while maintaining the most important information of the initial variables. The result is a series of uncorrelated linear combinations of the set that explain most of the variance, called the principal components (PCs), and are the solution to an eigenvector problem (Jollife & Cadima, 2016). The variable is obtained by retaining the first principal component of the data, which explains 91,23% of the variance. The Kaiser-Mayer-Olkin test (KMO) is rated at 0.7064, above the threshold (0.7), indicating the need to perform a PCA on the data.

Oil prices (*oilprice*), electricity prices (*electprices*), unemployment rate (*unemp*), and rural rate (*ruralrate*) are the control variables. Oil prices and electricity prices are a proxy for energy prices.

Their market behavior is expected to influence access to energy, mainly when a price rise occurs and, consequently, energy poverty. Unemployment is pointed out as one of the factors that hasten energy poverty by impacting a family's disposable income. Rural occupation rates are included to account for the possibility that energy poverty differs in non-urban locations. These variables will be used as controls and factors to address energy poverty. The descriptive statistics of all variables can be found in *Table 1*.

Table 1 – Descriptive Statistics

Variable	Obs	Mean	Std. dev.	Min	Max
ebuy	278	10.96468	3.421682	3.2	21.49
electprices	280	.1829971	.0578874	.0451	.4559
EPArrears	280	9.601071	8.427253	0	42.2
EPArrears_A60	280	7.564286	7.253461	.7	36.6
EPArrears_B60	280	19.59464	13.10565	4.6	65.4
EPThermal	280	9.319643	9.091073	.5	44.9
EPThermal_A60	280	7.222143	7.765654	.2	38.3
EPThermal_B60	280	19.23964	14.55285	2	69.7
infogs	279	68.09362	14.46507	25.71	95.63
levelnet	278	85.06259	9.539701	53.71	99.18
netdaily	279	55.44785	23.82217	4.16	96.13
netbank	279	73.81444	13.36463	32.2	96.3
nextgen	280	80.96214	16.12282	20.9	100
oilprices	280	75.91197	26.10305	43.12057	126.3116
pca	278	1.56e-09	1.654336	-4.684106	2.802309
ruralrate	280	26.38845	12.77352	1.847	46.668
unemp	280	8.023214	4.474547	2	27.8

The panel data model Ordinary Least Squares with Fixed Effects (OLS-FE) is the econometric technique applied to the data. Panel data models serve an important role by enabling the unobserved time-constant factors (a_{it}) to be correlated with the explanatory variables (x_{it}) and still obtain unbiased results. Considering that i represents each country, time sections are denoted by $t = 1,2, \dots, 10$ (years 2013 to 2022), $IndVar$ represents the primary digital variable for the models, and $u_{it}$is the idiosyncratic error, the time demeaned general expressions are the following (Wooldridge, 2013):

$$\ddot{EPArrears}_{it} = \beta_1 \ddot{IndVar}_{it} + \beta_2 \ddot{electprices}_{it} + \beta_3 \ddot{oilprices}_{it} + \beta_4 \ddot{ruralrate}_{it} + \beta_5 \ddot{unemploy}_{it} + \ddot{u}_{it} \quad (1)$$

$$\ddot{EPArrears\_A60}_{it} = \beta_1 \ddot{IndVar}_{it} + \beta_2 \ddot{electprices}_{it} + \beta_3 \ddot{oilprices}_{it} + \beta_4 \ddot{ruralrate}_{it} + \beta_5 \ddot{unemploy}_{it} + \ddot{u}_{it} \quad (2)$$

$$\ddot{EPArrears\_B60}_{it} = \beta_1 \ddot{IndVar}_{it} + \beta_2 \ddot{electprices}_{it} + \beta_3 \ddot{oilprices}_{it} + \beta_4 \ddot{ruralrate}_{it} + \beta_5 \ddot{unemploy}_{it} + \ddot{u}_{it} \quad (3)$$

$$\ddot{EPThermal}_{it} = \beta_1 \ddot{IndVar}_{it} + \beta_2 \ddot{electprices}_{it} + \beta_3 \ddot{oilprices}_{it} + \beta_4 \ddot{ruralrate}_{it} + \beta_5 \ddot{unemploy}_{it} + \ddot{u}_{it} \quad (4)$$

$$\ddot{EPThermal\_A60}_{it} = \beta_1 \ddot{IndVar}_{it} + \beta_2 \ddot{electprices}_{it} + \beta_3 \ddot{oilprices}_{it} + \beta_4 \ddot{ruralrate}_{it} + \beta_5 \ddot{unemploy}_{it} + \ddot{u}_{it} \quad (5)$$

$$\ddot{EPThermal\_A60}_{it} = \beta_1 \ddot{IndVar}_{it} + \beta_2 \ddot{electprices}_{it} + \beta_3 \ddot{oilprices}_{it} + \beta_4 \ddot{ruralrate}_{it} + \beta_5 \ddot{unemploy}_{it} + \ddot{u}_{it} \quad (6)$$

The fixed effects model assumes that u_{it} is uncorrelated with the independent variables over time, assuming strictly exogeneity (no endogeneity) and no omitted variable bias. The model works under the other OLS assumptions of normality, homoskedasticity and no serial correlation within u_{it}, across time periods, linear parameters, no perfect collinearity, and random samples (Wooldridge, 2013). The OLS FE model is used to control individual endogeneity isolating time-invariant factors, which is a common tool to assess panel data regarding the impact of technologies in the energy field.

The Variance Inflation Factor (VIF) test was performed to ensure the model does not have multicollinearity, heteroskedasticity is corrected with robust standard errors, and the model includes country clusters to account for serial correlation. As a pre-modeling step, the Fisher-type unit-root test based on augmented Dickey-Fuller tests is performed to ensure that the variables are stationary in order to avoid spurious regressions. The variables that exhibit non-stationary evidence are transformed into their logarithm value, identified with a "ln" at the beginning of the variable's label. Variables stationary at the level have their names displayed without modifications

Results

Building on the methodology outlined in the previous section, this section presents the results of the econometric models applied. The relationship between digitalization and its influence on energy poverty indicators is examined, focusing on arrears on utility bills and the inability to keep home adequately warm. We explore the variations in digital technology's effect across different household income levels, shedding light on ways digitalization interacts with energy poverty dynamics. The results are discussed contextualizing the results within the broader socio-economic landscape, providing a bridge between empirical findings and their implications for policy and practice in combating energy poverty through digital means.

Arrears on Utility Bills

The analysis of this subsection is going to focus on the "Arrears on Utility Bills (%households)" indicator (EPArrears), as well as its above and below clusters regarding income and poverty (EPArrears_A60 and EPArrears_B60, respectively). On average, in 2022, the share of households struggling to pay their utility bills on time is set at 7.51% for the European countries considered. However, the results differ when one divides the sample of countries by income status, focusing on different poverty levels. While around 5.9% of families above the poverty line have arrears on utility bills, the number is substantially higher within poorer households – 15.4% of households below the poverty line experience this type of energy poverty. Households below the median equalized income line usually struggle with many financial challenges, contributing to the higher incidence of debt on energy bills among this poverty threshold, hence utility bills can represent a significant financial hardship. Commonly, poorer households may also face problems with energy efficiency due to older or poorly insulated buildings that require more primary energy, therefore having higher expenditures. As a result, individuals may face a vicious cycle – the inability to pay their bills on time, rising arrears, and the incapacity to guarantee essential energy services. It is critical to find strategies for families to keep up with this burden and avoid the severe consequences of energy poverty.

Table 2 presents the results from individual testing of the independent variables *ebuy*, *infogs* and *nextgen* with dependent variables EPArrears, EPArrears_A60, and EPArrears_B60. As per the results, on average, ceteris paribus, a 1pp increase in the share of internet buyers, decreases the number of total households suffering from arrears on utility bills by 0.341pp (Column 1). The results are similar for families above and below the poverty line, with a decrease of 0.351pp and 0.332pp, respectively (Columns 2 and 3). The results prove that the e-commerce facet of digitalization can help cope with the financial aspect of energy poverty related to utility bills.

Table 2 – Individual Digitalization Variables (EPArrears) OLS Fixed Effects

	OLS Fixed Effects								
	EPArrears (1)	EPArrears A60 (2)	EPArrears B60 (3)	EPArrears (4)	EPArrears A60 (5)	EPArrears (6)	EPArrears (7)	EPArrears A60 (8)	EPArrears _B60 (9)
ebuy	**-0.341*****	**-0.351*****	**-0.332****						
	(0.001)	(0.001)	(0.016)						
infogs				**-0.145*****	**-0.126*****	**-0.231*****			
				(0.000)	(0.000)	(0.000)			
nextgen							**-0.076****	**-0.131****	**-0.060***
							(0.027)	(0.020)	(0.068)
unemp	0.680***	0.575***	1.045***	0.570***	0.502***	0.782***	0.654***	0.892**	0.590***
	(0.001)	(0.001)	(0.001)	(0.005)	(0.009)	(0.008)	(0.005)	(0.012)	(0.006)
electprices	15.209	13.850*	19.053	14.042*	12.390	19.070	16.023*	22.247	13.855*
	(0.112)	(0.095)	(0.293)	(0.087)	(0.101)	(0.215)	(0.052)	(0.161)	(0.068)
oilprices	0.009*	0.010*	0.017**	0.010*	0.011*	0.018**	0.008	0.014	0.009
	(0.086)	(0.085)	(0.039)	(0.096)	(0.094)	(0.043)	(0.183)	(0.113)	(0.150)
ruralrate	0.779	0.573	1.599*	0.253	0.073	0.935	0.067	0.601	-0.053
	(0.156)	(0.235)	(0.082)	(0.644)	(0.885)	(0.267)	(0.920)	(0.541)	(0.933)
_cons	-16.164	-11.582	-32.137	4.859	7.125	-0.463	5.204	2.001	5.852
	(0.270)	(0.361)	(0.201)	(0.748)	(0.608)	(0.985)	(0.791)	(0.947)	(0.750)
R^2	0.55	0.52	0.48	0.54	0.49	0.51	0.52	0.49	0.47
N	278	278	278	279	279	279	280	280	280

Note: * p<0.1; ** p<0.05; *** p<0.01. Values in brackets represent the P>| t |. R^2 is the within R-squared. N is the number of observations.

Moreover, increasing 1pp of the population's share of using the internet to learn about goods and services decreases the share of families with arrears on utility bills to 0.145pp for total households, 0.126pp for households above the poverty line, and 0.231pp for households below the line (Column 6). Similar to the previous variable, having digital access to information appears to contribute to a decrease in energy debts, especially in families with less income, where the result is higher. Lastly, the coefficients -0.076, -0.131, and -0.060 for EPArrears, EPArrears_A60, and EPArrears_B60, respectively (Columns 7, 8, 9), indicate that next-generation broadband connectivity decreases the share of families with energy debts; on average, everything else is constant. This digital variable can be a foster agent to help families in poverty alleviation, especially with higher income families, where the result is higher in absolute terms. Presumably, households with higher purchasing power will more likely feel the effects of modern technologies over families with outdated equipment.

Overall, the three digitalization variables show evidence of digitalization's ability to cope with arrears on utility bills. Firstly, e-commerce may seem a viable option to help reduce energy poverty as it can support users in a more sustainable and financially efficient strategy to reduce the arrears on utility bills, freeing up funds to allocate in such matters. The digital single market in Europe promotes ubiquitous connectivity, offering a wide range of practical, fast, and accessible solutions to users. E-commerce increased the offer of efficient and modern energy solutions alongside energy plans, incentivizing users to have sustainable energy consumption patterns. Individuals can increase their ability to pay bills on time by opting for more straightforward, affordable energy solutions. The expansion of digital trade can ultimately leverage buyers to make cost-effective choices that would otherwise be difficult to access and acquire. Leveraging digital technologies can help citizens reduce their consumption patterns. By incorporating smart meters that track household data, citizens are more aware of their energy demand, potentially preventing high bills. However, these assumptions highly depend on the user factor and the information used. Policies should incentivize incorporating smart technologies with initiatives that maximize their potential from the user side.

Furthermore, having online access to information about goods and services is tightly correlated with the increase in energy literacy, a fundamental dimension to promote a resilient and viable energy future. Digitally included citizens have easy and instantaneous access to information, empowering them to make informed decisions regarding utility bill payments. As mentioned above, the user side is essential to enhance technology use. Online information about goods and services can provide a complete experience for the user to maximize the potential of the equipment purchased, avoiding energy losses. Internet access is not limited to goods and services but to all facets of the energy system. Energy literacy can be eased through online platforms. Small improvement techniques can help upgrade insulation, for example. This may reduce consumption, decreasing the utility bill. The lower the expenses, the higher the probability of a user being able to pay them, especially on time.
Another essential step to empower individuals is having a stable, high-speed connection, such as a next-generation broadband connection. Consuming high-efficient energy products can reduce households' energy consumption as the connection is more secure and requires less primary energy. Moreover, this technology supports using smart home devices to boost energy management and potentially decrease bills. Next-generation broadband connections can also ease remote working or create new opportunities for citizens. By being digitally connected, users can expand their network, uplift their skills, and perform better at their jobs. The power of the internet plays a pivotal role in debt management, as it can affect the multidimensions of a family's life. Digitalization can expand access to essential services with a better value for money, promote energy efficiency, and help users reduce utility bills' arrears.

Table 3 presents the models considering the digitalization index developed via PCA. Everything else constant, on average, a 1pp increase in digitalization's index, reduces the share of total households with arrears on utility bills by 0.007pp (Column 1). Similarly, the results are 0.006pp and 0.099pp for households above and below the poverty line, respectively (Columns 2 and 3). The main effect remains when combining different aspects of the digitalization sphere – the phenomenon contributes positively to alleviating energy poverty. However, the results are now residual when compared to the individual testing. Nevertheless, combining daily Internet access with net banking and a household's Internet level can impact a family's consumption pattern and potentially reduce financial burdens and utility bills. In absolute terms, households below the poverty line show the most outstanding results over digitalization's impact in this energy poverty indicator.
Accordingly, digitalization can ease informed and responsible decision-making regarding energy products and empower financial management with the help of tools such as online banking. These

digital tools enable users to monitor savings, provide budgeting mechanisms to track expenses, and alert users when the next payment is scheduled. Despite not drastically changing the financial situation of the users or impacting the price of energy, these digital mechanisms can increase the household's commitment to pay utility bills in time, incentivize households to build saving funds, or even advise on how to invest their money. Educating consumers about budgeting, managing expenses, and accessing financial assistance programs can empower them to make informed decisions regarding utility bill payments.

Not only can net banking cope with utility bills, but also the other dimensions included in the Digitalization Index. As seen, digitally included citizens appear to be more likely to have access to modern and efficient technologies that can help them with utility bills.

Table 3: Digitalization Index (EPA) OLS Fixed Effects

OLS Fixed Effects	EPArrears (1)	EPArrears_A60 (2)	EPArrears_B60 (3)
EDig	-0.750***	-0.649***	-0.999***
	(0.001)	(0.003)	(0.002)
unemp	-0.024	-0.056	-0.308
	(0.812)	(0.546)	(0.401)
electprices	1.366	2.502	-2.362
	(0.614)	(0.345)	(0.704)
oilprices	0.003	0.004	0.003
	(0.316)	(0.237)	(0.793)
ruralrate	0.297	0.195	0.655
	(0.110)	(0.191)	(0.171)
_cons	-1.495	-0.601	-3.363
	(0.642)	(0.821)	(0.683)
R^2	0.33	0.28	0.24
N	146	146	146

Note: * p<0.1; ** p<0.05; *** p<0.01. Values in brackets represent the P>| t |. R^2 is the within R-squared. N is the number of observations.

Inability to Keep Home Warm

In this subsection, the focus is on the "Inability to Keep Home Warm (%population)" indicator (EPThermal), as well as its above and below clusters regarding income and poverty (EPThermal_A60 and EPThermal_B60, respectively). In 2022, the share of households that could not keep their homes warm was 8.41% for the European countries of the sample. Similar to the indicator EPArrears, the results have distinct patterns when examining income status. Among households above the poverty line, around 6.42% encounter the same problem. In contrast, 17.96% of households below the poverty line grapple with the inability to keep home warm.

The indicator EPThermal follows a similar trend as the previous form of measuring energy poverty. Inded, the variables EPArrears and EPThermal have a correlation coefficient of 0.67. By definition, a household incapable of properly warming their home is more likely to struggle with financial difficulties and have arrears on utility bills. To pay those debts, families sometimes lower their energy consumption to a degree where thermal comfort is not guaranteed. Moreover, low-income households usually struggle with unemployment or single parenting, and the causes are not mutually exclusive. Instead, they influence each other and aggravate the adverse effects. Considering this, their behavior regarding digital factors is most likely to be significantly related. It is important to remember that this indicator (EPThermal) is a self-assessment of citizens' energy needs. Socio-economic and cultural backgrounds highly impact what a household describes as inability; this indicator is subjective and could be affected by denial bias (European Commission, 2023).

