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IAEE Energy Forum

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Editor: IAEE Headquarters

PRESIDENT'S MESSAGE

Earlier this month I participated in the XIX meeting of the Spanish Affiliate in Granada. I met wonderful (new!) people and was thrilled by the high share of attendance of young people. This boosted my energy level and made up for a rather difficult start of the year. Following a truly competitive selection process and interviews with highly qualified candidates, the Executive committee of the Association welcomes Julie Sutter, CAE as our new Executive Director. Julie joined us in Istanbul—please make sure to meet her and remember her face, the new face of IAEE headquarters.

From the business` perspective there are several tasks we as Association need to tackle in the next months. One is certainly communication, where we aim to establish routines to keep our members informed. It will be key to find the right level/amount of content to send your way, so please engage, provide feedback, let us know what you wish for and maybe also be a bit patient with us. Another one is a better understanding of what we can do for our members and affiliates. At this point allow me to emphasize again that the change in our dues structure introduced earlier this year aims to be more inclusive while keeping up with increased cost due to inflation. It is a tiered approach based on the World Bank's national income categories. A final point to touch upon in the second half of my presidency is a close monitoring of the development of our two academic publications in terms of quality and relevance. Most of the points raised above were agenda items on our Council Meeting, which we held during the whole day before the 27th International Conference in Istanbul started. Main takeaways from Istanbul will be topic in the next edition of the Energy Forum

Now I invite you to dive into this issue of the energy forum. Three key buzzwords—AI, digitalization and (energy) transition—are currently mentioned in one breath. The topic is of interest to all stakeholders in society—not only those in the energy sector—for very different reasons. For the ongoing energy transition, digitalization is expected to unlock flexibility potentials in the electricity sector using machine learning. But there are also interrelations with expected increased demand for power in data centres. If and how the fossil fuel sector will be affected by these trends is unclear to me. Therefore, I asked our members to share their thoughts, ideas and visions which we share on the following pages. Several aspects get touched upon, but numerous questions remain unanswered and others still need to be asked.

It was good meeting many of you in person in Istanbul and good luck to all who are following Wimbledon, Tour de France or the Olympic Games!

Take care of yourself and your loved ones.

Anne Neumann
IAEE President

Published By:

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Message from Executive Director

I am fortunate to have the opportunity to serve IAEE members and the Council as the organization's executive director. I joined IAEE and the Talley Management Group, the association management firm engaged by IAEE, in early June. Good fortune continued as I was able to attend the Council meeting and annual international conference in Istanbul within a few weeks of my start.

Much of our discussion during our Council meeting focused on the strategic plan and priorities to operationalize it. The Council is united in their commitment to help IAEE grow to the next level of its development as a member-driven organization. This means actively listening to members to learn about their needs, collecting and analyzing data about customer insights—gleaned from members and non-members—and then making decisions to meet those needs.

Since the global COVID-19 pandemic, many organizations, including IAEE, adapted and considered new approaches to maintain global connection with members. The new strategic plan emphasizes the role of IAEE as a convenor and connector to share knowledge and insights about the energy sector, from important discussions about research findings to forecasting trends and providing analysis and policy insights. Energy has grown from the fossil fuels that once dominated the agenda of IAEE's founding. Now energy is top-of-mind for consumers, business leaders, and policy makers as they consider the development of new and emerging energy sources and their impact. Just as the sector has grown, so too has the membership and their needs. With nearly 4,000 members and almost 30 affiliates, IAEE's influence continues to grow.

IAEE has a strong tradition to build on as it evolves. We will continue to host exceptional conferences, support students in their development, and publish leading publications. New priorities include enhancing and freshening our communications and hosting programs that better align with IAEE's three pillars of academia, business, and government and policy. Technology enables IAEE to connect practitioners in energy economics during the year even if they are unable to travel to attend a conference.

Another key priority is ensuring that IAEE reflects the diversity of its members, reflected as gender, race, ethnicity and geography, throughout its programs and governance and balanced across the three pillars of academia, business, and government and policy.

I am excited to have joined you at this exciting point in IAEE's trajectory. I am surrounded by a team of talented leaders. Council and affiliate leaders are subject matters in their areas of expertise: research, scholarship and teaching, business, and other professional practice. Colleagues at Talley share knowledge of association best practices, supplementing my own experience in linking organizational mission to execute strategic plans. While the energy sector is new to me, decades of experience with other membership organizations informs my approach to implementing the strategic plan, made stronger by the Council's wisdom in overseeing its direction. Our mutual aim is to serve the membership.

Over these next few months, I will continue to listen and learn and evolve the plan. And I look forward to meeting members in Louisiana for the USAEE Conference on November 3-6, 2004. If you have thoughts, comments, or suggestions to share, please reach out to me at jsutter@iaee.org.

All best wishes,

Julie Sutter, MS, CAE
Executive Director

Careers, Energy Education and Scholarships Online Databases

IAEE is pleased to highlight our online careers database, with special focus on graduate positions. Please visit http://www.iaee.org/en/students/student_careers.asp for a listing of employment opportunities.

Employers are invited to use this database, at no cost, to advertise their graduate, senior graduate or seasoned professional positions to the IAEE membership and visitors to the IAEE website seeking employment assistance.