Table 4 presents the results from individual testing of the independent variables *ebuy, infogs* and *nextgen* with dependent variables EPThermal, EPThermal_A60, and EPThermal_B60. An analysis of the results shows that a 1pp increase in the share of the population using the internet to place online orders increases, on average, ceteris paribus, the ability to keep home warm by 0.325pp in total households, and by 0.324pp in households above the poverty threshold (Columns 1 and 3). Interestingly, poorer households did not show significant results. This might be due to the fact that conditions in poorer households have to be drastically improved in order for e-commerce to implement changes efficiently. Nevertheless, the result is close to being statistically relevant. Similarly, infogs has a decreasing effect on domestic inability to keep home warm. Everything else constant, on average, digital information about goods and services can decrease the incapacity of keep home warm by 0.124pp on total households, 0.114pp on households above the income, and by 0.170pp on households below the income level, with 1 pp increase in the indicator (Columns 4, 5 and 6, respectively). Next-generation broadband did not show statistically significant results on EPThermal, and subsequent poverty thresholds. The reasons behind digitalization's impact on this energy poverty indicator can be many. By enhancing digital factors, families can leverage their knowledge on optimizing their homes' heating with small behavioral changes. This can optimize heating habits to spend less while benefiting the most, with enormous potential to uplift citizens' lives. As digitalization penetrates the energy system, more innovative and modern equipment can help maintain habitations warm for extended periods and more efficiently than older devices. E-commerce expands such an offer, heat pumps are an example of a technology prompted by digitalization that is far more efficient than boilers and can produce heat from renewable sources.

However, more than simple digital inclusion is needed to acquire the ability to keep houses warm. Similar to the past indicator, offering targeting support with adopting energy-saving technologies for families struggling with the burden is needed. In addition, when adopting energy efficient technologies, energy literacy has to be enhanced to successfully mitigate energy poverty.

Table 4 - Individual Digitalization Variables (EPThermal) OLS Fixed Effects

	OLS Fixed Effects								
	EPThermal	EPThermal A60	EPThermal B60	EPThermal	EPThermal A60	EPThermal B60	EPThermal	EPThermal A60	EPThermal B60
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ebuy	**-0.325***** (0.023)	**-0.324**** (0.016)	**-0.303** (0.156)						
infogs				**-0.124**** (0.022)	**-0.114**** (0.030)	**-0.170**** (0.029)			
nextgen							**-0.048** (0.286)	**-0.037** (0.378)	**-0.084** (0.263)
unemp	0.523*** (0.006)	0.482*** (0.005)	0.535* (0.081)	0.438*** (0.038)	0.414** (0.035)	0.366 (0.236)	0.551** (0.022)	0.531** (0.019)	0.481 (0.181)
electprices	18.800 (0.153)	19.033 (0.102)	15.418 (0.463)	17.269 (0.137)	17.354* (0.089)	14.865 (0.436)	18.298 (0.112)	17.969* (0.079)	17.317 (0.348)
oilprices	0.010 (0.243)	0.010 (0.199)	0.016 (0.176)	0.011 (0.165)	0.012 (0.128)	0.017 (0.141)	0.009 (0.280)	0.010 (0.215)	0.013 (0.259)
ruralrate	0.741 (0.163)	0.585 (0.203)	1.504 (0.143)	0.252 (0.660)	0.113 (0.824)	0.965 (0.338)	0.188 (0.776)	0.092 (0.877)	0.765 (0.477)
_cons	-15.018 (0.268)	-12.768 (0.266)	-25.390 (0.335)	3.622 (0.827)	4.616 (0.754)	-1.570 (0.956)	-0.251 (0.990)	-0.510 (0.978)	-2.206 (0.946)
R^2	0.45	0.45	0.30	0.42	0.41	0.31	0.40	0.38	0.29
N	278	278	278	279	279	279	280	280	280

Note: * p<0.1; ** p<0.05; *** p<0.01. Values in brackets represent the P>| t |. R^2 is the within R-squared. N is the number of observations.

Table 5 presents the results from including the constructed Digitalization Index via PCA (levelnet, netbank and netdaily) as a substitute for the individual digital variables considered previously.

Table 5 – Digitalization Index (EPI) OLS Fixed Effects

OLS Fixed Effects	EPThermal (1)	EPThermal_A60 (2)	EPThermal_B60 (3)
lnpca	-0.257* (0.083)	-0.156 (0.287)	-0.626*** (0.057)
unemp	-0.007 (0.959)	0.050 (0.702)	-0.270 (0.194)
electprices	9.132* (0.063)	10.963** (0.028)	-0.906* (0.875)
oilprices	0.004 (0.411)	0.003 (0.524)	0.007 (0.478)
ruralrate	-0.653*** (0.000)	-0.585*** (0.000)	-0.836*** (0.008)
_cons	16.662*** (0.000)	13.313*** (0.000)	30.730*** (0.000)
R^2	0.15	0.14	0.07
N	146	146	146

Note: * p<0.1; ** p<0.05; *** p<0.01. Values in brackets represent the P>| t |. R^2 is the within R-squared.

The Digitalization Index is relevant for total households but especially for households below the poverty line since the results are not statistically significant for households above the line. A 1% increase in a country's Digitalization Index is conducive to a 0.006pp decrease in the share of households unable to keep their homes warm (Column 3). Contrary to what happened with e-commerce, small increments in digital connectivity appear to have higher marginal gains in poorer households where energy poverty is more intense. The components of the constructed variable may present a reasonable explanation, especially net banking, that can empower individuals financially.
In this model it is possible to observe that the higher the occupation of rural location, the lower the incapacity to warm homes. The relationship might seem odd. However, rural locations can have certain advantages in what concerns warming homes. The overall cost of energy in rural areas might seem less expensive than in urban areas, increasing the available disposable income of families. Moreover, as this indicator is a self-assessment report, it is likely that rural populations have different considerations on cold environments, therefore are more prepared to face lower temperatures without needing a great amount of heat.

Conclusions

The cleaner energy transition has a long and challenging path to overcome. Deploying more resilient, secure, accessible, and sustainable energy systems is a complex process that includes efforts from both decision-makers and users and depends on technological advancements.

The results indicate that, on absolute terms, e-buy is the most relevant digital indicator to help cope with energy poverty. However, online information about goods and services helps to tread the path to a more informed user experience, and an optimized grid. Next-generation broadband connectivity is only relevant for decreasing the incapacity to timely pay utility bills. The constructed indicator suggests that combining different aspects of digitalization hinders energy poverty.

Digitalization can help leverage energy access by offering practical and accessible solutions to the grid. Whether incorporating digital technologies into the infrastructure or changing some citizens' micro-consumption habits, the policy implications and strategies should be tailored to countries and poverty indicators. The direct effects of digitalization on energy poverty indicate that the digital world can impact energy systems. Digitalization can thread the path to clean energy and fight the inequality crisis exacerbated by this challenging endeavour. There is an urgent need to invert the poverty trend and curb the poverty line.

Policymakers should support and promote the offer of modern and accessible alternatives. Moreover, it is necessary to expand digital electrification in all spheres of modern life to have less energy loss, and more information to help responsible authorities use such data to enhance the power systems. Another suggestion is incorporating renewable energy in the mix and deploying policies to limit environmental damage, propelled by digital initiatives. Countries should understand the importance of analog complements of the digital revolution, like education, to guarantee the practical impacts of digitalization. Energy literacy is transversal to all digitalization spheres and adequately enhance, should create informed and responsible generations, attentively seeking efficient energy management and cost-effective alternatives. Governments should incentivize educational programs so the population can manage energy consumption more efficiently, change energy patterns, and maximize the potential of digital grids to curb the trend of energy poverty. These policy implications, however, depend on the indicator utilized to measure energy poverty and should be adapted accordingly.
Future research should try to incorporate more complete variables and a larger group of cou
ntries. Other energy poverty indicators, such as "low absolute energy expenditure," could be considered, as well as more controls. Moreover, a simple approach to PCA was conducted with a single component retained. The suggestion is for more components to be retained in the future and to consider different indicators for the digitalization index to get a more comprehensive view of the process. Dynamic modeling should be tested since energy suffers from a path dependency effect; the present article neglects the lag effect of the dependent variable. Different econometric approaches can be further explored with instruments to correct for possible endogeneity with a larger sample to fit the model better. Another suggestion is the mediating role analysis to understand how a third variable could lead digitalization to affect energy poverty—the rapid pace of digitalization demands tailored analysis for optimal results.

Acknowledgements

This work is financed by national funds through the FCT - Foundation for Science and Technology, I.P., under the project 2022.08870.PTDC (https://doi.org/10.54499/2022.08870.PTDC). Inês Carrilho-Nunes and Margarida Catalão-Lopes gratefully acknowledge financial support from Fundação para a Ciência e a Tecnologia (FCT) through UIDB/ 00097/2020.

References

European Commission. (2023). Energy Poverty in the EU. Available at: https://energy.ec.europa.eu/topics/markets-and-consumers/energy-consumer-rights/energy-poverty-eu_en

European Commission. (2022). Digitalisation of the energy system. Available at: https://energy.ec.europa.eu/topics/energy-systems-integration/digitalisation-energy-system_en

European Parliamentary Research Service. (2022). Energy poverty in the EU. https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733583/EPRS_BRI(2022)733583_EN.pdf

Fouquet, R., & Hippe, R. (2022). Twin transitions of decarbonisation and digitalisation: A historical perspective on energy and information in European economies. Energy Research & Social Science, 91, 102736. https://doi.org/10.1016/J.ERSS.2022.102736

EMERGING SECURITY AND ECONOMIC CHALLENGE WITHIN RENEWABLE ENERGY COMMUNITIES: COST COMPARATIVE ANALYSIS AGAINST CYBERSECURITY ISSUES IN THE EVOLVING RECs SCENARIO

Christian Mari
Dipartimento di Ingegneria Gestionale, Politecnico di Milano, Milano, Italy,

Silvia Ricciuti
Sustainable Energy, Fondazione Bruno Kessler, Trento, Italy

Salvatore Manfredi
Center for Cybersecurity, Fondazione Bruno Kessler

Simona Stoklin
CIRIAF, University of Perugia, Perugia, Italy

Massimiliano Zanchiello
Università Sapienza, Roma, Italy

Francesca Giuliano
Dipartimento di Economia Internazionale, delle Istituzioni e dello Sviluppo, Università Cattolica del Sacro Cuore, Milano, Italy

Overview

In the context of the decarbonization of the energy system, the European Union promoted Directive 2018/2001/EU (European Union, 2018), also known as RED II, proposed a new legal framework for the development of renewable energy sources (RES) and, above all, to increase citizen participation in the energy transition through two new tools: collective self-consumption systems (CSC) and renewable energy communities (REC). The implementation of an energy community in Italy must pursue environmental, social but also economic goals, although not purely financial (Gazzetta Ufficiale, 2020). To do this, the Italian State has provided a financial contribution with the aim of incentivizing the installation of renewable energy production plants capable of producing and sharing the energy produced (MASE, 2024) inside the same primary sub-station (GSE Gestore Servizi Energetici, 2024; Mappa Interattiva delle Cabine Primarie, s.d.).This economic and governmental measure is part of a broader project that includes a series of implementation packages for the installation of renewable sources within the framework of a European energy transition project (*Figure 4*) with the aim of reducing dependence on fossil fuels (GSE, Legambiente, 2024).

	Bioenergy	*Photovoltaic*	*Eolic*	*Hydro*	*Geothermal*	*Waste*	*Termic*	*Total*
	MW	*MW*	*MW*	*MW*	*MW*	*MW*	*MW*	*MW*
Installed power on 2023	*4,100*	*24,200*	*11,700*	*22,800*	*900*	*500*	*55,400*	*119,000*

63,700

FER X		*50,000*	*16,500*	*630*				
CACER		*5,000*						
Energy Release		*5,500*						
Transizione 5.0		*1,000*						
On 2030	*4,100*	*87,000*	*28,200*	*23,430*	*900*			

144,300

Figure 4: Italian Government Energy Transition Measures

The creation, management and optimization of these new realities of widespread energy production and consumption require the use of ICT technologies, without which the integrated production, distribution and efficient use of renewable energy would not be possible (Nijuis, Gibescu, & Cobben, 2015). The massive use of ICT technologies essential for the functioning of such systems brings with it the risk of threats from malicious actors, whose objectives may include undermining the stability, functioning and reliability of the community itself (Gaggero, Piserà, Girdinio, Silvestro, & Marchese, 2023). Unfortunately, the necessary implementation of cybersecurity (Ricciuti, et al., 2024) can negatively impact the benefits derived by the energy community.

Method

Considering the small number of existing RECs and the quite young age of the existing ones, the main method was to review literature examples in similar context to try to predict possible future scenarios on cyber vulnerability in the context of RECs. The method is strengthened by following as case study different real newborn energy communities. The impact on cost follows typical cost analysis based on benefit and prevention. The idea is to highlight the potential security and economic challenge that will spread together with the emerging energy communities. The background of the formation of a REC goes through the compilation of a deed of incorporation and the drafting of internal regulations. These indicate the rights and obligations each participating entity (e.g., members) have, the modality of participation, and the composition of community bodies (of which the Scientific Technical Committee is a part) and the board of directors. The purely bureaucratic nature of these documents has a simple yet correct focus on the main objectives (e.g., the installation of renewable energy systems, the purpose of sharing of the energy produced and the dissemination of its value) while leaving as unsaid how the sharing is executed. Upon joining the CER, each household must connect an Internet-connected device to its electric meter, a smart meter. This smart meter will take care of monitoring the power shared at each instant, sharing the information in real time with a centralized monitoring system (e.g. commercial platform) and used by a manager, a member with the role of checking the usage values to evaluate the energy consumption, partition costs and earnings.

While from an energy management standpoint these smart meters are the sufficient means to enable power consumption analysis, they are a dangerous gateway to cyber-related risks. Given the economic, as well as environmental, nature of CER, a digitized monitoring system must anticipate the presence of risks related to the presence of both external and internal attackers, entities who act with malicious intent to compromise a system. Smart meters, which facilitate two-way communication between consumers and utility providers, are particularly susceptible to cyber-attacks due to their reliance on wireless communication and the inherent weaknesses in their design and implementation (Baskaran et al., 2021) (*A Conceptual Model for Mitigating Security Vulnerabilities in IoT-Based Smart Grid Electric Energy Distribution Systems | Scientific.Net*, n.d.) (*Cyber-Attacks on Smart Meters in Household Nanogrid: Modeling, Simulation and Analysis*, n.d.).

In a system like CERs, an attacker can take advantage of an incorrect use of smart meters in mainly three ways: (i) they can tamper with the participant's energy consumption, either by lowering his own transmitted consumption or by increasing the others' to force a different partitioning of costs and earnings (data falsification), (ii) exfiltrate REC participants' personal data, and (iii) learning the habits of the tenants of a certain housing unit. The last behavior is expected to enhance the management of power consumption; however, an unethical application of this information may serve to determine whether it is feasible to trespass.

1. Data falsification attacks can occur when an adversary gains unauthorized access to a smart meter, allowing them to manipulate consumption data. This manipulation can lead to significant financial losses for both consumers and utility companies, as it distorts the actual energy usage and can result in incorrect billing (Gunduz & Das, 2024).
2. Smart meters have the capability to collect and transmit detailed data about energy consumption patterns. This data can be leveraged to learn user behavior, which presents both opportunities and significant privacy concerns. The dual functionality of smart meters—facilitating energy management while simultaneously collecting sensitive user data—raises critical issues regarding user privacy and the potential for unauthorized access or misuse of this information (Tabrizi & Pattabiraman, 2012).
3. The ability of monitoring real-time energy usage allows REC to optimize energy distribution and manage costs effectively. However, this same capability can be exploited by malicious actors to infer personal habits and behaviors of users. For instance, detailed consumption data can reveal when individuals are home, their daily routines, and even the types of appliances

they use (Douha, Sasabe, Taenaka, & Kadobayashi, 2023) (McLaughlin, McDaniel, & Aiello, 2011). Such insights can lead to targeted cyber-attacks or invasions of privacy, as attackers could use this information to plan physical break-ins or other malicious activities (Yussof, Rusli, Yussoff, Ismail, & Ghapar, 2014).

Another factor to consider is that the deed of incorporation, by regulating the formation of a new legal entity, regulates its establishment in accordance with the civil code. Being an entity which processes personal data as part of the activities, a REC is subject to the requirements set by GDPR (Union). The GDPR (General Data Protection Regulation, 2016/679) provides a comprehensive legal framework for data protection in the European Union and establishes principles, rights of the data subject, and duties of data controllers or processors. It defines the critical role of the Data Protection OffiREC (DPO), an entity tasked with ensuring that organizations comply with GDPR requirements and that the rights of data subjects are upheld. This role is defined in Article 37 of the GDPR, which delineates the criteria for the appointment of a DPO, underscoring the significance of this position in promoting transparency and accountability in data processing activities.