The IAEE is also pleased to highlight the Energy Economics Education database available at http://www.iaee.org/en/students/eee.aspx Members from academia are kindly invited to list, at no cost, graduate, postgraduate and research programs as well as their university and research centers in this online database. For students and interested individuals looking to enhance their knowledge within the field of energy and economics, this is a valuable database to reference.

Further, IAEE has also launched a Scholarship Database, open at no cost to different grants and scholarship providers in Energy Economics and related fields. This is available at http://www.iaee.org/en/students/ListScholarships.aspx.

We look forward to your participation in these new initiatives.

Editor's Notes

In this issue of the Energy Forum, we start with an article on the previous topic of Energy Communities. Subsequent articles are focused on AI, Digitalization and Energy - the triumvirate of the 21st century.

There is no way around it: statistical methods, energy transition and digitalization are here to stay and it is up to mankind using it to the benefit of all people.

All sectors of the economy in all parts of the world are affected by the restructuring of production processes in order to achieve net-zero and what has been taught as empirical methods is now called AI using machine learning.

Increasing levels of decentralization of energy production and digitalization partnered with increased electricity production from intermittent sources lend themselves for the topic for this Issue of the Energy forum. This could be a case study in forecasting heat demand in a heating network as well as solar yield whilst optimizing electricity purchase of a large heat pump and providing optimal scheduling of heat pumps and operation mode of the heat network. Or it could be digital technologies making it possible to design and operate entirely new energy systems at the device, plant and regional scales. It can also be a critical assessment of any of the ingredients.

We will be reaching out soon with a new topic for the next issue and we earnestly solicit your input.

Alessandra Motz writes that despite much interest in the public debate and many information events, renewable energy communities in Italy are not taking off. Delays in the legislation, incoherent incentives, and problems in finding the best set-up are holding them back. She provides some insights from the experience of a grassroots project.

Qiang Li and **Lin Zhang** report that AI is making big waves in China's energy consumption and production. This Energy Forum article explores how AI can transform China's energy sector, focusing on driving innovation, improving operational efficiency, and reducing environmental impact. They also discuss the opportunities and challenges it brings.

Boris Ortega Moreno and **Laura Andolfi** state that digitalization has become an integral part of today's energy system, with households slowly taking on a more proactive role in adopting cutting-edge technologies. This study surveyed Luxembourgish households to characterize early adopters of smart energy technology. The findings show a strong positive correlation among technology awareness, adoption, energy literacy, and some household characteristics. Nevertheless, technology awareness is relatively low, highlighting the need for energy education and increased visibility of smart energy products to encourage adoption.

Timothy C. Coburn and **Ronald D. Ripple** discuss challenges facing energy policy makers in the Big Data analytics era, including how best to promote new approaches to energy delivery arising from the industry's embrace of digitalization, and how to reconcile differences in resource reporting arising from disparate rates of digitization and inconsistent data handling.

Daniel Davi-Arderius, Manuel Llorca, Golnoush Soroush, Emanuele Giovannetti, and Tooraj Jamasb inform us that a market-based energy transition requires active customers, which means they offer their energy flexibility through data-driven services. Implementing these services requires data interoperability standards and processes, and single common front doors. In economic terms, data interoperability lowers the barriers to participate in those services and improves their liquidity and efficiency.

Sara Zaidan and **Mutasem El Fadel** explore digital transformation in the oil and gas sector within the context of the Gulf countries. They highlight the latest trends in Industry 4.0 technologies, along with other advances related to renewable energy, alternative fuels, carbon removal, methane abatement and flaring control. The article highlights the transformative abilities of these technologies in revolutionizing oil and gas operations and sculpting the forthcoming narrative of the Gulf region and beyond. The discussion also delves into the opportunities, applications, and real-world use cases highlighting how technologies are driving the clean energy transition. The challenges in transforming the sector are then examined, followed by recommendations of critical success factors as enablers for governments and national oil companies to decarbonize the energy system in the region in pursuit of accelerating the realization of the net zero emissions agenda.

Lydia Yusuf and **Adewale Adesanya** posit that the sustainable energy transition is advancing with the integration of renewables, but challenges such as efficient renewable integration and the need for predictive maintenance remain significant. Harnessing AI can address these issues by optimizing energy systems and improving maintenance strategies, which is crucial for a reliable and sustainable energy future.

Reid Lifset and **Alan Porter** state that the energy consumed in training generative and other computationally-intensive forms of artificial intelligence (AI) is attracting increasing attention from computer scientists, energy modelers, policy makers, and the public. However, the development and use of AI has other potential energy and environmental impacts. Building on bibliometric analysis, this article describes impacts that are the focus of cur-rent research—energy use in training AI—those starting to be characterized in the research literature—energy use in inference—and those impacts that exist or are hypothesized to exist but have drawn little attention from researchers—including indirect impacts from the use of AI, rebound effects, and misleading inferences in environmental management and policy relying on the use of AI.

CONFERENCE OVERVIEW

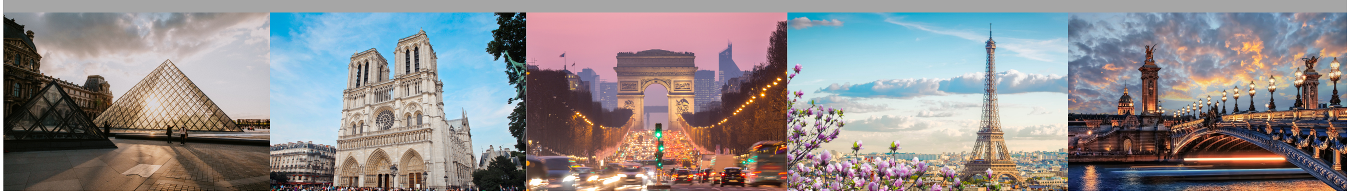
The 46th IAEE International Conference takes place in Paris, France, 15 – 18 June 2025, with the main theme "ENERGY SOLUTIONS FOR A SUSTAINABLE AND INCLUSIVE FUTURE"

The 46th IAEE International Conference will focus on the economies of the different energy solutions envisioned for a sustainable future. It will also examine contemporary and emerging policy and regulatory questions to energy and climate.The event will bring together an international audience of academics, industry executives, experts, analysts, regulators and policy makers.
For further information please visit:
iaee2025paris.org

CONFERENCE VENUE


Palais des Congrès Paris

The conference will be held at the Palais des Congres, the leading venue for international congresses in Paris.
On the first conference day, delegates will enjoy a welcome reception at the Conference hotel: Le Meridien. The Hotel interior is inspired by mid-century modern design, with clean lines accentuated by sculptural forms and rich fabrics, that are unmistakably reflective of Paris.
Conference's Gala dinner will be hosted by the City of Paris at the Hôtel de Ville. This unique venue will open its doors only for our delegates to guarantee an exclusive experience of the French hospitality, cuisine and fine wine.



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AEE Association des Economistes de l'Energie

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King Abdullah Petroleum Studies and Research Center

British Institute of Energy Economics – Policy Conference
Wednesday 18 September 2024, One Birdcage Walk, London

Delivering the energy transition: pace over perfection

It is time to scale up delivery and bring down uncertainty in the GB energy transition.

The BIEE's biennial policy conference is a key opportunity for expert debate and discussion, with its unique ability to bring together experts in policymaking and delivery, academia and business. This year we will ask how GB can firm up the next steps in its energy transition in both delivery and policymaking, navigating both the gaps in current understanding and the political hurricane.

Key themes include:

- First-hand experience from policymakers and delivery bodies. How do we balance strategic plans and the power of markets?
- The links between the energy transition and the economy at large. Is the UK too late to the international race?
- Whole system design, market reforms and future system operation. How to incentivise the right things, in the right places, at the right times?
- Bringing in the consumer. Can households and the energy transition help each other?
- Crowding in finance and scaling up investment. What role for public investment and how to avoid delay?

Early bird discounts available until 31 July 2024.
Website/registration: www.biee.org/conference/biee-policy-conference-2024

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2024 MEMBERSHIP PRICING

JOIN NOW

IAEE's council has approved a tiered approach to membership based on World Bank national income categories. Council hopes to expand IAEE's outreach in emerging and developing countries while keeping up with cost inflation since our last rate increase in 2019. More information can be found at: https://datatopics.worldbank.org/world-development-indicators/the-world-by-income-and-region.html

HIGH INCOME

High income economies are those with a GNI per capita of $13,846 or more.

INDIVIDUAL MEMBER **$145**

AFFILIATE MEMBER **$135**

STUDENT MEMBER **$75**

UPPER MIDDLE INCOME

Upper middle income economies are those with a GNI per capita between $4,466 and $13,845.

INDIVIDUAL MEMBER **$115**

AFFILIATE MEMBER **$110**

STUDENT MEMBER **$60**

LOWER MIDDLE INCOME

Lower middle income economies are those with a GNI per capita between $1,136 and $4,465.