Furthermore, two more legal texts are bound to outline the functioning of a CER: NIS2 and CRA. NIS2 is an EU-wide cybersecurity legislation that aims to establish a standardized level of cybersecurity across all EU Member States (European Union). It expands the scope of the original directive by including not only traditional critical infrastructure sectors, but also digital service providers and other important entities that play a role in the digital economy

The energy sector is particularly sensitive to the directive due to its critical infrastructure status, as it is a primary target for cyberattacks and provides essential services to the public. Consequently, the Directive imposes specific obligations on energy companies to protect their networks and information systems (NIS2 DIRECTIVE).

The CRA (Cyber Resilience Act) (European Union, 2019) mandates cybersecurity requirements for manufacturers and retailers to safeguard consumers and businesses that acquire software or hardware products that contain a digital component. These requirements govern the planning, design, development, and maintenance of these products. These responsibilities must be fulfilled at each stage of the value chain. ('Cyber Resilience Act - Read the Annexes to Enhance Cybersecurity', n.d.). A REC will therefore benefit from the requirements imposed by the Cyber Resilience Act as the employed smart meter will undergo a rigorous certification phase, resulting in a sound product.

Results

Renewable Energy Communities potentially have excellent profitability, but also a high volatility of returns (Manso-Burgos, Ribó-Pérez, Gómez-Navarro, & Alcázar-Ortega, 2022) with the IRR of the investment that, in Italy, can vary between 9.5% and 88% and related Payback Times that oscillate between 13.6 and 1.1 years (Cirone, Bruno , Bevilacqua, Perrella, & Arcuri, Techno-Economic Analysis of an Energy Community Based on PV and Electric Storage Systems in a Small Mountain Locality of South Italy: A Case Study, 2022). The economic return of the two configurations can vary depending on numerous parameters such as the cost of energy and the percentage of incentive returned to the end user (Moretti & Stamponi, 2023), but also on the size of the self-consumption configuration itself and therefore on the number and type of actors involved in the "community" with values that oscillate overall between 360 and 160 €/year for residential users of a CER, and in particular 97 €/year for residential users in a collective self-consumption (Franzò, Chiaroni, Chiesa, & Frattini, 2021). A recent study (PoliMi, UniTrento, LEAP, Agosto 2024) has hypothesized even lower net revenues due to the incentive, ranging between €29.2 and €52.3/year, depending on the coordination effort or not in optimizing self-consumption among community members. Unfortunately, the expected economic benefit constantly decreases over the years and each new simulation has a negative impact, decreasing the expected economic return/economic benefit of those who participate in the energy community (*Figure 5*).

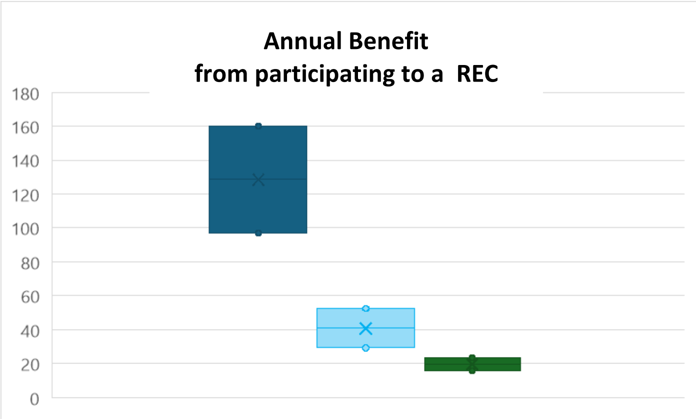


Figure 5: Individual Expected Annual benefit in participating to a REC

The framework implemented to counter the dangers of cyber-attacks has a high cost (Zhang, He, Li, & Abdous, 2021). In fact, they require the purchase of high-performance and expensive IT systems, as well as the use of specific software that requires constant updating. At the same time, the implementation of renewable energy communities requires the implementation of complex IT and monitoring networks which, by their very nature and configuration, can be attacked by external malicious actors. However, current earnings forecasts (communities are evolving now) linked to self-consumption of electricity are poor and therefore in conflict with the costs necessary to implement adequate cyber security barriers. This suggests that sensitive areas will be created that are easily exposed to cyber-attacks and it will be necessary to arrive at a sort of trade-off between energy sales revenues and cyber security implementation costs. The problems unfortunately connected and found in the implementation of a cybersecurity system could be of a double nature: on the one hand, in fact, they would further reduce the economic benefit of those who wanted to participate in a CER, because their financial income would be reduced by up to 15% (Safitra, Lubis, & Fakhrurroja, 2023) increasing the negative trend of the simulations already carried out but above all by lowering the incentive even further from the expectations of those who would like to actively participate in an energy community, and secondly because this will further lower the annual revenue value compared to the expected value, which, 80% of those who want to participate in a CER (Politecnico di Milano, 2024), should be higher than 100€/y (*Figure 6)*.

Conversely there are some benefits of implementing cybersecurity measures in Renewable Energy Communities (REC):

a) prevention of economic damage from cyber-attacks because cyber-attacks can cause direct operational damage, including downtime, data loss, and system recovery costs. The economic value of these benefits can be quantified by comparing the cost of a cyber-attack with the cost of implementing security measures: the avoided cost is the difference between the security implementation costs and the potential costs of an unprevented attack.

b) Reduction in recovery and downtime costs: downtime costs can be high, especially for critical infrastructures like energy systems. Estimating these costs can be done by calculating the average system downtime and the hourly operational cost of a REC. The economic benefits of cybersecurity are obtained by multiplying the downtime reduction (thanks to advanced security systems) by the average hourly downtime cost.

c) Compliance with regulations and avoidance of penalties becuase it is required compliance with data protection and critical infrastructure security regulations. The economic benefits are quantifiable by estimating the cost of potential fines and comparing them to the implementation costs of security solutions, which are significantly lower than the fines for non-compliance.

d) Improvement of reputation and consumer trust: cybersecurity also affects the reputation of a REC, which can lead to increased user participation. The economic value can be calculated by evaluating the increase in memberships or the reduction in user cancellations. A good example is the increase in participation in communities that offer strong data protection, with measurable economic returns from increased subscriptions.

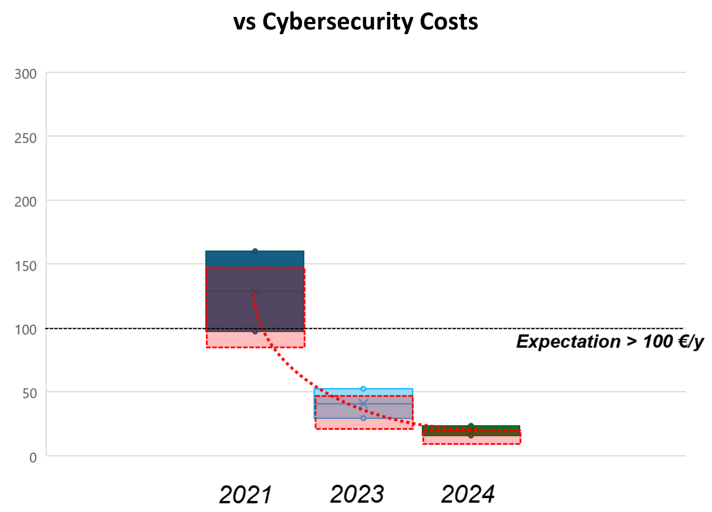


Figure 6: Cybersecurity Expected Impact vs Individual Benefit Expectation

Conclusions

In these new worldwide energy scenarios in which renewable energy communities (REC) are taking on an increasingly relevant role, the risk, for them, of being exposed to cyber-attacks consequently increases. Despite the social purpose and impact on energy poverty that RECs are expected to have, the risk of malicious intent should not be underestimated. From a software and hardware point of view, there are possible strategies to prevent such risks, however the implementation of the latter requires an additional investment which could affect small/medium sized energy communities, which often have difficulties with the availability of economic resources going into contrast with the financial revenues generated by the communities which are not always so relevant. To maintain low costs and the economic sustainability of renewable energy communities, it will be necessary to shift attention from the expensive implementation of purely technological cyber prevention, based on objective security and the quality of physical cybersecurity tools, to subjective prevention where the informed, trained community's member, is placed at the center, with an active and aware role not only as active member of the community, but aware of the pitfalls arising from cyber-security issues.

In conclusion, it is unreasonable to require such commitment from REC members, as the objective of these communities should not be to take care of their entire cyberphysical infrastructure. In the same way that certifications exist for the behavior and construction of energy-related assets (e.g., electric meters) to ensure their safe use, a regulation must be in place to manage the certification of the monitors that transmit this data in a (hopefully) safe manner. The "Cyber Resilience Act" is the name of this certification. It is not entirely the responsibility of members to ensure their own security, as the majority of the responsibility has to be carried by the vendors, who are required to provide secure devices that can safeguard both the data of users and their energy assets.

References

Cirone, D., Bruno , R., Bevilacqua, P., Perrella, S., & Arcuri, N. (2022). Techno-Economic Analysis of an Energy Community Based on PV and Electric Storage Systems in a Small Mountain Locality of South Italy: A Case Study. *Sustainability, 14*(13877). Tratto da https://doi.org/10.3390/su142113877

Decreto Legislativo 504. (1995, ottobre 26). *Testo unico delle disposizioni concernenti le imposte sulla produzione e sui consumi e relative sanzioni penali ed amministrative*. Gazzetta Ufficiale n.279 del 29-11-1995.

Douha, N. Y.-R., Sasabe, M., Taenaka, Y., & Kadobayashi, Y. (2023). An Evolutionary Game Theoretic Analysis of Cybersecurity Investment Strategies for Smart-Home Users against Cyberattacks. *Appl.Sci., 13(7)*(4645). doi: https://doi.org/10.3390/app13074645

European Union. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast). *Official Journal of the European Union, L 328/82.*
European Union. (2019). *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on horizontal cybersecurity requirements for products with digital elements and amending Regulation (EU) 2019/1020.* Tratto da Access to European Union Law: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022PC0454
European Union. (s.d.). *Directive (EU) 2022/2555 of the European Parliament and of the Council of 14 December 2022 on measures for a high common level of cybersecurity across the Union, amending Regulation (EU) No 910/2014 and Directive (EU) 2018/1972, and repealing Directive (E.* Tratto da Access to European Union Law: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32022L2555
Franzò, S., Chiaroni, D., Chiesa, V., & Frattini, F. (2021). *Aggiornamento del modello di valutazione tecnico-economica della realizzazione di energy community e configurazioni di autoconsumo collettivo ed applicazione a casi di studio reali. Analisi del potenziale di mercato delle suddette applicazioni.* Milano: Politecnico di Milano - School of Management.
Gaggero, G. B., Piserà, D., Girdinio, P., Silvestro, F., & Marchese, M. (2023). Novel Cybersecurity Issues in Smart Energy Communities. *1st International Conference on Advanced Innovations in Smart Cities (ICAISC)*, (p. 1-6). doi:10.1109/ICAISC56366.2023.10085312
Gazzetta Ufficiale. (2020, 05 19). Decreto Legge 19 maggio 2020, n.34 Misure urgenti in materia di salute, sostegno al lavoro e all'economia, nonche' di politiche sociali connesse all'emergenza epidemiologica da COVID-19. *Gazzetta Ufficiale della Repubblica Italiana*.
GSE Gestore Servizi Energetici. (2024). *DECRETO CACER e TIAD – Regole operative per l'accesso al servizio per l'autoconsumo diffuso e al contributo PNRR.* Roma: GSE.
GSE, Legambiente. (2024). Rapporto 2024 Comunità Energetiche Rinnovabili, Il punto della situazione in Italia. In E. Rapiti (A cura di).
Gunduz, M. Z., & Das, R. (2024). Smart Grid Security: An Effective Hybrid CNN-Based Approach for Detecting Energy Theft Using Consumption Patterns. *Sensors, 24(4)*(1148). doi: https://doi.org/10.3390/s24041148
Manso-Burgos, Á., Ribó-Pérez, D., Gómez-Navarro, T., & Alcázar-Ortega, M. (2022). Local energy communities modelling and optimisation considering storage, demand configuration and sharing strategies: A case study in Valencia (Spain). *Energy Reports, 8*, 10395-10408. Tratto da https://doi.org/10.1016/j.egyr.2022.08.181
Mappa Interattiva delle Cabine Primarie. (s.d.). Tratto da GSE: https://www.gse.it/servizi-per-te/autoconsumo/
MASE. (2024). Decreto Ministeriale n.414, Decreto CACER.
McLaughlin, S., McDaniel, P., & Aiello, W. (2011). Protecting consumer privacy from electric load monitoring. *Proceeding of the 18th ACM conference on Computer and communication security.*
Moretti, E., & Stamponi, E. (2023). (Moretti e Stamponi, The Renewable Energy Communities in Italy and the Role of Public Administrations: The Experience of the Municipality of Assisi between Challenges and Opportunities 2023). *Sustainability, 15*. Tratto da https://www.mdpi.com/2071-1050/15/15/11869#
Nijuis, M., Gibescu, M., & Cobben, J. F. (2015). Assessment of the impacts of the renewable energy and ICT driven energy transition on distribution networks. *Renew. Sustain. Energy Rev., 52*, 1003-1014. doi: 10.1016/j.rser.2015.07.124
NIS2 DIRECTIVE. (s.d.). Tratto da Essential Entity Energy Sector: https://nis2directive.eu/energy/
PoliMi, UniTrento, LEAP. (Agosto 2024). *Comunità energetiche: gli strumenti della ricerca per analisi tecniche, economiche e sociali.* Gruppo di Sistemi Elettrici per l'Energia, Dipartimento di Energia, Politecnico di Milano, Sustainable Energy Laboratory, Dipartimento di Ingegneria Civile, Ambientale e Meccanica, Università degli Studi di Trento, Smart Energy Systems, LEAP.
Politecnico di Milano. (2024). Electricity Market Report 2024.
Ricciuti, S., Stoklin, S., Giuliano, F., Mari, C., Zanchiello, M., & Manfredi, S. (2024). Emerging Security and Legal Challenges Within Renewable Energy Communities: Key Prevention and Defence Strategies. *AEIT International Annual Conference (AEIT).* Trento: IEEE. doi: 10.23919/AEIT63317.2024.10736786
Safitra, M. F., Lubis, M., & Fakhrurroja, H. (2023). Counterattacking Cyber Threats: A Framework for the Future of Cybersecurity. *Sustainability, 15 (18)*(13369). doi: https://doi.org/10.3390/su151813369
Tabrizi, F. M., & Pattabiraman, K. (2012). A model for security analysis of smart meters. *IEEE/IFIP International Conference on Dependable Systems and Networks Workshops.* IEEE. doi:https://doi.org/10.1109/DSNW.2012.6264682
Union, E. (s.d.). *Regulation (EU) 2016/679.* Tratto da access to European Union Law: https://eur-lex.europa.eu/eli/reg/2016/679/oj
Yussof, S., Rusli, M. E., Yussoff, Y., Ismail, R., & Ghapar, A. A. (2014). Financial impacts of smart meter security and privacy breach. *Proceeding of the &th International Conference on Information Technology and Multimedia*. doi: 10.1109/ICIMU.2014.7066595
Zhang, J., He, W., Li, W., & Abdous, M. (2021). Cybersecurity awareess trainig programs: a cost-benefit analysis framework. *Industrial Management & data Systems*. doi: http://dx.doi.org/10.1108/IMDS-08-2020-0462

INTEGRATING BMS AND BIM TO IMPROVE INTEROPERABILITY BETWEEN SIMULATION AND ENERGY MANAGEMENT ENVIRONMENTS

Federico Rossi
University of Padua, Italy

Beatrice Maria Toldo
University of Padua, Italy

Carlo Zanchetta
University of Padua, Italy

Overview

Recent changes in energy efficiency legislation impose increasingly stringent targets for reducing energy consumption. European housing stock is particularly old; in fact, buildings represent the most energy-intensive sector, accounting for approximately 40% of the European Union's energy consumption and 35% of CO_2 emissions. (European Commission, 2024).

The need to reduce the energy consumption of buildings requires the development of new strategies to optimize their energy profiles (Economidou et al., 2020). This objective can be achieved through predictive simulations of the building-plant system's behavior in response to variations in climatic conditions and user usage patterns. Identifying the gap between the predicted and actual energy performance of a building serves as the starting point for energy optimization. This process involves creating a digital twin of the building within Building Information Modeling (BIM) platforms (Cespedes-Cubides & Jradi, 2024). Predicted energy behavior is simulated using Building Energy Modeling (BEM), while actual energy performance is monitored and managed using Building Management Systems (BMS).

From this perspective, communication between BMS systems and energy simulation environments becomes a strategic priority. Currently, these two environments primarily communicate using proprietary protocols, which makes effective dialogue nearly impossible. Consequently, there is a pressing need to establish open protocols to facilitate seamless information exchange.
This research leverages the Industry Foundation Classes (IFC) protocol for information standardization. Its goal is to provide a unified digital representation of the construction industry (buildingSMART, 2024). The IFC standard was first proposed in 1995 by the International Organization for Standardization: this format is capable of comprehensively describing information relating to various architectural engineering disciplines (Laakso & Kiviniemi, 2012). To date, there are many software packages that read and import the IFC file format. Consequently, IFC represents the standard for the international exchange of construction data (An et al., 2024).