INDIVIDUAL MEMBER **$85**

AFFILIATE MEMBER **$80**

STUDENT MEMBER **$45**

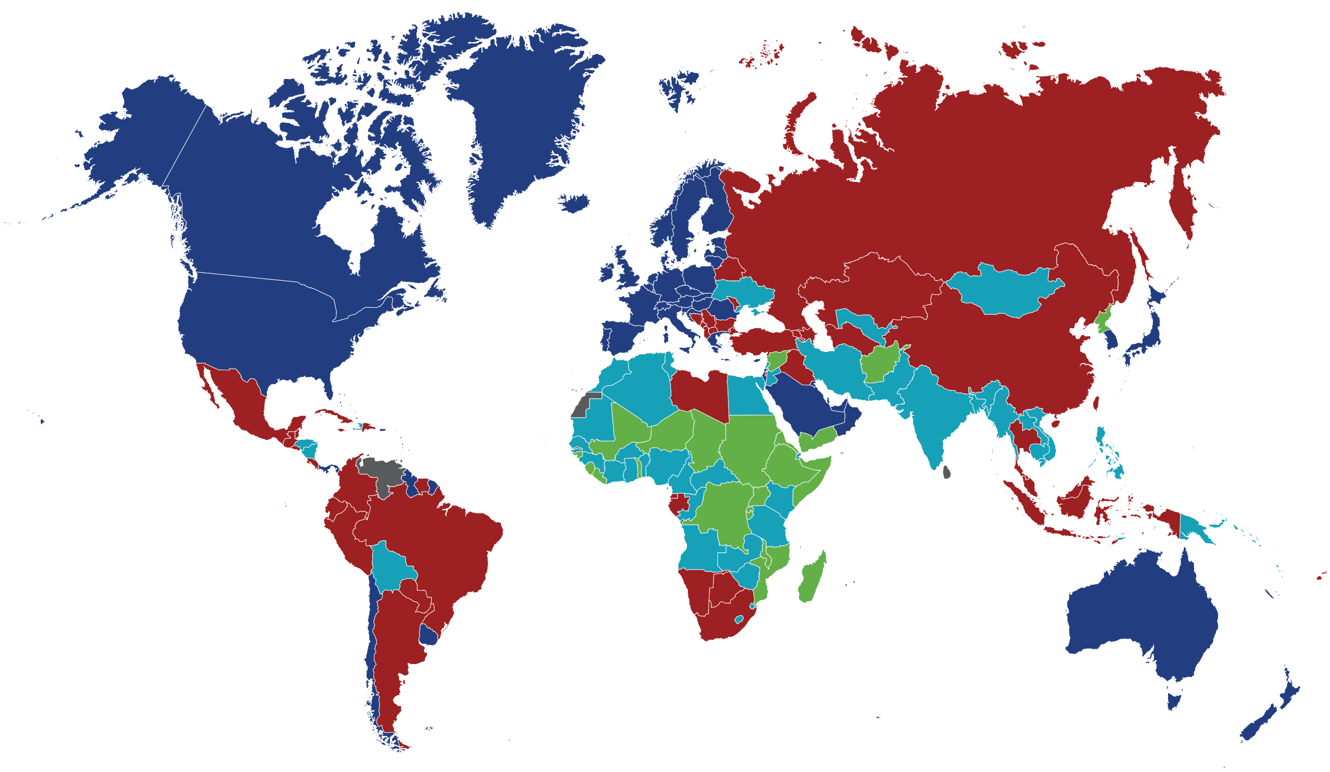
LOW INCOME

Low income economies are defined as those with a GNI per capita of $1,135 or less.

INDIVIDUAL MEMBER **$60**

AFFILIATE MEMBER **$55**

STUDENT MEMBER **$30**



Renewable Energy Communities in Italy: Why Still so Few? Insights from the Journey of a Grassroots Initiative

BY ALESSANDRA MOTZ

Alessandra Motz is a researcher in energy economics at the Institute for Economic Research, Università della Svizzera italiana, Lugano (Switzerland). E-mail: alessandra.motz@usi.ch.

Despite much interest in the public debate and many information events, renewable energy communities in Italy are not taking off. Delays in the legislation, incoherent incentives, and problems in finding the best set-up are holding them back. Here's some insights from the experience of a grassroots project.

More than five years after the introduction of renewable energy communities (RECs) in the EU legislative framework[1], the picture for RECs in Italy is mixed, and the country is lagging behind its peers. The number of RECs registered in Italy is indeed low: no official data have been published, but the environmental protection organization Legambiente estimates around 20 RECs[2], and the research centre ENEA around 17 with an overall installed capacity below 1.5 MWp[3]. These numbers clash with the targets set in the legislation recently approved in the country, that aims at reaching 5 GWp of new renewable-based generation plants within RECs by 2026, also thanks to the 2.2 billion euros provided by the National Recovery and Resilience Plan for RECs in small municipalities[4]. They clash even more with the statements of the Minister in charge of the energy transition, Gilberto Pichetto Fratin, that spoke of around 15'000 or even 40'000 RECs over the next few years.[5]

What is the problem with RECs in Italy? Why is their number so small, and what are the prospects for the next few years? I will provide some insights based on my own experience as an energy economics researcher at the Università della Svizzera italiana (Lugano, Switzerland), but also as one of the founding members of Energia Nostra, an association working on a grassroots REC in Cormons, my hometown in the North-East of Italy.

A lengthy legislative process

Step 1: the provisional framework

RECs were first introduced in Italy in December 2019. The legislation[6], set up as a provisional framework, described RECs as small groups of consumers and prosumers[7] entitled to collectively receive an incentive for every kWh of the so-called "shared energy". Despite its misleading name, "shared energy" is not actually shared or traded among REC's members, but simply computed, for every hour, as the smallest between the aggregate grid injections of the REC's producers and prosumers, and the aggregate net withdrawals of its members.

The legislation was designed with a prudential approach: RECs were not allowed to manage the distribution grid, nor to supply electricity to their members, nor to enable virtual electricity exchanges within the community, as the computation of the "shared energy" is a simple accounting exercise performed by the GSE, a central entity in charge of paying the incentives to each REC. Even the size of the RECs was constrained within the low-voltage substations and under the threshold of 200 kWp per individual plant. In practice, the main activities that RECs were asked to perform were maximising the use of renewable-based electricity production at the local level, and engaging residents and local stakeholders in the energy transition by promoting local investments in renewables.

Despite positive reactions among local institutions, a good coverage in the press, and a number of initiatives organized by associations and citizens[8], few RECs actually came to light, among which RECOCER, the REC of the Comunità Collinare del Friuli district, in the North-East of the country. The most cited obstacles were the high administrative burden and the small geographical size, that allowed the inclusion of very few members in each REC and thus dwarfed any expectation of a decent economic outcome[9].