<u>BEM</u>
Building energy performance analysis is the first step in characterizing the energy behavior of a building. The results then become the input for the plant sizing process of an HVAC system. BEM predicts building energy consumption, CO_2 emissions, peak demands, energy cost and renewable energy production (Gao et al., 2019). BEM can be created by designing the building from scratch in the simulation environment or starting from an existing architectural model, known as the BIM to BEM process. In this process, the advent of BIM provides a great opportunity to activate an integrated and shared workflow among different professionals due to its nature as an information database (Alexandrou et al., 2021).

<u>BIM to BEM</u>
Building Energy Modeling represents the energy model of a building and it is obtained from a BIM model, which is simplified in geometric terms and enriched with information useful for energy simulation (U.S. Department of Energy, 2024).

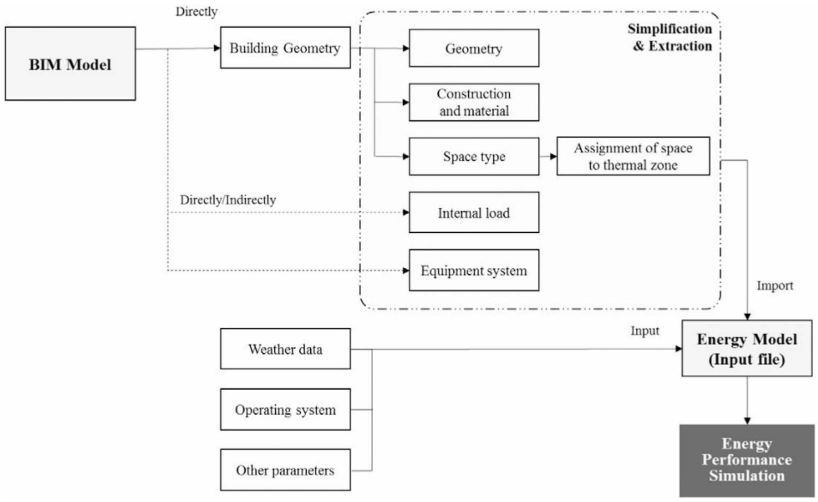


Figure 7: Data flow of the general BIM-based energy performance assessment (EPA) (Choi et al., 2016)

The simplification of geometry concerns only the energy exchange surfaces and those generating any shading. Specifically, the input data includes the materials' thermal characteristics, the plant configuration, and the utilization profiles of the different rooms and devices that are inside the building.
The BIM to BEM interoperability is based on two open information standards, such as IFC and gbXML (Ciccozzi et al., 2023). Both aim to transfer information between different proprietary platforms without loss of data. The objective of the BIM-BEM integration is to create a streamlined and efficient process that facilitates the evaluation of building performance while minimizing rework during energy simulation (Bastos Porsani et al., 2021).

<u>BMS</u>
Most buildings are equipped with numerous devices and control systems to provide services such as lighting, heating, and air conditioning. Much of this infrastructure is supported by sensors networked to a BMS for remote monitoring and operation. The primary goal of a BMS is to enhance the operational efficiency of buildings, optimize occupant comfort, reduce energy costs, and facilitate predictive maintenance (Sayed & Gabbar, 2017).
The BMS collects data from sensors and devices distributed throughout the building and processes it to ensure that various systems operate efficiently. Through automation, it is possible to implement advanced logic to manage different scenarios, such as reducing energy usage when the building is unoccupied or adjusting air conditioning based on the presence of occupants.
BMS platforms are rather closed and use proprietary communication protocols (Toldo & Zanchetta, 2024). To date, open protocols have been developed that enable interoperability, including KNX, BACnet, DALI, DMX, Modbus and LonWorks.

<u>BEM-BMS</u>
Advancements in technology and the growing use of sensors in buildings have significantly improved the efficiency of data collection and sharing, driven in part by the rise of the Internet of Things. Integrating real-time data from the field into BEM platforms enhances energy modeling, allowing it to span the entire lifecycle of the building. However, while BMS collects a large amount of data, different sensor suppliers and installers use custom rules for managing metadata. This creates the need to perform an interface mapping between BMS and BEM in order to conduct energy analyses (Zhan et al., 2021). In Wu et al. (2023) the topic of BIM to BEM integration is addressed, proposing an automatic framework based on an ontology to integrate multiple data sources and automatically generate BEM models.

Methods

The methodology used for the analysis follows these steps (*Figure 2*): a BIM model of the building is created, and an IFC file is generated to serve as the link between the BEM and the BMS. Due to its interoperable nature, the IFC file facilitates the integration of the building's geometric, physical, and functional information with energy data from the BEM and real-time operational data from the BMS. The primary goal of this methodology is to compare the simulated data, generated through BEM energy simulations, with real data provided by the BMS. This methodology is applied to a real-world case study.

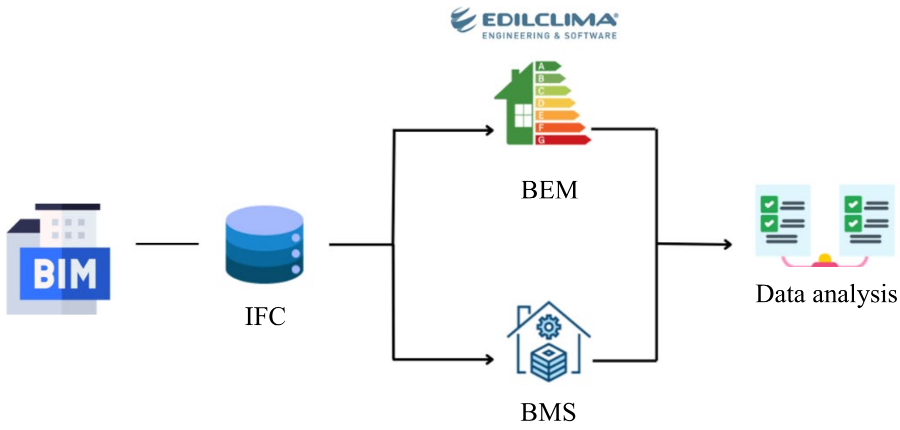


Figure 8: Methodology

Case Study

The experimentation starts from the establishment of a partnership with SMACT Competence Center, one of the 8 Industry 4.0 Competence Centers established in Italy at the instigation of the Ministry of Economic Development. It is based on a network of public-private partnerships, based on the sharing of expertise from research, technology providers and early adopter companies. The project is being developed in Triveneto as part of an innovation ecosystem involving 50 partners, including the University of Padua. Its primary objective is to initiate composite actions that enhance, multiply, and share existing relationships, thereby boosting their capacity for innovation (SMACT CC Società Consortile Per Azioni, 2024). The case study focuses on a building located on Niccolò Tommaseo Street, near the Padua Fairgrounds. Inside the building, Schneider installed various devices for intelligent building control and management. Schneider is a global leader in industrial technologies, renowned for its expertise in electrification, automation, and digitization, driving smart industries, resilient infrastructure, future-proof data centers, smart buildings, and intuitive homes.

The building spans an area of 3,000 sqm across four levels. It serves two primary purposes: production on the lower levels and administrative spaces on the top floor. The production unit includes a brewery, a bakery and a kitchen, all aligned with Industry 4.0 standards. The facility is equipped with six AHUs and VRF systems.

Case Study: Building information modeling

The first step in the process is the creation of the BIM model, which is essential to ensure an accurate digital representation of the building. To define this model, a thorough analysis of the existing conditions is conducted by reviewing available documentation, including drawings, reports, and system schematics. Additionally, several on-site inspections are performed to verify the actual state of the building, during which discrepancies between the initial design and the current condition are identified. These discrepancies are carefully documented, and the BIM model is updated accordingly to ensure an accurate and up-to-date representation of the building. This preliminary step lays the groundwork for the subsequent development of the IFC file and its integration with energy simulation and management systems.

The creation of the information model is the first step in defining a digital twin and is carried out using Autodesk Revit. The building model is divided into disciplines, such as architectural and mechanical. In the architectural model (*Figure 3*), the building is designed with detailed material characterization for its component elements, and thermal zones are clearly defined.

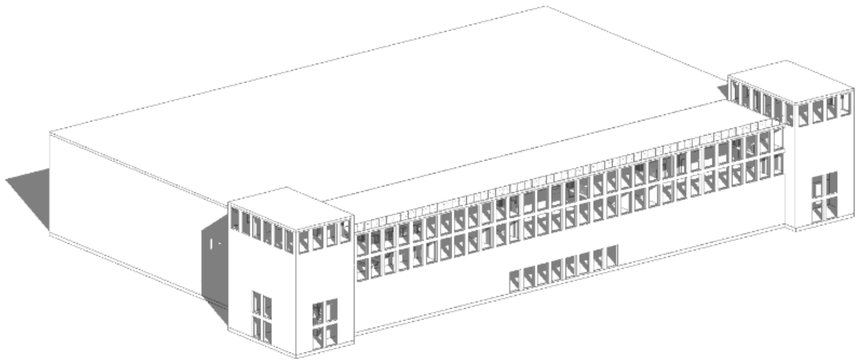


Figure 9: Architectural Model

In particular, the architectural model is enriched with information. The definition of the stratigraphic sequence of the opaque components is based on the structure schedules provided by the architects involved in the project. Additionally, each material is characterized in terms of its energy properties to ensure it can be directly recognized by the simulation environment *(Figure 4*).

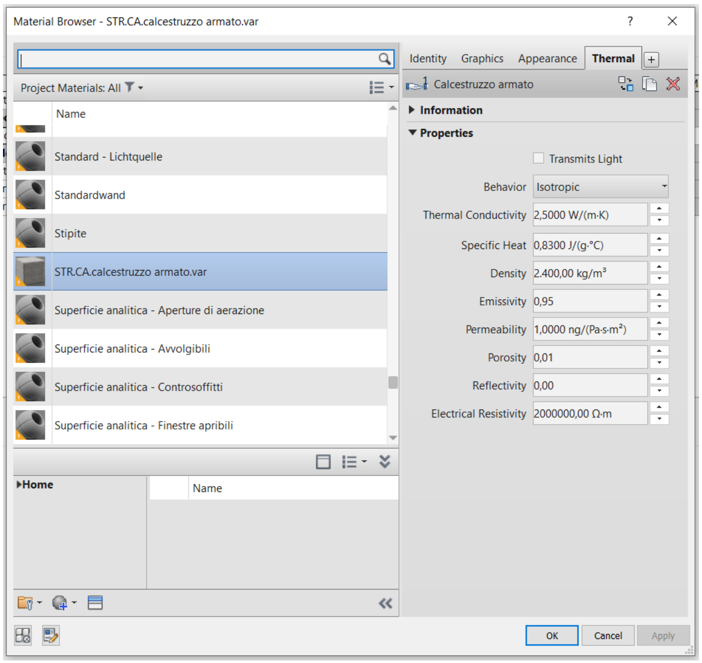


Figure 10: Thermal characterization of materials

In the mechanical model, the building's HVAC system is modeled (Figure 5). The review of the mechanical drawings allowed for the reproduction of the system configuration and the division of the building's spaces into mechanical zones.

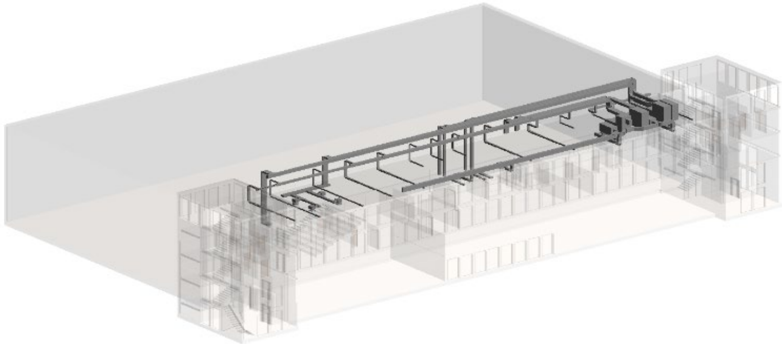


Figure 11: Mechanical model

Case Study: IFC file creation

Once the BIM model is fully defined, the process involves exporting it in the IFC exchange format. This is a crucial step for the integration of Building Energy Modeling with the Building Management System.

Exporting the BIM model in an open format is crucial for transitioning from a federated model, created within a BIM authoring software, to a non-proprietary format, ensuring seamless information exchange between the simulation environment and the energy management system. At this stage, exporting the IFC file is key to defining the input model for energy simulation. The architectural BIM model serves as the starting point for this process. It is simplified in order to remove unnecessary architectural information and elements for the energy simulation, such as railings, guardrails, and stairs. In this regard, the choice of the most appropriate Model View Definition (MVD) is made. It represents a subset of the IFC schema that defines a data exchange for a specific use or workflow. MVDs can be as broad as almost the entire schema (e.g., for project archiving) or as specific as a pair of object types and associated data (e.g., for determining the price of a continuous wall) (*Model View Definitions (MVD)*, s.d.). In fact, the stakeholders involved in a project have different expertise related to the purpose of their work, which gives rise to specific informational needs. By creating data subsets (MVDs), it is possible to filter the IFC schema into project views limited to the informational requirements of the recipient.

In the context of energy simulation, calculating the energy behavior of a building does not require detailed geometry. In fact, it is necessary to simplify the starting architectural model, as it contains many details that are irrelevant to the purpose of the energy analysis. The reason for this lies in the concept of energy transmission implemented in all energy performance evaluation software: the energy flow is exclusively perpendicular to the exchange surface, ignoring two-dimensional and three-dimensional transmissions.

The IFC format defines the geometry of the envelope as a set of surfaces, called space boundaries (Weise et al., 2011). These represent polygons that define the spaces and indicate the direction of energy flow (outward or inward) depending on the spatial configuration.

The experiment tested two different MVD:

- IFC 2x3 GSA Concept Design BIM 2010, created specifically for energy purposes;
- IFC4 Design Transfer View (Figure 6).

The choice of these two specific MVD versions is based on the import capabilities of the energy simulation software used in the subsequent stages of the experiment.

The IFC 2x3 GSA Concept Design BIM 2010 proved to be more effective in managing the BEM data, ensuring accurate and efficient data transfer between the systems. In particular, the IFC4 DTV version demonstrated inefficiency in transferring certain building parameters, including the thermal characterization of materials.

The geometric and informational consistency of the IFC file with the BIM model is verified using the BIMvision viewer: the subsequent import into the simulation environment allowed for the validation of the energy information transfer.

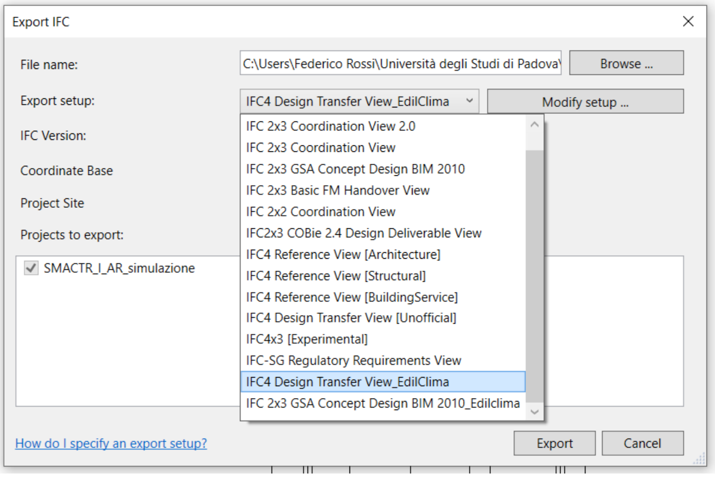


Figure 12: Export IFC

<u>Case Study: Building energy modeling</u>

The choice of the energy simulation environment is the first step in determining the building's performance. The experiment focused on Edilclima EC700: it is the calculation engine for the energy performance of buildings, including both the monthly method according to UNI/TS 11300 and the hourly dynamic method according to UNI EN ISO 52016-1 (*EC700 Energy performance of buildings » Edilclima Engineering & Software*, s.d.)

Recent software developments have introduced new features for importing IFC files as input for energy analysis, including the ability to upload a new version of the same file, supporting the exchange of information between the stakeholders involved in the design process.

The BIM to BEM process ends with the simulation environment: the architectural model, simplified and exported in the IFC format, serves as the input for energy analysis. However, the file does not contain all the necessary information: the software automatically imports some data, including:

- Localization;
- Geometry and stratigraphic sequence of the opaque envelope;
- Spaces and division into thermal zones.

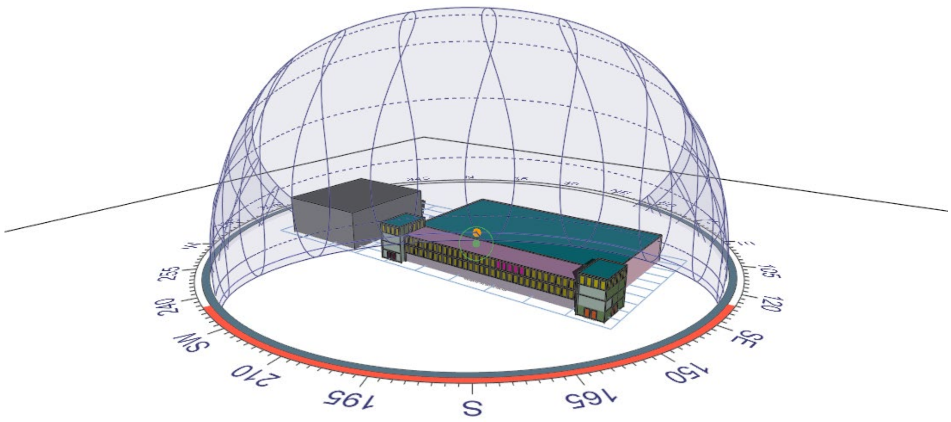


Figure 13: Simulation input model

As shown in *Figure 7*, the envelope is reconstructed in Edilclima. The inclusion of spaces in both conditioned and non-conditioned rooms allow for the assignment of the exchange function of each envelope component (e.g., whether it adjoins the exterior).

The remaining information must be entered directly into the simulation environment. This is due to the specificity of the required data and the incomplete BIM to BEM interoperability, which remains an open issue. This includes the configuration and properties related to heating, cooling, domestic hot water production, and renewable energy systems, as well as the characterization of thermal bridges, shading, and usage profiles for the spaces.

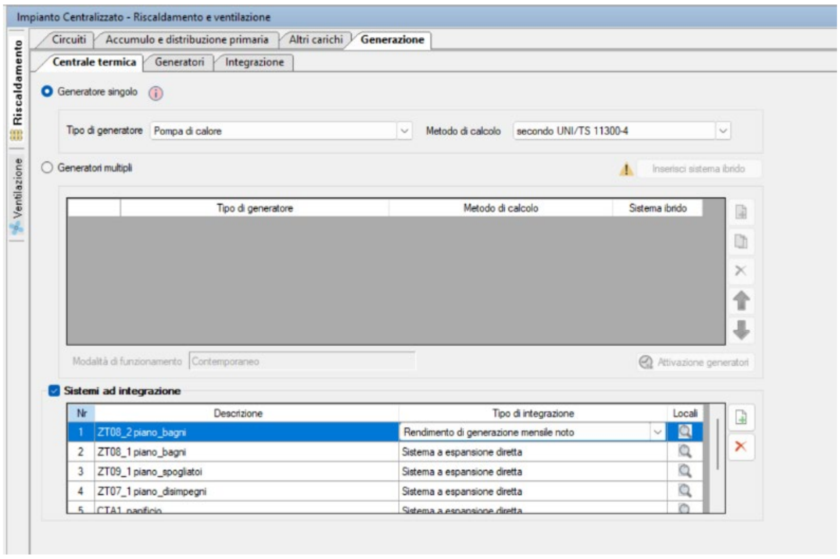


Figure 14: HVAC system configuration into Edilclima environment

The main purpose of the energy simulation is to define the expected energy behavior, which will serve as the starting point for comparison with real data provided by the Building Management System. The comparison of the results serves as the validation tool for the Building Energy Model.

<u>Case Study: Building management system</u>
The case study is equipped with a BMS system associated with the EcoStruxure Building Operation (EBO) platform by Schneider Electric. The building management software integrates systems and application data to simplify the monitoring, management, and optimization of building performance. The platform allows for the centralization of all information from various systems (such as HVAC, lighting, security, and energy control), providing a comprehensive, real-time view of the building's performance. Thanks to this platform, it is possible to view the instantaneous consumption of installed equipment in real time, as well as monitor the operational status of each device, enabling more efficient management and a prompt response to maintenance and optimization needs. Through customizable dashboards, operators can generate detailed reports and predictive analyses, thereby improving operational efficiency and reducing management costs. Additionally, the system allows for timely intervention in case of anomalies, optimizing consumption and planning preventive maintenance activities, ensuring more sustainable and reliable infrastructure operation.

Consequently, the connection to the BMS platform allows us to acquire a history of energy data: access to the BMS platform ensured an understanding of the real energy behavior. The extracted data covers the period from January 2023 to November 2024 and reflects the continuous operation of the site. The initial cumulative data (*Figure 9*) are processed to obtain daily consumption values (*Figure 10*).

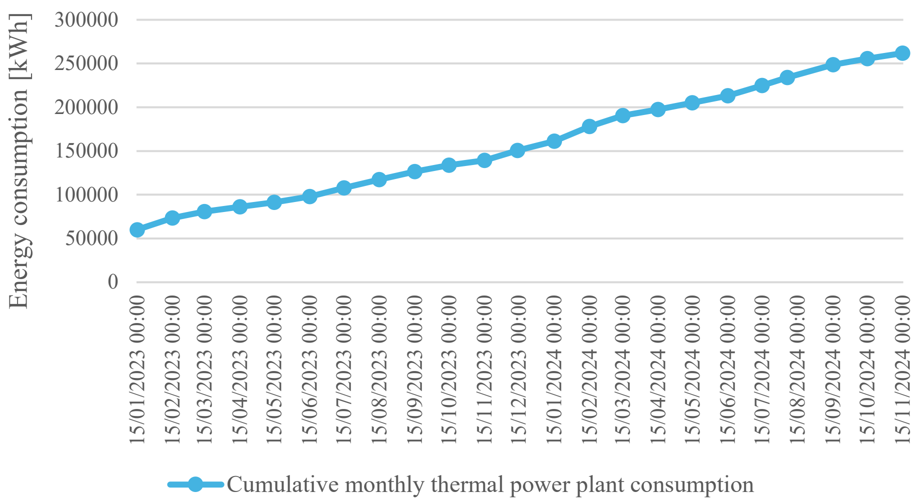


Figure 15: Cumulative monthly thermal power plant energy consumption

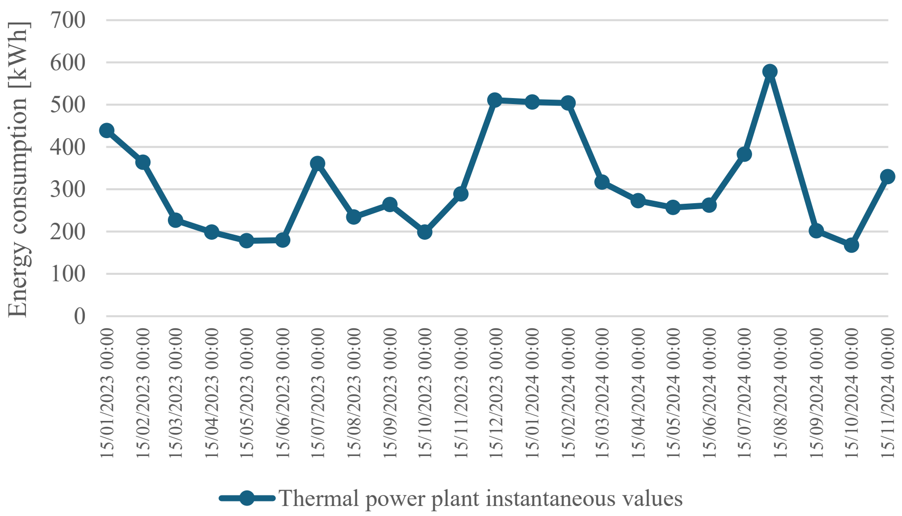


Figure 16: Monthly thermal power plant energy consumption

The extracted real data is then processed to create trends, which are used for comparison with the predictive data. This process provides a solid basis for analyzing energy performance and validating the predicted simulations. In particular, the analysis focuses on the energy consumption related to the thermal plant for the period between December 2023 and November 2024. The choice to consider a one-year period is useful for obtaining a comprehensive and representative overview of seasonal variations, as the entire annual cycle includes all variables related to climate changes and seasonal variations, such as summer and winter temperatures, which influence the energy demand for heating and cooling. Additionally, this period reflects the building's full operational status: the building has been operational for about a year, making the collected data particularly meaningful and free from distortions related to an initial startup or testing phase of the structures.

Results

The application of the methodology to the case study highlights how the import of the IFC file into the simulation environment is not error-free. Manual intervention is required: the end user is obligated to integrate the missing energy-related information directly within the simulation environment. This step is essential for starting the energy analysis.

The extraction of input data enables the creation of benchmarks between simulation environments and management environments. By comparing data, it allows for the validation of simulated energy behavior based on thermodynamics through BMSs.
The methodology considers the consumption data of the thermal power plant: two curves are obtained (*Figure 11*): the green one represents simulated energy behaviour, while the blue one represents actual energy consumption.

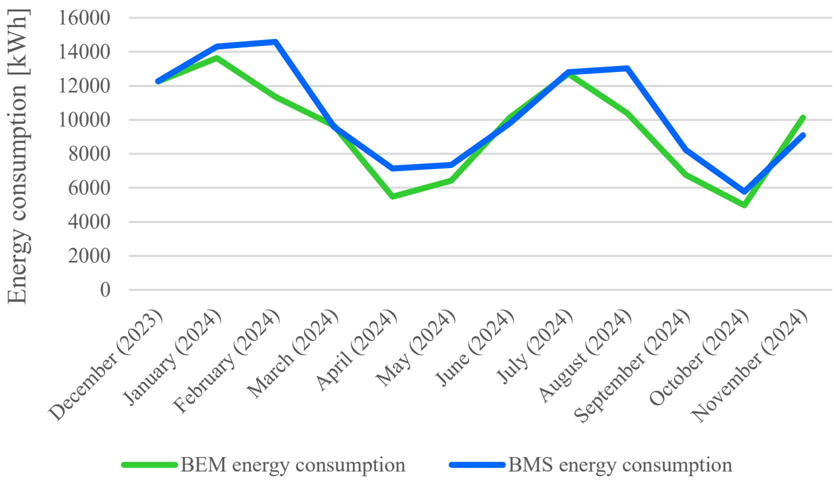


Figure 17: BEM and BMS energy consumption

Month	BEM energy consumption [kWh]	BMS energy consumption [kWh]
December (2023)	12257	12267
January (2024)	13634	14313
February (2024)	11353	14584
March (2024)	9663	9576
April (2024)	5474	7136
May (2024)	6415	7343
June (2024)	10134	9783
July (2024)	12703	12803
August (2024)	10392	13021
September (2024)	6764	8233
October (2024)	4975	5773
November (2024)	10125	9097

Table 2: BEM and BMS energy consumption comparison

Considering an average difference of 10% in the trend between the energy behavior exhibited by the simulation and the real data, the validity of the simulated results is verified by analyzing the trend of the external temperatures recorded by the two environments, BEM and BMS (*Table 2*).

Month	Average BEM temperature [°C]	Average BMS temperature [°C]
December (2023)	4,8	2,4
January (2024)	3	4
February (2024)	3,6	4
March (2024)	8,6	10
April (2024)	12,8	14
May (2024)	18,9	19
June (2024)	22,3	24
July (2024)	23,7	28
August (2024)	23,7	27
September (2024)	18,6	23
October (2024)	13,9	16
November (2024)	8,3	11

Table 3: Simulated temperature and real temperature

Month	Gap in energy consumption	Gap in temperatures
December (2023)	0,08%	50,00%
January (2024)	4,98%	33,33%
February (2024)	28,45%	11,11%
March (2024)	0,90%	16,28%
April (2024)	30,36%	9,38%
May (2024)	14,46	0,53%
June (2024)	3,46%	7,62%
July (2024)	0,78%	18,14%
August (2024)	25,29%	13,92%
September (2024)	21,71%	23,66%
October (2024)	16,04%	15,11%
November (2024)	10,15%	32,53%

Table 4: Difference in consumption and difference in external temperatures (real and simulated)

The analysis shows that, while the simulated energy consumption in some months closely matches the real consumption, discrepancies in external temperatures, especially during colder months, may play a significant role in the deviations in energy performance (Table 3). Improving the accuracy of temperature forecasts, perhaps by incorporating more detailed climate data or integrating real-time environmental factors, could help enhance the overall accuracy of the energy consumption prediction model. In fact, the most significant discrepancies occur in February (2024) with a gap of 28.45%, followed by April (2024) at 30.36%. At the same time, there is a difference between the measured and simulated temperatures, however, further investigation is needed to clarify this result: analyzing the internal temperatures of the spaces could justify this consumption gap.

Further discrepancies are concentrated in August and September (2024), which show a percentage difference in energy consumption greater than 20%. This can be explained by the higher external temperatures provided by the BMS compared to those simulated.

In June and July, despite higher actual temperatures, consumption are similar to that simulated occurred. The reason for this may be a decrease in building operation: these are hypotheses that can later be verified through predictive simulations and more in-depth comparisons.

Conclusions and future works

The paper highlights the importance of integrating BIM, BEM, and BMS through the IFC standard to optimize building energy consumption. The methodology is tested on a real-world case study by comparing simulated energy performance (BEM) with actual consumption data collected via BMS. The research focused on analyzing the simulation results alongside the BMS data to enhance the building's energy efficiency. The process began with the development of a BIM model, which is exported in IFC format to serve as the informational foundation for the BEM platform. This allowed the extraction of key data such as geometry, spaces, thermal zones, and materials used to conduct the energy simulation.
It is expected in the future to create an independent BMS platform will be developed for real-time data acquisition from sensors within buildings. This can reduce operational costs associated with proprietary software and enhance the overall performance of the system. Additionally, the definition of predictive energy simulation frameworks is foreseen. With this technology, it would be possible to simulate and predict the system's thermal loads using real data collected from sensors, combined with customized usage profiles for each building or environment. This approach would enable the optimization of energy performance by dynamically adapting to changes in external conditions and the actual use of spaces, while also improving occupant comfort.

References

Alexandrou, K., Artopoulos, G., Calcerano, F., Martinelli, L., & Ispc, B. (2021). *State of the art analysis on BIM and numerical simulation interoperability*.

An, N., Li, X., Yang, H., Pang, X., Gao, G., & Ding, D. (2024). From Building Information Modeling to Building Energy Modeling: Optimization Study for Efficient Transformation. *Buildings*, *14*(8), 2444. https://doi.org/10.3390/buildings14082444

Bastos Porsani, G., Del Valle de Lersundi, K., Sánchez-Ostiz Gutiérrez, A., & Fernández Bandera, C. (2021). *Interoperability between Building Information Modelling (BIM) and Building Energy Model (BEM)*. https://www.mdpi.com/2076-3417/11/5/2167

buildingSMART. (2024). *Industry Foundation Classes (IFC)* [Industry Foundation Classes (IFC)]. https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/

Cespedes-Cubides, A. S., & Jradi, M. (2024). A review of building digital twins to improve energy efficiency in the building operational stage. *Energy Informatics*, *7*(1), 11. https://doi.org/10.1186/s42162-024-00313-7

Choi, J., Shin, J., Kim, M., & Kim, I. (2016). Development of openBIM-based energy analysis software to improve the interoperability of energy performance assessment. *Automation in Construction*, *72*, 52–64. https://doi.org/10.1016/j.autcon.2016.07.004

Ciccozzi, A., De Rubeis, T., Paoletti, D., & Ambrosini, D. (2023). BIM to BEM for Building Energy Analysis: A Review of Interoperability Strategies. *Energies*, *16*(23), 7845. https://doi.org/10.3390/en16237845

EC700 Energy performance of buildings » Edilclima Engineering & Software. (s.d.). Recuperato 12 dicembre 2024, da https://en.edilclima.it/software/ec700-energy-performance-of-buildings/

Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., & Castellazzi, L. (2020). Review of 50 years of EU energy efficiency policies for buildings. *Energy and Buildings*, *225*, 110322. https://doi.org/10.1016/j.enbuild.2020.110322

European Commission. (2024). *Energy Performance of Buildings Directive adopted to bring down energy bills and reduce emissions*. https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_24_1965/IP_24_1965_EN.pdf

Gao, H., Koch, C., & Wu, Y. (2019). Building information modelling based building energy modelling: A review. *Applied Energy*, *238*, 320–343. https://doi.org/10.1016/j.apenergy.2019.01.032

Laakso, M., & Kiviniemi, A. (2012). *The IFC Standard—A Review Of History, Development, And Standardization*.

Model View Definitions (MVD). (s.d.). buildingSMART Technical. Recuperato 12 dicembre 2024, da https://technical.buildingsmart.org/standards/ifc/mvd/

Sayed, K., & Gabbar, H. A. (2017). Building Energy Management Systems (BEMS). In H. Gabbar (A c. Di), *Energy Conservation in Residential, Commercial, and Industrial Facilities* (1ª ed., pp. 15–81). Wiley. https://doi.org/10.1002/9781119422099.ch2

SMACT CC Società Consortile Per Azioni. (2024). *SMACT Competence Center*. SMACT Competence Center. https://www.smact.cc/

Toldo, B. M., & Zanchetta, C. (2024). Building Management System and IoT technology: Data analysis and standard communication protocols for Building Information Modeling. *Building Information Modeling*.

U.S. Department of Energy. (2024). *About Building Energy Modeling*. About Building Energy Modeling. https://www.energy.gov/eere/buildings/about-building-energy-modeling

Weise, M., Liebich, T., See, R., Bazjanac, V., Laine, T., & Welle, B. (2011, febbraio). *Space Boundaries for Energy Analysis*.