Step 2: the final framework is outlined

In November 2021 the legislation was amended[10] with a final definition of RECs, that confirmed most of the above-mentioned constraints, but allowed a significant increase in the RECs' size, up to the medium-voltage substation and renewable generation plants up to 1 MWp each. The news was welcomed with enthusiasm among citizens, associations, and stakeholders working on environmental and social issues, as a bigger size of the RECs was expected to yield benefits in terms of scale economies and lower administrative burdens.

Step 3: missing implementing acts leave Italian RECs in the provisional framework

Before the new, bigger RECs were actually allowed to take off, however, three implementing acts had to be approved: a ministerial decree defining the new incentives, and two technical regulations defining the procedures for the registration and management of the RECs.

The ministerial decree, expected by June 2022, was only approved in December 2023 and published in January 2024[11], after one public consultation, a change in the government, several leaks, and much gossiping. One of the technical regulations was approved at the end of January 2024, the other one is still missing at the time of writing. The latter is, of course, the one providing the most important details for each REC's business plan.

As a result, by mid February 2024, five years after the approval of Directive (EU) 2018/2001 and two years after the introduction of the final framework in the Italian legislation, Italian RECs are still stuck in the provisional setting.

Energia Nostra: insights from a practical experience

The journey of Energia Nostra, the REC I am contributing to build together with six other residents of Cormons, a town of around 7'000 inhabitants in the hills of Friuli Venezia Giulia, developed in parallel with the Italian legislation. It is thus interesting to sum it up and get some insights into what is working and what is not.

From the idea to the decision

In Spring 2022, under the expectation of a quick implementation of the final legislation for RECs, I started discussing the possibility of building a REC together with a small group of local citizens interested in environmental protection. Our goals were:

- Increasing the use of renewables at the local level,
- Engaging households and firms in the energy transition,
- Collecting resources to protect weaker citizens or support projects of local relevance,
- Facilitating the use of roofs, parking lots and similar spaces for new photovoltaic installations, in order to protect landscapes and ecosystems.

Our working group first got in touch with our neighbours of the above mentioned RECOCER, that, as a pilot project, had received 5.4 million euros from the regional government to register a small REC under the provisional legislation, and experiment with this new framework[12]. Their REC was too small to pay its administrative costs without external support, but they were optimistic that the final legislation would have been adopted soon, and suggested to start informing the residents and collecting informal memberships.

In October 2022, with the help of the local branch of Legambiente, we organized our first public event, gathering around 130 citizens, entrepreneurs, and stakeholders. The worries for the skyrocketing energy prices of Summer 2022 obviously helped raising interest toward our project, but we were impressed by this positive response, and decided to go on.

One year of work

In February 2023 we officially registered our association, drafted our statute, opened a bank account, subscribed an insurance for our information events, set up a website[13] and opened our social media accounts. The ministerial decree allowing RECs to start operations was still missing, but at least the map of the medium voltage substations had finally been published, and we were thus able to focus on the most suitable area. It turned out, indeed, that our municipality was split in two substations. The bulk of it, including two thirds of the residents and a small industrial park, belonged to a substation covering seven other smaller municipalities – all in all, around 25'000 residents. We decided to start with this area.

Between April and November 2023 we organized eight information events in Cormons and the neighbouring villages covered by the same substation, reaching around 500 people. We often received (moral) support from the mayors, but the burden of organizing, promoting, and conducting the events was entirely on our shoulders. We were also invited in events organized by other local stakeholders, such as Legambiente, the University of Udine, the local section of the Chamber of Commerce, and others. As the only expert in energy economics, I was lucky enough that the other six members of Energia Nostra, whose professional path has nothing to do with energy, were quick learners, and rapidly become able to present the project, explain technical details, and answer most questions on their own.

The challenges

The main challenges we faced were:

- Getting in touch with mayors and stakeholders,
- Organising and conducting information events in the various municipalities,
- Collecting funds to cover the cost of these activities,
- Explaining to the audience that our project had a social and environmental purpose, rather than a commercial one.

The latter point may seem trivial, but it is not, as most Italian residents receive frequent phone calls or e-mails from energy suppliers, installers of photovoltaic panels, energy service companies, and other commercial entities broadly associated to the energy field. For the layperson, it is often difficult to see the difference between these offers and a grassroots initiative like ours, that is entirely based on volunteering and aims at environmental and social outcomes.

The first outcomes

By the end of 2023, the outcome of our effort was the following: 116 among households and companies had informally registered for the REC, 80 of which were based in the appropriate geographical area. Together, these 80 prospective members held 329 kWp of photovoltaic generation capacity, and their net consumption summed up to 690 MWh per year. No municipality had joined our REC, first due to the incomplete legislative framework, and secondly because of some uncertainties regarding the legal conditions under which a municipality could join a REC set up by a different entity. It turned out that the best legal entity to register and manage a grassroots REC is a cooperative, but setting up a cooperative requires approximately 3'000 euros, that we decided not to pay before having a complete picture of the legislative framework.

The ministerial decree and its problems

And then, in December 2023, the ministerial decree was published and our project got stuck, at least temporarily, like many others with which we had been in touch.