Wu, Z., Cheng, J. C. P., Wang, Z., & Kwok, H. H. L. (2023). An ontology-based framework for automatic building energy modeling with thermal zoning. *Energy and Buildings*, *296*, 113267. https://doi.org/10.1016/j.enbuild.2023.113267

Zhan, S., Chong, A., & Lasternas, B. (2021). Automated recognition and mapping of building management system (BMS) data points for building energy modeling (BEM). *Building Simulation*, *14*(1), 43–52. https://doi.org/10.1007/s12273-020-0612-7

WHAT ARE EUROPEAN OIL REFINERIES NAVIGATING? WILL THEY BE ABLE TO DECARBONISE EFFECTIVELY, MAINTAINING THEIR COMPETITIVENESS?

Tommaso Bonini
Centre for Energy Markets, School of Management, Technical University of Munich, 80333 Munich, Germany,

Svetlana Ikonnikova
Centre for Energy Markets, School of Management, Technical University of Munich, 80333 Munich, Germany,

Abstract

European economy still relies substantially on fossil fuels, with oil taking the lion's share – a testament of the strategic importance that oil refineries still play. This situation is in stark contrast with the Block's ambitious decarbonisation targets and highlights the interesting problematic of how European oil refineries might approach the net-zero transition without losing their competitiveness or running out of business. As an initial response to this challenge, we start by making as assessment of the regulatory status quo in Europe. Then, an exploratory analysis of a European oil refineries database is proposed to lay the foundations of a model aimed at quantifying the willingness to pay of oil refineries vis-à-vis costlier, yet less polluting, technological solutions – such as clean hydrogen.

Keywords: Europe, Decarbonisation, Hard-to-abate, Industrial Competitiveness

1. Introduction

Despite being amongst the most important advocates for actions against climate change, Europe still massively relies on fossil fuels, with oil making the lion's share – circa 40%. It is thus apparent the role of strategic energy infrastructures that oil refineries currently play.

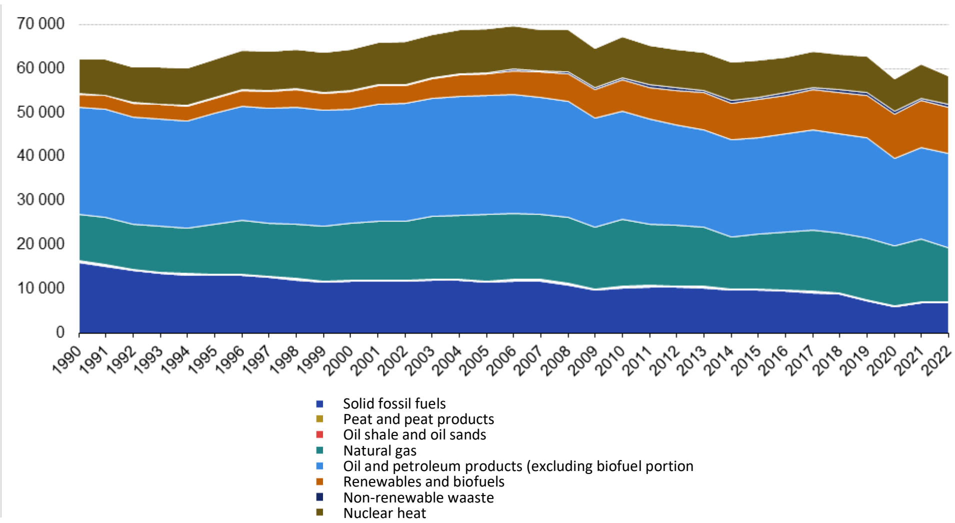


Figure 18: Gross available energy by fuel type in the European Union (PJ), 1990-2022

This situation represents a challenging task for the European Union decarbonisation targets (Coulon, 2021; European Commission, 2022; GCAP UNFCCC, n.d.; Group of Seven, 2021; IEA, 2021; IPCC, 2018, 2021; UNFCCC, 2016, 2020) that is worth exploring. European industrial activities, whilst being the third most important emitter of the European Union (European Environment Agency, 2024), represent also one of the pillars of its economic prosperity.

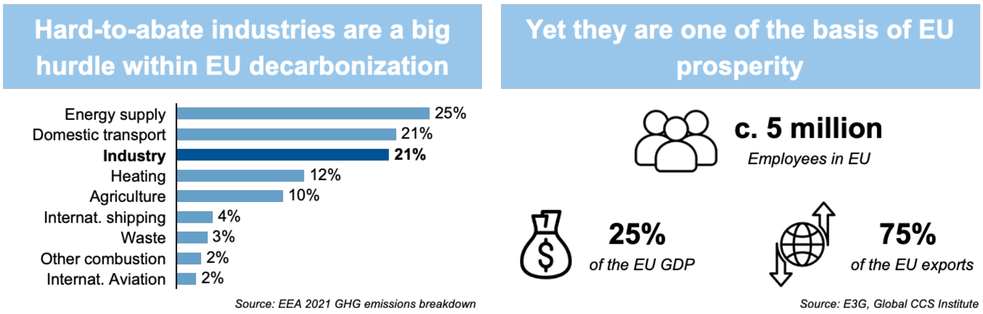


Figure 19: The emission impact and the economic importance of industrial activities in Europe

The core challenge that this paper wants to address is how the Block's net-zero ambitions may be achieved, not at detriment of hard-to-abate industrial activities, and by reaching a delicate equilibrium between environmental and economic performances.
Based on this challenge, the purpose of the present work is twofold. First, we lay the foundation of the *status quo* that European oil refineries are currently navigating, looking at the legislation that is, directly or indirectly, addressing their activity, and the technological solution that they might have at hand. Second, we delve empirically a novel approach for oil refineries production analysis that allows to derive the demand and willingness to pay for cleaner energy substitutes, like clean hydrogen.
During our analysis, we focus on clean hydrogen as a primary natural gas substitute. Collecting the data characterizing European oil refineries, we aim at analysing a combination of fossil fuels and electricity determining sector's production possibilities. Adding costs of energy and output into the consideration, we turn to the study of the past and possible future scenarios for the sector under the carbon emission associated constraints. In sum, we present a consistent and comprehensive framework for decarbonisation strategies in an industrial sector, subject to the energy and carbon prices and constraints. To verify our approach, we perform scenario analysis and build the future projections based on the EU carbon targets.
This agenda translates into a set of intertwined questions defining our research:

1. What are European oil refineries currently navigating?
2. What are the technological, societal and economic variables that must be considered by oil refineries whilst navigating the decarbonization of the continent?

We found that the existing literature is structured in three main macro topics: (a) assessment of the industrial activity's economic optimum, (b) practical analysis of specific technological solutions, (c) impact studies of the decarbonisation policies and regulations. (Shoesmith, 1988) highlights the classical U-shaped average cost curve in petroleum refining, suggesting both economies and diseconomies of scale, contradicting earlier simplistic models. He asserts the presence of economies of scope, advocating for the joint production of multiple refined products. The review by the Energy Information Administration further supports these findings, illustrating diverse operational scales among U.S. refiners and their implications on cost structures. Studies such as those by Measday (1982) and the National Petroleum Council (1979) indicate a minimum efficient scale, essential for competitive viability. Decarbonization efforts within the industry are critically reviewed, emphasizing sociotechnical systems and policy options to mitigate environmental impacts, as noted in a comprehensive systematic review. Additionally, specific regional studies, such as those analysing the UK refining sector, provide insights into the unique economic dynamics and regulatory challenges faced by different countries. Overall, these works collectively underscore the complexity of the oil refining industry, driven by both economic efficiencies and evolving technological and policy landscapes.
This paper is structured as follow: we start by describing the status quo that European oil refineries are currently navigating, and that is constituted of (a) the regulatory landscape, and (b) the decarbonisation technologies available – amongst which we will be focusing on clean hydrogen. We then move forward by explaining our theoretical contribution analytically on how we might calculate the willingness to pay for clean hydrogen, then we empirically derive the production function for oil refineries in Europe. We close the paper by writing conclusive remarks, main insights and the potential next steps for further research.

2. Status Quo for European oil refineries

2.1 European Policy Landscape – Fit for 55 and EU ETS

The European decarbonisation policy landscape that is directly or indirectly affecting European oil refineries is currently complex and varies geographically, resulting in a difficult environment to navigate for geographically dependent businesses like oil refineries.
The regulation package that is mostly concerning for our case is the so-called "*Fit for 55*", which sets to realise the European Climate Law objectives: climate neutrality by 2050 and 55% reduction in CO_2 emissions (compared to 1990 levels) by 2030.

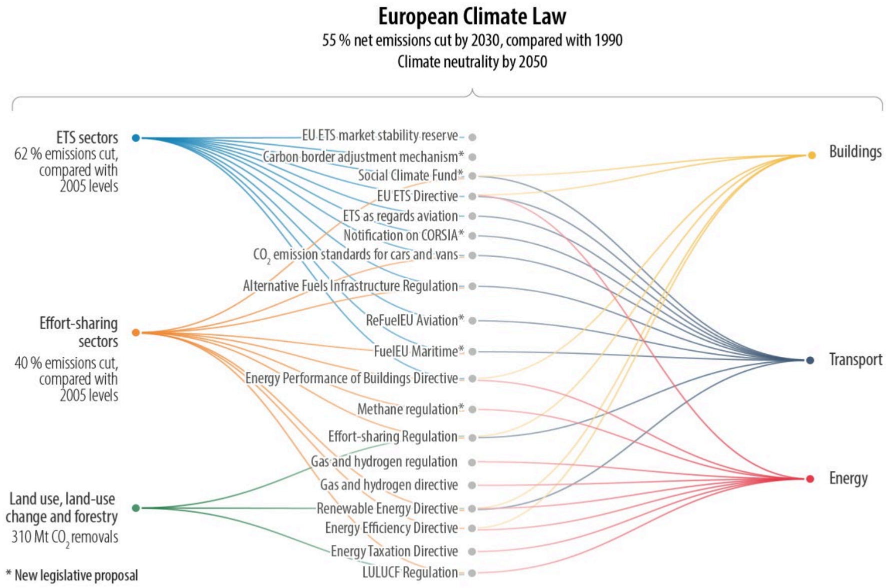


Figure 20: A visual representation of what is entailed in the Fit for 55 (Erbach et al., 2024)

It is a set of several interlinked proposals, of which we will excerpt the ones that are, or will be, affecting the most European oil refineries business activities, such as:

1. REDIII – imposing a target of adoption in renewable power and in RFNBO hydrogen across industrial sectors.
2. ReFuelEU Aviation – imposing an e-SAF volume target specifically regarding aviation, to decarbonise the current aviation fuels production.
3. FuelEU Maritime – lowering the GHG of maritime fuels would mean having a more difficult environment for the heavier oil products – such as heavy fuel oil.
4. CO_2 emissions standard for cars and vans – a push towards car manufacturer in decarbonising the new fleet of cars and vans is increasing pressure on oil refineries to be able to sell low to net-zero fuels.

These legislations have been accepted by the European Parliament and are now in the midst of being translated into national laws by all the Member States.

Oil refineries are also fully considered within the EU ETS, which is currently in its first period of phase 4 (2021-2025). Estimated free emission allowances for this period cover c. 65% of the total oil refinery sector's GHG benchmark (DG Climate Action, 2021), whilst in the previous EU ETS period was attested more on the 70-80% (Pye, 2014). Thus, the impact of the EU ETS in the oil refineries is still now entirely

2.2 Decarbonisation technologies available

Oil refineries emissions are largely associated (c. 85%) with the combustion processes that happen as part of the refining of petroleum, and from the production of hydrogen – an essential feedstock in the refinery process.

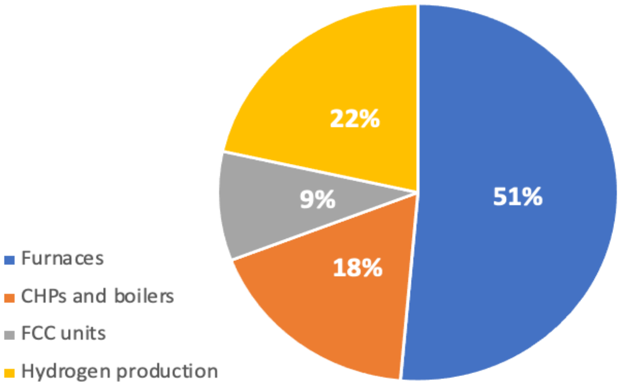


Figure 21: Oil refineries CO_2 emission in Netherlands in 2021, million tonnes of CO_2 per annum (Oliveira & Schure, 2020)

To decrease considerably the amount of CO_2 emission through the years, the most feasible technological options are the following (Byrum et al., 2021):

1. Green/clean hydrogen adoption,
2. Electrification of heat,
3. Carbon capture and utilisation
4. Energy efficiency

Green/clean hydrogen adoption is taken as the reference decarbonisation solution in this research for two main reasons. First, because of its value in decarbonising a highly emitting yet essential feedstock, the so called "grey hydrogen" that is being produced from SMR facilities and from methane. Second, because hydrogen usage is directly related with the capacity for higher purity, less emitting petroleum products. Thus, we see this feature as an essential part on the pre-2040 decarbonisation of oil refineries.

3. Database

Aligned with the aim of this research, we want to understand European oil refineries historical production trends so to derive the potential for hydrogen adoption and to show how certain correlations have changed over time and per region. We do that by leveraging on a database focussed on European oil refineries – description below – and with a consequential exploratory analysis to define what are the main insights that gives us.

The IEA database of the World Energy Balance has been used relies on a set of independent variables that spans over a specific set of countries and years:

- Countries: Belgium, France, Germany Italy, Netherlands, Poland and Spain.
- Timeline: 1999-2018.

The countries selected represent the seven most important countries per primary oil refinery capacity as of the end of 2021.

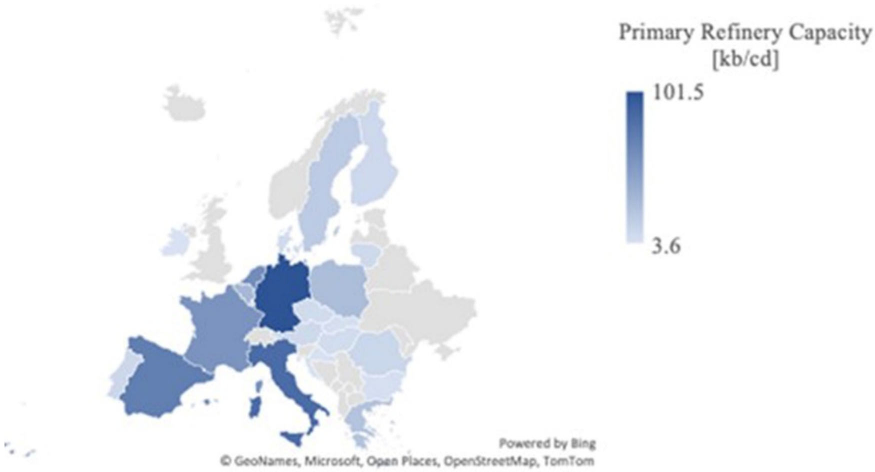


Figure 22: Map of EU-27 countries ranked by their refinery capacity as of end 2021 (Cooper, 2022)

The timeline has been taken in accordance with the databases we relied on. Moreover, it was arbitrarily decided to take 1999-2018 to appreciate the establishment of a tighter European Union market, both in monetary terms – establishment of the € currency – and in the emission reduction regulations – establishment of the Emission Trading System (ETS).

The set of fundamentals variables as in Table 1 refers to the principal energy input in the European refineries (Bourgeois et al., 2012), thus simplifying the whole energetic input into four main factors: (a) oil, (b) natural gas, (c) electricity, (d) heat. This simplification will be kept in the performed modelling. The relationship between each variable differs based on the geography, for instance France and Belgium would rely much more on the electricity then Netherlands and Italy. A deep dive on that is given on Appendix A.

Table 5: Fundamental variables of the EU oil refineries database

Data Name	Description and UoM	Reference
Refine_Y_TJ	[TJ] Transformation output - refineries and petrochemical industry - refinery output	EUROSTAT Complete energy balances [nrg_bal_c__custom_11310950]
Refine_Y_mln$	[MUSD] Value of the Output in the for the value C19 "Coke and refined petroleum products".	OECD harmonised national Input-Output tables
Diesel_Gas_Y_Ratio	[#] Gas oil and diesel oil (excluding biofuel portion) over Motor gasoline (excluding biofuel portion)	EUROSTAT Complete energy balances [nrg_bal_c__custom_11310950]
p_CO_2_$_tn	[$\$/t_{CO2}$] Price of emission allowances as per the ETS. A same average price in Europe has been taken. This does not account on national additional emission taxation (e.g., Netherlands).	Trading Economics
q_Oil_TJ	[TJ] Energy input in oil refineries as oil.	IEA World Energy Balances
q_NG_TJ	[TJ] Energy input in oil refineries as natural gas.	IEA World Energy Balances
q_E_TJ	[TJ] Energy input in oil refineries as electricity.	IEA World Energy Balances

q_Heat_TJ	[TJ] Energy input in oil refineries as heat.	IEA World Energy Balances
p_Heat_$_TJ	[$/TJ] Market price per energy unit of heat. Caveat: it is the same price as the NG but increased of 10%.	Energy Institute Statistical Review of World Energy
p_E_$_TJ	[$/TJ] Market price per energy unit of electricity for industries.	EUROSTAT Electricity prices for industrial consumers - bi-annual data (until 2007) [nrg_pc_205_h$defaultview]
p_Oil_$_TJ	[$/TJ] Market price per energy unit of oil.	Energy Institute Statistical Review of World Energy
p_NG_$_TJ	[$/TJ] Market price per energy unit of natural gas for industries.	Energy Institute Statistical Review of World Energy
e_NG_tnCO_2_TJ	[t_{CO2}/TJ] Emission per energy unit of natural gas.	(British Petroleum, n.d.)
e_E_tnCO_2_TJ	[t_{CO2}/TJ] Emission per energy unit of electricity.	Source: National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism, Aprsil 2024 provided by European Environment Agency (EEA) Complete energy balances (nrg_bal_c) provided by Statistical Office of the European Union (Eurostat)
e_Heat_tnCO_2_TJ	[t_{CO2}/TJ] Emission per energy unit of heat. Caveat: it is the emission per energy unit of natural gas but increased of 10%.	

3.1 Explorative Analysis

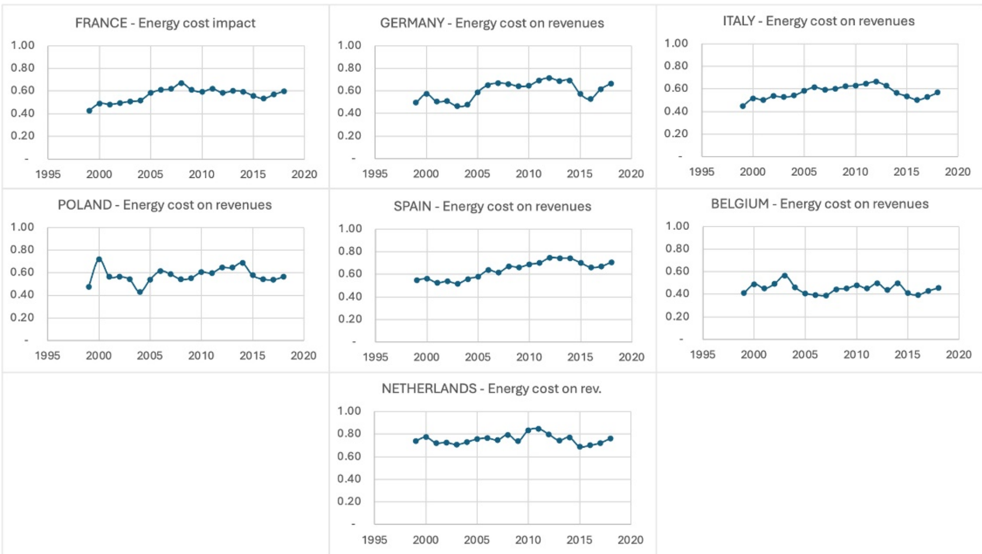


Figure 23: The impact of fossil fuel energy cost on oil refinery revenues, 1999-2018

The figure above shows that all geographies have experienced a growth in the impact of the selected energy input (i.e., natural gas, oil and electricity) over the oil refinery revenues. This phenomenon might make apparent the influence of the EU ETS system, which was gradually introduced in the European economy starting in 2005.

Secondly, we try to understand amongst the main energy input, namely natural gas and electricity, how they behaved in the timeframe considered normalised on the oil refineries production:

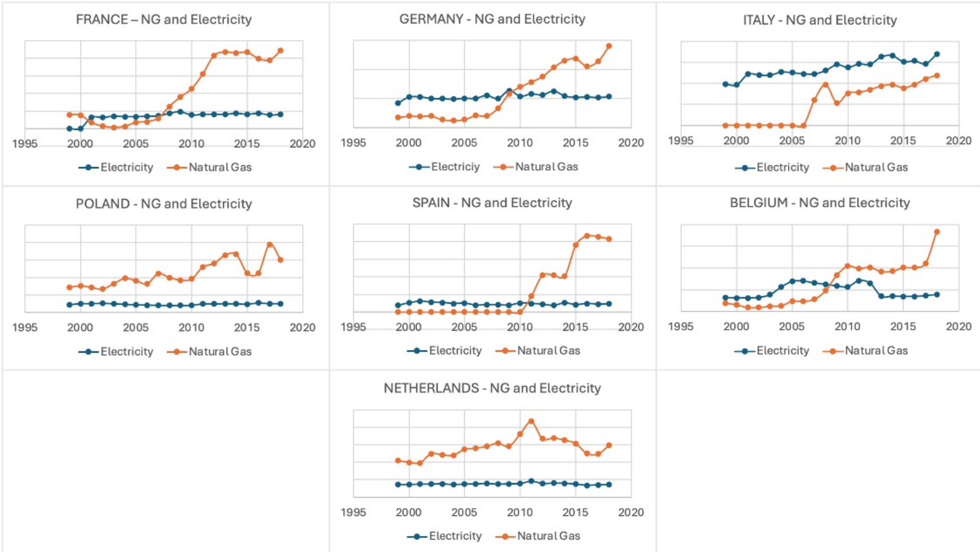
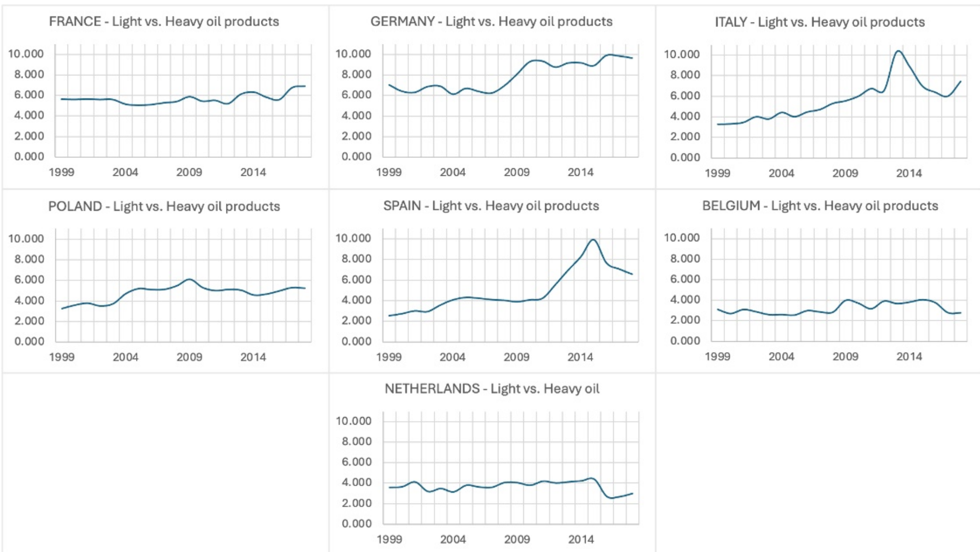


Figure 24: Cost of energy input as percentage on oil refineries revenues – normalized over refinery's output, 1999-2018

What entails the increasing adoption of natural gas in oil refineries? (a) Production of electricity, or heat, (b) Production of hydrogen to have lighter products.

Thirdly, and to better delve on the increasing adoption of natural gas experienced by oil refineries in European countries – with the exception of Belgium and Netherlands – we want to see how much the oil refineries shifted towards lighter, and less polluting products.



It is clear that almost all geographies has experiences during the year a bigger portion of their output being light petroleum products. One of the elements that have pushed the adoption of natural gas is an increasing demand of the European market for lighter products (such as road and air transport fuels) over heavier ones such as heavy fuel oil. Lighter oil products indeed require more hydrogen, which is currently produced from natural gas through SMR processes. Netherlands and Belgium have an almost stable ratio of light vs. heavy oil products because of the proximity to large bunkering markets such as Rotterdam and Antwerp, which still require the production of heavy fuel oil. Natural gas is thus a variable that not only gives us information about the size of the oil refinery, but also whether the oil refinery is "advanced", thus capable of future-proof, light, oil products, or "not advanced".

4. Theory

The European economy is still substantially relying on fossil fuels, particularly oil. Amid this situation, we want to establish a theory that can represent how net-zero transition can be achieved through higher-cost, low-carbon technologies (such as hydrogen) without dampening Europe's economic growth – which is strictly intertwined with the industrial activity.
We start by indicating a production function of the form $Y = f(..,q_i,..)$ to represent the industrial oil processes and their marketable output Y. This function captures the dependence of output and its composition on the quantities of input factors q_i which regroup the fossil fuel-based nature of the current oil refineries operations. Both elements, q_i and Y, will have their own indicative associated prices, p_i and p_Y respectively.

$$Y \sim f(q_i) \tag{1}$$

Based on Appendix B, we have demonstrated that marketable output and energy input volumes are endogenous factors of the model we are building, bearing exogeneity to prices – both the energy input prices p_i, and marketable output p_Y. The next step is to represent the oil refineries' ability to pay for cleaner, costlier technologies. Pragmatically, *ceteris paribus*, whether a portion of the operational profits can be allocated to the procurement:

$$\Pi = p_Y Y - C(Y) - C(CO_2) \tag{2}$$

Where p_Y is the average price per unit of output, $C(Y)$ and $C(CO_2)$ are the costs incurred to purchase the energy input needed for the business to run and to buy EU ETS allowances, respectively. In this way, we are describing an environment that is characterized by *mandated* GHG reduction targets: through EU ETS and the supply/demand of the allowances.
We impose that to have a procurement capacity means effectively to study the allocability of a portion of business profits to the costlier cleaner technologies. Following that logic, we start by considering the maximum of the profit function as expressed in equation (2), whereas lie the maximum ability to pay:

$$\max_{q_i} \Pi = \frac{\partial \Pi}{\partial q_i} = \begin{cases} MR \sim \epsilon MC, & short\ term \\ p_Y Y \sim \epsilon C(Y), & \Pi \geq 0 \rightarrow const. \end{cases} \tag{3}$$

To navigate towards that condition, an oil refinery (see Appendix B) can either have a short-term strategy of making marginal revenues proportionate to marginal cost as per a margin coefficient ϵ, or having a long-term strategy of reaching a non-negative value of profits through calibrating the costs. We base our analysis on the latter case of equation (3).

$$\begin{cases} Y = f(q_{ng}, q_e) = \sum_{i=1}^{n} q_i^{\alpha_i} = q_{ng}^{\alpha_{ng}} + q_e^{\alpha_e} \\ C(Y) = f(p_{ng}, p_e) = \sum_{i=1}^{n} q_i p_i = q_{ng} p_{ng} + q_e p_e + q_{CO2} p_{CO2} \end{cases} \tag{4}$$

Where ng the natural gas, e the electricity and $CO2$ refers to the EU ETS. Other inputs or raw materials that have been considered as not fundamentals can be nested into the energy efficiency coefficients allowing for the above practical simplification. Please refer to Appendix A. From the equation (3) now we derive the price of the output:

$$p_Y = \frac{C(Y) + C(CO_2)}{\mathrm{Y}} = \zeta + \epsilon \frac{q_{ng}p_{ng} + q_e p_e + q_{CO2}p_{CO2}}{q_{ng}^{\alpha_{ng}} + q_e^{\alpha_e}} = \zeta + \frac{q_{ng}}{q_{ng}^{\alpha_{ng}} + q_e^{\alpha_e}} p_{ng} + \frac{q_e}{q_{ng}^{\alpha_{ng}} + q_e^{\alpha_e}} p_e + \frac{q_{CO2}}{q_{ng}^{\alpha_{ng}} + q_e^{\alpha_e}} p_{CO2}$$

$$p_Y = \zeta + \beta_{ng}p_{ng} + \beta_e p_e + \beta_{CO2}p_{CO2} \tag{5}$$

Where ζ, β_{ng}, β_e, are constant and parameters to be empirically estimated through the database described above. We then finalise the assessment of the ability to pay for clean hydrogen by imposing a relationship between the natural gas and clean hydrogen – our working hypothesis being clean hydrogen a direct substitute of it:

$$q_{ng} = \eta_h q_h \tag{6}$$

By substituting (6) in (5)

$$p_Y = \zeta + \frac{\eta_h q_h}{(\eta_h q_h)^{\alpha_{ng}} + q_e^{\alpha_e}} p_h + \frac{q_e}{(\eta_h q_h)^{\alpha_{ng}} + q_e^{\alpha_e}} p_e + \frac{q_{CO2}}{(\eta_h q_h)^{\alpha_{ng}} + q_e^{\alpha_e}} p_{CO2}$$

$$p_Y = \zeta + \gamma_h p_h + \gamma_e p_e + \eta_{CO2}p_{CO2} \tag{7}$$

From which we can derive the equation regarding the inverse demand function for the clean hydrogen:

$$p_h = \frac{p_Y - \zeta - \gamma_e p_e - \eta_{CO2}p_{CO2}}{\gamma_h} \tag{8}$$

With equation (8) it is now possible to interface with the database and empirically derive the figures to the ability to pay for clean hydrogen by the European oil refineries.

5. Results

In this chapter, we empirically derive the Y and $C(Y)$ understanding their parameters through the model-based recursive partitioning method. We decided to use two parameters to get to the best approximation of the: Country and Year.

5.1 Production function empirical estimation

$$Y = \xi + q_{ng}^{\alpha_{ng}} + q_e^{\alpha_e}$$

Table 6: Main results of the parameters for the production function of European oil refineries.

```
$`2`

Call:
lm(formula = Refine_Y_TJ ~ q_NG_TJ + q_E_TJ)

Residuals:
    Min      1Q  Median      3Q     Max 
-248801 -116541  -40592   91546  423738 

Coefficients:
              Estimate Std. Error t value Pr(>|t|)    
(Intercept)  3.956e+06  1.381e+05  28.643 7.91e-16 ***
q_NG_TJ     -2.499e+01  2.028e+00 -12.321 6.71e-10 ***
q_E_TJ      -2.465e+00  1.066e+01  -0.231     0.82    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 191600 on 17 degrees of freedom
Multiple R-squared:  0.8993,	Adjusted R-squared:  0.8875 
F-statistic: 75.92 on 2 and 17 DF,  p-value: 3.353e-09
```

```
$`6`

Call:
lm(formula = Refine_Y_TJ ~ q_NG_TJ + q_E_TJ)

Residuals:
    Min      1Q  Median      3Q     Max 
-445848 -162801  -46435   76703  764317 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)    
(Intercept) 506899.206 162784.596   3.114  0.00434 ** 
q_NG_TJ        -23.212      9.234  -2.514  0.01821 *  
q_E_TJ         186.977      6.194  30.186  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 278300 on 27 degrees of freedom
Multiple R-squared:  0.9787,	Adjusted R-squared:  0.9771 
F-statistic: 620.7 on 2 and 27 DF,  p-value: < 2.2e-16
```

```
$`7`

Call:
lm(formula = Refine_Y_TJ ~ q_NG_TJ + q_E_TJ)

Residuals:
    Min      1Q  Median      3Q     Max
-453421 -103809    8345  177044  340550

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -56444.544 113045.201  -0.499 0.621606
q_NG_TJ         10.540      2.715   3.882 0.000604 ***
q_E_TJ         162.128      4.790  33.850  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 212500 on 27 degrees of freedom
Multiple R-squared:  0.9775,    Adjusted R-squared:  0.9758
F-statistic: 586.8 on 2 and 27 DF,  p-value: < 2.2e-16
```

```
$`8`

Call:
lm(formula = Refine_Y_TJ ~ q_NG_TJ + q_E_TJ)

Residuals:
    Min      1Q  Median      3Q     Max
-144940  -40552   -2333   54517  100326

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  2.602e+06  1.220e+05  21.324 1.05e-13 ***
q_NG_TJ      2.351e+00  3.431e-01   6.851 2.82e-06 ***
q_E_TJ      -7.764e+00  1.032e+01  -0.752    0.462
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 69850 on 17 degrees of freedom
Multiple R-squared:  0.7342,    Adjusted R-squared:  0.703
F-statistic: 23.48 on 2 and 17 DF,  p-value: 1.284e-05
```

```
$`10`

Call:
lm(formula = Refine_Y_TJ ~ q_NG_TJ + q_E_TJ)

Residuals:
    Min      1Q  Median      3Q     Max
-158252 -104853    7879   97952  199609

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) 1.321e+06  1.892e+05   6.984 6.44e-05 ***
q_NG_TJ     2.204e+01  4.106e+00   5.368 0.000452 ***
q_E_TJ      5.778e+01  2.844e+01   2.032 0.072752 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 134600 on 9 degrees of freedom
Multiple R-squared:  0.8998,    Adjusted R-squared:  0.8776
F-statistic: 40.43 on 2 and 9 DF,  p-value: 3.185e-05
```

```
$`11`

Call:
lm(formula = Refine_Y_TJ ~ q_NG_TJ + q_E_TJ)

Residuals:
    Min      1Q  Median      3Q     Max
-499552  -96896   36233  100695  391724

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) 683802.25  189123.67   3.616  0.00132 **
q_NG_TJ         29.27       2.95   9.920 3.77e-10 ***
q_E_TJ          64.14      21.82   2.939  0.00699 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 213400 on 25 degrees of freedom
Multiple R-squared:  0.8364,    Adjusted R-squared:  0.8233
F-statistic: 63.88 on 2 and 25 DF,  p-value: 1.493e-10
```