The ministerial decree, indeed, set up relatively generous incentives for the "shared energy" of RECs, and provided a grant up to 40% of the investment cost to investors in new renewable generation capacities within RECs located in municipalities with less than 5'000 residents.

Next to this positive aspect came some major problems.

First and foremost, while the primary legislation published in November 2021 stated that all renewable-based plants below 1 MWp starting operations after December 15th 2021 could join a REC, the ministerial decree seems to suggest that the incentive for the "shared energy" is only paid for the productions of the new renewable-based plants that start operations "after the registration of the REC". It is understandable that the Ministry is only willing to incentivize new plants developed within the framework of a REC, but the delay in the completion of the legislative framework has been such that the underpinnings of this provision are, at the very least, shaky. The ministerial decree is not entirely clear on this point, and we'll need to wait for the last piece of technical regulation to discover what will happen. It is obvious, however, that this point is crucial for both the investors who have built their own plant during 2022 and 2023, and the RECs in which they are engaged. In Energia Nostra, we estimated that 169 kWp of the 326 kWp of renewable-based generation capacity that joined our REC might receive the incentive according on the legislative decree of November 2021, but only 8.3 kWp would be entitled to the incentive pursuant to what we seem to read in the ministerial decree of December 2023.

Secondly, while the ministerial decree provides generous funding for new renewable-based plants joining RECs in municipalities with less than 5'000 residents, it is not clear if each municipality will need to have its own REC. If so, this could hinder the exploitation of scale economies and thus the success of RECs in rural areas. Moreover, there is no funding at all for setting up the REC itself, a challenge that is often beyond reach for short-staffed local administrations or groups of goodwill citizens. These two aspects, combined to the fact that the funding for new plants should be requested already by March 31st 2025 and the new plants should be commissioned by June 30th 2026, may seriously undermine the success of this provision.

A third negative aspect comes from the interaction between the ministerial decree and the support schemes for renewables set up, often hastily, by the national and regional governments in the past four years. The ministerial decree (correctly) suggests that new renewable-based plants receiving any grant exceeding 40% of the investment cost may join RECs, but they are not entitled to any incentive for the "shared energy". In the aftermath of the Covid crisis, however, the national government introduced the "Superbonus 110%"[14], a stimulus to building renovation that provides a fiscal rebate up to 110% of the investment cost, and set up a number of grants for companies investing in renewables through the National Recovery and Resilience Plan. The government of Friuli Venezia Giulia, the region in which Energia Nostra is located, also introduced a grant up to 40% of the investment cost for families and firms investing in renewables[15], and allowed this support scheme to be added on top of the ordinary 50% fiscal rebate provided by the national legislation for the investments in renewables that do not qualify for the "Superbonus 110%". As for the other Italian regions, while is hard to compile a list of the different support schemes, it is also well known that most administrations set up comparable, albeit less generous measures. As a result, any owner of a new renewable generation plant needs to choose between these grants and fiscal rebates, providing quick refunds based on the investment costs, and the uncertain outcome of the REC incentive, that depends on the hourly production and consumption profile of a community of producers, prosumers, and consumers. It is rather obvious who is going to win this contest, and how support schemes favouring individual investment will crowd-out the incentives set up for RECs.

When the going gets tough, the tough must get going

What does this mean for Energia Nostra and the other grassroots initiatives at the starting line? It is still too early to draw conclusions, first of all because the most crucial question, that is, which new plants will be entitled to receive the incentive, is still to be clarified in the missing piece of technical regulation.

Our back of the envelope estimates suggest that if all plants commissioned after December 15th 2021 will receive the incentive, our initial configuration will receive approximately 14'000 euros per year, a decent basis on which we may be able to grow. Otherwise, we would have to start with as little as 800 euros per year, hardly worth the effort. The picture may change if, as we hope, some bigger investors not benefitting from additional support schemes should join our community later on… but hard work will be needed to get things done.

So what? Missing steps and lessons learned

The future of RECs in Italy is not (yet) doomed, but these initiatives, including Energia Nostra, will have to navigate carefully through the many obstacles and delays outlined above.

It is hard to see how small or medium-sized municipalities might develop, in just a few years, the technical skills needed to set up their own RECs ensuring transparency and democracy for their citizens. Energy service companies may play a role in supporting municipalities and other local stakeholders, but it is unclear to what extent they will be seen as a reliable partner by households and small firms. Environmental organisations and local associations could be able to fill the trust gap, but they will need to work on educating their members and sharing best practices to overcome the technical challenges entailed in the construction of a REC. A general lack of transparency about the RECs that completed or failed the registration process does not help the many people working on these projects. All in all, the Italian framework for RECs does not seem able to actually bring citizens on board of the energy transition, and thus fulfil the main goal of RECs according to Directive (EU) 2018/2001.

While Italy is well positioned to face the technical and financial challenges of the energy transition, a lot is missing in the social dimension. More work should be done in designing policies that favour democratic processes and active participation of households and business consumers, and in coordinating national and regional support schemes to avoid undesirable outcomes.

Footnotes

[1] Directive (EU) 2018/2001.

[2] Legambiente, 2021: "Comunità rinnovabili 2021", (https://www.legambiente.it/wp-content/uploads/2021/07/Comunita-Rinnovabili-2021.pdf).