5.2 Cost function empirical estimation

$$\mathrm{p_y} = \zeta + \beta_{ng} q_{ng} p_{ng} + \beta_e q_e p_e + \beta_{CO2} p_{Co2}$$

```
$`3`

Call:
lm(formula = p_Y ~ p_NG + p_E + p_CO2)

Residuals:
       Min         1Q     Median         3Q        Max
-0.0049943 -0.0014928 -0.0000631  0.0014467  0.0056717

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  4.838e-03  1.489e-03   3.249  0.00175 **
p_NG         2.661e-06  1.467e-07  18.142  < 2e-16 ***
p_E         -2.096e-07  7.245e-08  -2.893  0.00503 **
p_CO2       -6.636e-05  3.924e-05  -1.691  0.09507 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.00237 on 73 degrees of freedom
Multiple R-squared:  0.8357,    Adjusted R-squared:  0.829
F-statistic: 123.8 on 3 and 73 DF,  p-value: < 2.2e-16
```

```
$`4`

Call:
lm(formula = p_Y ~ p_NG + p_E + p_CO2)

Residuals:
       Min         1Q     Median         3Q        Max
-0.0067585 -0.0025357  0.0004059  0.0027291  0.0061337

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -5.133e-03  9.258e-03  -0.554    0.589
p_NG         4.008e-06  5.848e-07   6.854 1.76e-05 ***
p_E          1.363e-07  4.140e-07   0.329    0.748
p_CO2       -4.012e-05  1.521e-04  -0.264    0.796
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.004029 on 12 degrees of freedom
Multiple R-squared:  0.8261,    Adjusted R-squared:  0.7826
F-statistic:    19 on 3 and 12 DF,  p-value: 7.49e-05
```

```
$`5`

Call:
lm(formula = p_Y ~ p_NG + p_E + p_CO2)

Residuals:
       Min         1Q     Median         3Q        Max 
-0.0025362 -0.0007248  0.0006872  0.0009032  0.0017488 

Coefficients:
              Estimate Std. Error t value Pr(>|t|)    
(Intercept) -1.592e-03  3.504e-03  -0.454   0.6603    
p_NG         2.028e-06  2.645e-07   7.668  3.1e-05 ***
p_E          2.465e-07  1.687e-07   1.461   0.1781    
p_CO2       -2.637e-04  9.015e-05  -2.925   0.0169 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.001579 on 9 degrees of freedom
Multiple R-squared:  0.881,	Adjusted R-squared:  0.8414 
F-statistic: 22.22 on 3 and 9 DF,  p-value: 0.0001698
```

Once these two equations have been properly parametrized, the substitution of natural gas with hydrogen might play based on the equation (8).

6. Conclusions and Next Steps

We proposed a germinal research on decarbonisation of oil refineries in Europe.
Oil refineries in Europe are heavily scrutinised by the regulation, present and future. This gives a clarity – still underway as national rules are yet to be implemented – that not all sectors of the economy are benefitting. And market is reacting in a positive way. For instance, it is not too long ago that TotalEnergies has signed a binding, 15-year agreement with Air Products for the furniture of 70,000 tonnes per annum of green hydrogen to decarbonise oil refineries operations in Northwest Europe (Air Products, 2024). The versatility of clean hydrogen as a feedstock to decarbonise current operation, if well leveraged by compliance to regulation, can become also a competitive feedstock for new typology of synthetic fuels (e.g., e-SAF).

To reach that, several are the variables in place, and of different nature. From the technological efficiency of the different fuels, to the commodity prices (part of worldwide supply chains) and finally the price of carbon emission which is mainly driven by policy and regulation. A pragmatic decarbonisation is difficult, and a complex endeavours. We have studied the decarbonisation of the economy done in the respect of current industrial activities which are the basis of European prosperity even if entangled with oil refineries and fossil fuels

As next steps, a more numerical approximation of the ability to pay should be pursued, as well as the enlargement of scope of the research, including some additional European hard-to-abate industries such as steel, cement and others.

Bibliography

Air Products. (2024). *Decarbonization of European Refineries: A first agreement signed between TotalEnergies and Air Products for the delivery of Green Hydrogen*.

Bourgeois, L., Ahmann, M., Albertos, F., Allevi, B. C., Bergh, M., Cabrera, M., Csoka, G. A., De Montessus, H., Delebecque, J.-C., Edwards, N., Haupt-Herting, S., Herlakian, N., Hernandez, S., Holst, B. A., Kozakowski, G., Krupa, P., Lobban, J., Loonen, R., Mackenzie, A. R. D., … Pokela, S. (2012). *EU refinery energy systems and efficiency*. www.concawe.org

British Petroleum. (n.d.). *Methodology for calculating CO 2 emissions from energy use*. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

Byrum, Z., Pilorgé, H., & Wilcox, J. (2021). Technological Pathways for Decarbonizing Petroleum Refining. *World Resources Institute*. https://doi.org/10.46830/wriwp.21.00004

Cooper, J. (2022). *FuelsEurope Statistical Report 2022*.

Coulon, P.-J. (2021). Opinion of the European Economic and Social Committee on “Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions-A hydrogen strategy for a climate-neutral Europe.” *Official Journal of the European Union*.

DG Climate Action. (2021). *Update of benchmark values for the years 2021-2025 of phase 4 of the EU ETS Benchmark curves and key parameters*.

Erbach, G., Jensen, L., Chahri, S., & Claros, E. (2024). *BRIEFING Towards climate neutrality*.
European Commission. (2022). *Renewable energy targets*. Https://Energy.Ec.Europa.Eu/Topics/Renewable-Energy/Renewable-Energy-Directive-Targets-and-Rules/Renewable-Energy-Targets_en.
European Environment Agency. (2024, August 13). *EEA greenhouse gases — data viewer*.
GCAP UNFCCC. (n.d.). *Climate Ambition Alliance: Net Zero 2050*. Https://Climateaction.Unfccc.Int/Views/Cooperative-Initiative-Details.Html?Id=94 .
Group of Seven. (2021). *Carbis Bay G7 Summit Communique*. Https://Www.G7uk.Org/Wp-Content/Uploads/2021/06/Carbis-Bay-G7-Summit-CommuniquePDF-430KB-25-Pages-1-1.Pdf .
IEA. (2021). *Net Zero by 2050*.
IPCC. (2018). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Https://Www.Ipcc.Ch/Sr15/ .
IPCC. (2021). *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis*. Https://Www.Ipcc.Ch/Report/Ar6/Wg1/Downloads/Report/IPCC_AR6_WGI_SPM.Pdf .
Oliveira, C., & Schure, K. M. (2020). *Decarbonisation options for the Dutch refinery sector*. www.pbl.nl/en.
Pye, N. (2014). *Allocation 2013-2020 Results of Free Allocation of Emission Allowances to Incumbent Installations for the Third Trading Period, 2013-2020*. www.dehst.de/EN
Shoesmith, G. L. (1988). Economies of scale and scope in petroleum refining. *Applied Economics*, *20*(12), 1643–1652. https://doi.org/10.1080/00036848800000094
UNFCCC. (2016). *Decision 1/CP.21: Adoption of the Paris Agreement, Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015, Addendum, Part two: Action taken by the Conference of the Parties at its twenty-first session*. Https://Www.Oecd.Org/Officialdocuments/Publicdisplaydocumentpdf/?Cote=COM/ENV/EPOC/IEA/SLT(2021)3&docLanguage=En .
UNFCCC. (2020). *Race to Zero*. Https://Racetozero.Unfccc.Int/ .

APENDIX A

In this Appendix we are calculating the correlation matrixes of the selected countries:

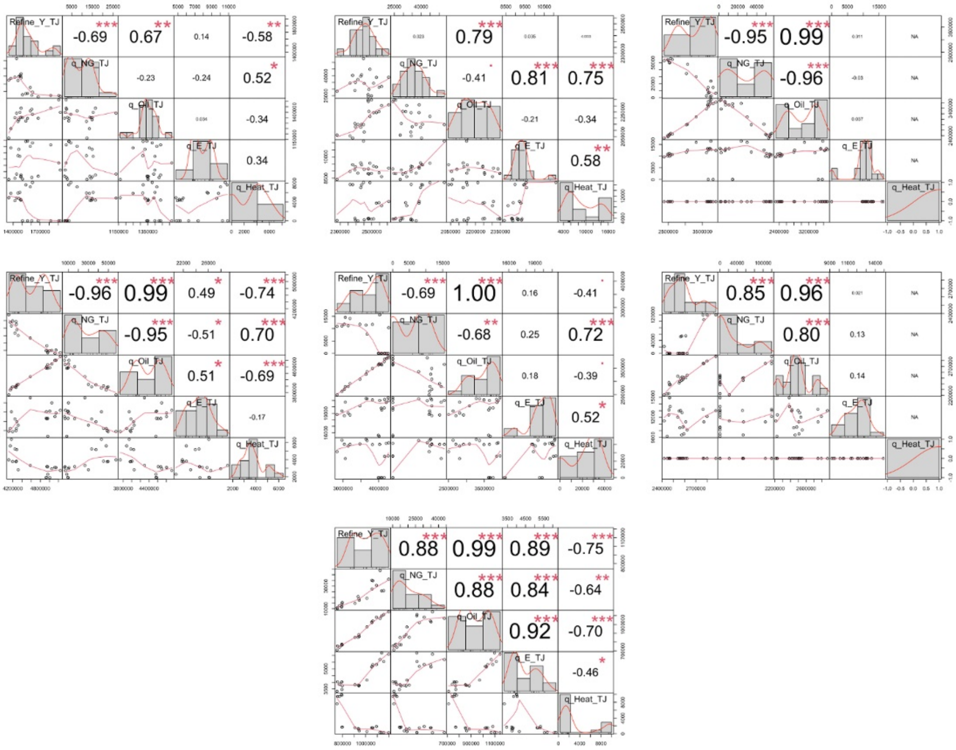


Figure A.1: Correlation Matrices of all the countries. In order, from left to right and from top to bottom: Belgium, Netherlands, France, Germany, Italy, Spain, Poland.

Based on them, we can deduce two major points:

1. The difference in correlation between electricity/heating and natural gas, which varies by country. That one is justified by the different electricity profile that a country might have.
2. Oil is very well correlated with the overall production of oil refineries; thus, it will not be considered as a factor in the estimation of production function. Only natural gas and electricity will be.

APPENDIX B

Relying on the oil refinery database, we plotted the relationship between energy input and revenues through the whole years and countries, as below:

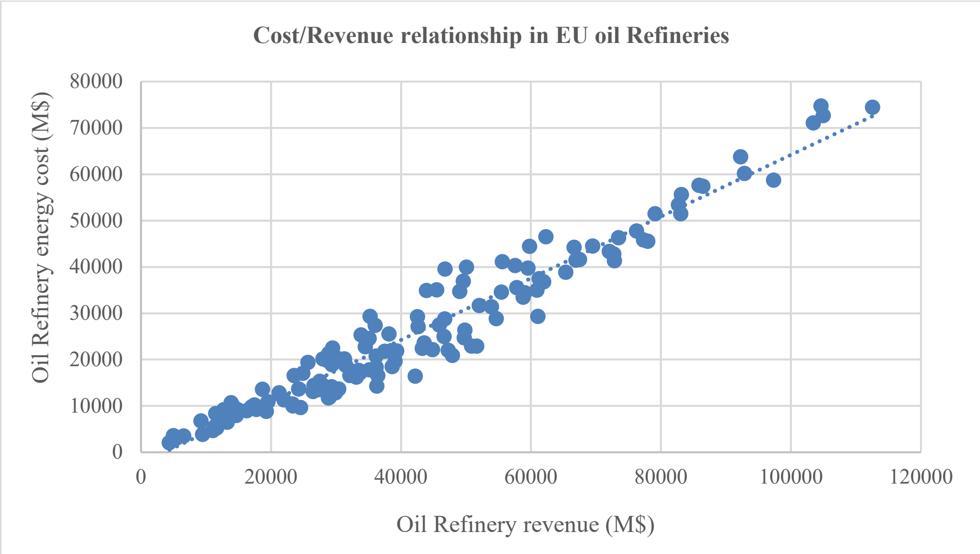


Figure B.1: Cost and revenue relationship in oil refineries between 1999-2018 (M$)

It is proven by Figure B.1 that there is a clear proportional relationship between the cost incurred by an oil refinery to procure its input and the price that the oil products are sold to the market. This fact fits well in the nature of oil refineries as critical, pass-through, energy infrastructure: they refine crude oil, their primary feedstock, to produce intermediary products for other industries (e.g. polymers etc…) or fuels.

APENDIX C

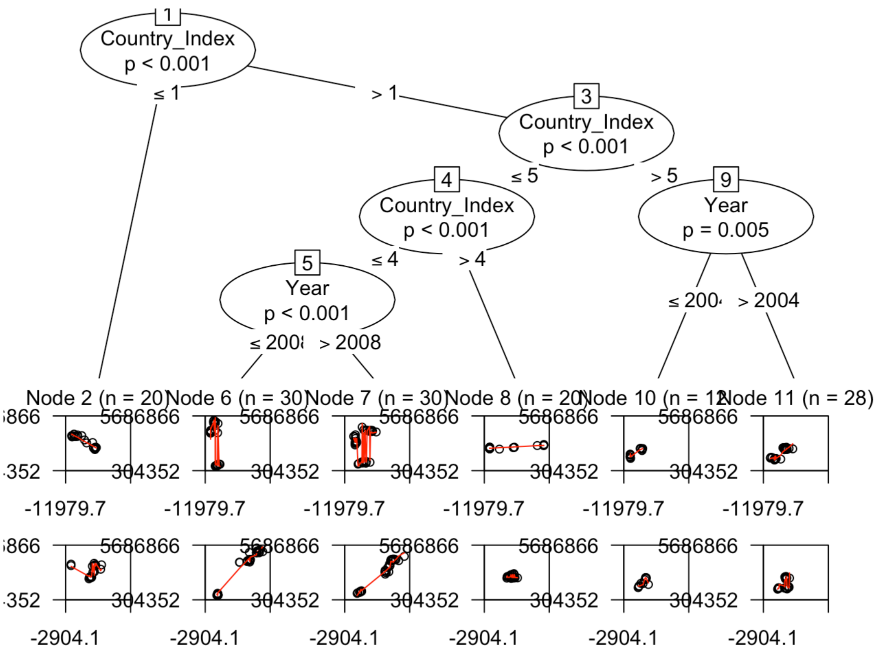


Figure C.1: Model-based recursive partitioning for the calculation of the parameters of the production function, using as splitting parameters the Country and the Time

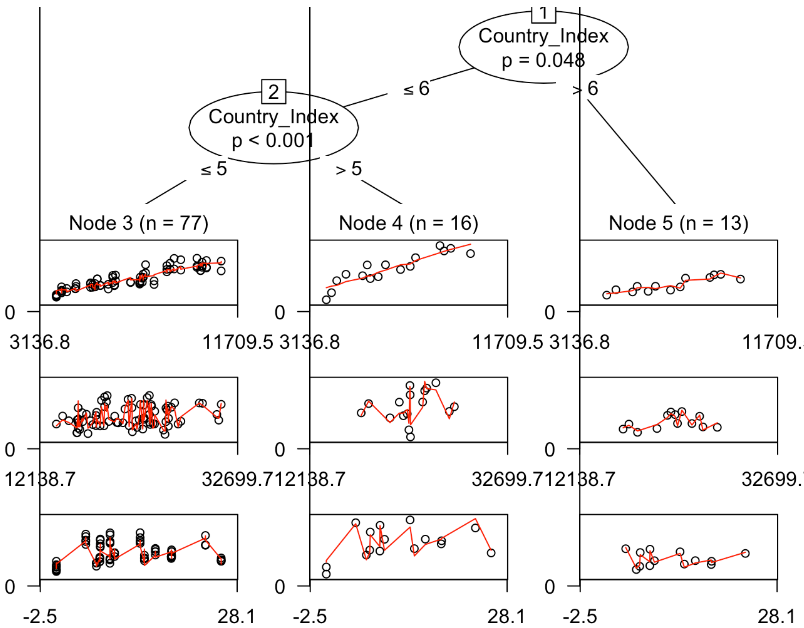


Figure C.2: Model-based recursive partitioning for the calculation of the parameters of the cost function, using as splitting parameters the Country and the Time.

ANALYTICAL INDEX

ANALYTICAL INDEX

Abstracts index by Presenter

Papers index by Presenter