[3] Qualenergia, 2023: "Comunità energetiche, ad oggi 54 esistenti e quasi cento in formazione" (https://www.qualenergia.it/articoli/comunita-energetiche-oggi-54-esistenti-quasi-cento-formazione/).

[4] https://www.italiadomani.gov.it/it/Interventi/investimenti/promozione-rinnovabili-per-le-comunita-energetiche-e-l-auto-consumo.html.

[5] Gramigni N., 2023: "Comunità energetiche, ecco la mappa dei progetti nelle principali città italiane", Il Sole 24 Ore, March 23rd 2023 (https://www.ilsole24ore.com/art/comunita-energetiche-ecco-mappa-progetti-principali-citta-italiane-AEh0Y54C?refresh_ce); D'Alessandro J., 2023: "Il ministro Pichetto Fratin: "Nel 2030 due terzi dell'energia dalle rinnovabili. Ma il gas ci accompagnerà fino al 2050", La Repubblica, June 10th 2023, (https://www.repubblica.it/green-and-blue/dossier/festival-greenandblue-2023/2023/06/10/news/earth_for_all_gilberto_pichetto_fratin_gas_rinnovabili_2050-403474096/).

[6] Law-decree 162/2019.

[7] A prosumer is a consumer who also owns a renewable-based generation plant serving its own consumption.

[8] De Vidovich L., Tricarico L., Zulianello M., 2021: "Community energy map - Una ricognizione delle prime esperienze di comunità energetiche rinnovabili", Franco Angeli.

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The Impact of AI on the Energy Sector in China

BY QIANG LI AND LIN ZHANG

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Abstract

AI is making big waves in China's energy consumption and production. This energy forum article explores how AI can transform China's energy sector, focusing on driving innovation, improving operational efficiency, and reducing environmental impact. We also discuss the opportunities and challenges it brings.

The push for net-zero emissions worldwide has led to a widespread use of AI technology in various industries, especially in the energy sector. China, a major player in energy consumption and production, is facing significant challenges as it aims to shift to cleaner energy sources while also dealing with increasing energy needs. In the following, we discuss how AI is being used in China's energy sector and explore the opportunities and challenges it brings.

AI in China's Energy Sector

AI is making big waves in the energy sector, especially in China, a global powerhouse in energy consumption and production. It's revolutionizing how energy is managed and paving the way for more sustainable and eco-friendly systems. China's energy sector covers a wide range of sources like coal, natural gas, oil, nuclear power, hydropower, wind, solar, and biomass. As the world's top emitter of greenhouse gases, China is under pressure to cut carbon emissions, shift to renewable energy, and boost energy efficiency.[1] The country's rapid urbanization and industrialization have led to a surge in energy demands, driving the need for smarter ways to generate, distribute, and use energy.

AI plays a crucial role in transforming traditional energy systems into smart, efficient, and sustainable networks. First, by using AI algorithms, energy companies can gain valuable insights into energy consumption patterns and predict changes in demand. Smart grid technologies use AI algorithms to balance energy supply and demand, integrate renewable energy sources, and enhance grid resilience. Second, AI technology could optimize equipment performance and thus strengthen grid reliability. AI-powered predictive maintenance models help prevent equipment failures, reducing downtime and maintenance costs. Third, the use of artificial intelligence in China's energy sector extends to various areas such as energy storage and energy efficiency. Energy storage systems with AI capabilities optimize energy storage and distribution, improving overall system efficiency and reliability. Overall, AI-driven solutions enable real-time monitoring, autonomous decision-making, and proactive maintenance, ultimately leading to cost savings, energy conservation, and reduced environmental impact.[2]

Successful implementation of AI in China's Energy Sector

Amidst the fast-paced changes in the Chinese energy sector driven by new technology, AI has become a powerful tool for making operations more efficient, boosting productivity, and making data-driven decisions. In this section, we look at real-life examples that show how AI is being used across different areas in the energy sector. These examples give us valuable insights into best practices, and the real benefits of using AI.

Case 1: Smart Grid Management and Optimization

In Guangzhou, the utility company has set up a smart grid management system with AI technology to make the power grid more stable and reliable.[3] The system uses advanced machine learning to keep an eye on how power is flowing, predict when the transmission infrastructure needs maintenance, and automatically find and fix any problems. As a result, there have been big drops in power outages, the grid is better at bouncing back from issues, and energy transmission is more efficient.[4] This all helps with saving energy and bringing the grid up to date. Similar AI-powered technologies have now been tested and installed in 27 provincial branches of the State Grid, the largest utility provider in China.

Case 2: Predictive Maintenance in Power Generation Facilities

Heilongjiang branch of China Huaneng Group, a top-notch thermal power plant, has started using an AI-powered predictive maintenance solution to spot equipment issues before they happen and plan maintenance more effectively. Another example is the Gulou substation of Nanjing.[5] By analyzing sensor data, past performance, and using machine learning, the plant could predict potential problems with turbines, boilers, and other systems, allowing them to step in less than 10 minutes and reduce unexpected downtimes. This smart use of AI-led maintenance not only saved money but also increased operational time and extended the lifespan of their equipment, showing how AI can really boost power generation efficiency.[6]

Case 3: Renewable Energy Forecasting and Integration

In the province of Inner Mongolia, Dongrun Energy Technology Co. that works on renewable energy used advanced AI models to improve how they predict and use wind power.[7] They looked at weather data, past wind patterns, and computer simulations to figure out how much wind energy they could produce. This helped the people who manage the power grid to better prepare for changes in wind power and match it with how much power people need. By using AI to predict wind energy, they were able to bring more renewable energy into the power grid, reduce the need for fossil fuels, and support China's shift to cleaner energy.

Case 4: Energy Consumption Pattern Analysis for Demand-Side Management

Advanced AI technology has entered Shenzhen. In the commercial area of the city, such technology has been used to figure out how much energy each building was using and come up with better ways to manage energy use.[8] By using big data analysis, special algorithms, and data from smart meters, the city managers were able to spot unusual energy use, times when energy demand was highest, and when they could shift energy use to different times. This AI-led energy analysis helped them find more precise ways to save energy, cut down on peak energy costs, and lower overall electricity use.[9] This all adds up to making the city more sustainable and using resources more efficiently.

Challenges and Opportunities of AI in China's Energy Sector

The use of AI in China's energy sector brings both challenges and opportunities for industry players as the country works to modernize its energy infrastructure, improve grid management, and shift to sustainable energy sources. Effectively integrating AI technologies is crucial in this changing landscape. In the following, we provide a detailed analysis of the challenges and opportunities involved in adopting AI in China's energy sector, by exploring the regulatory framework, technological advancements, and operational implications driving this dynamic evolution.

Challenge 1: Regulatory Landscape and Policy Framework

The regulatory environment assumes a pivotal role in shaping the trajectory of AI adoption in China's energy sector.[10] Governmental policies, in particular standards and regulations that pertain to data privacy, cybersecurity, and technology deployment, can exert a significant influence on the integration of AI solutions. However, there is no clear guidance and workable guidelines so far. The evolving regulatory framework, oriented towards fostering innovation while safeguarding data integrity, poses challenges for energy companies navigating the complexities of AI utilization. Concurrently, aligning AI strategies with national energy objectives and policy directives presents opportunities for cultivating an enabling ecosystem conducive to the assimilation of AI technologies.

Challenge 2: Technological Challenges and Advancements

The smooth implementation of AI in the energy sector is hindered by various technical challenges, such as data quality, interoperability, scalability, and the complexities of algorithms. One significant obstacle is obtaining high-quality and diverse datasets that are necessary for training AI models. This challenge is particularly pronounced in China's intricate energy systems. However, there have been notable advancements in AI technologies, including deep learning, reinforcement learning, and predictive analytics, which offer promising solutions to overcome these hurdles.[11] By harnessing these technologies, the energy industry can unlock the full potential of AI in areas such as boosting energy production, improving demand forecasting accuracy, and optimizing grid operations.

Challenge 3: Operational Implications and Industry Readiness

The incorporation of AI technologies brings about significant operational consequences for energy companies. This calls for the need to implement effective change management strategies and make necessary adjustments to infrastructure. It is crucial to foster a culture that values data-driven decision-making and promotes collaboration between subject matter experts and data scientists.[12] These actions are essential for reaping the benefits of AI adoption. The readiness of the industry to embrace AI innovations, invest in digital transformation initiatives, and update outdated systems plays a vital role in streamlining operations, increasing efficiency, and reducing environmental impacts.

Challenge 4: Talent Development and Skill Gap

The lack of qualified experts who are proficient in AI, machine learning, and data science presents a significant challenge to the widespread implementation of AI in China's energy industry.[13] It is crucial to foster a talent pool equipped with the necessary skills to develop, deploy, and maintain AI solutions, and this requires coordinated efforts from educational institutions, industry partners, and government entities. By investing in specialized training programs, promoting knowledge transfer initiatives, and establishing partnerships across different sectors, we can bridge the skills gap and cultivate a workforce that is capable of driving innovation in the energy sector through AI.

Conclusions

The integration of AI into the energy industry in China has had a profound impact, marked by a convergence of challenges and opportunities that require a thorough understanding of various dynamics. The utilization of AI technologies has brought about a significant shift, presenting unprecedented potential for innovation, increased efficiency, and sustainability.

However, it also poses intricate obstacles that call for strategic navigation and proactive mitigation.

The regulatory, technological, operational, and economic aspects of AI implementation in China's energy sector are intertwined and together shape the transformational landscape.[14] Addressing concerns regarding data privacy is of utmost importance, necessitating the establishment of robust governance frameworks and security architectures to protect sensitive information. At the same time, fostering the development of talent and bridging the gap in skills related to AI, machine learning, and data science becomes crucial. This serves as a key factor in driving innovation and ensuring long-term competitiveness.

In order to fully harness the benefits of AI in the energy sector, it is imperative to address the challenges. This requires a comprehensive understanding of the multifaceted dynamics at play. By leveraging AI technologies, the energy industry in China can unlock new avenues for achieving "dual carbon" target while simultaneously addressing the complex issues that arise. With a strategic approach and proactive measures, the integration of AI can pave the way for a sustainable and prosperous future.

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Digitalizing Whom? On the Early Adopters of Smart Energy Technology

BY BORIS ORTEGA MORENO AND LAURA ANDOLFI

Abstract

Digitalization has become an integral part of today's energy system, with households slowly taking on a more proactive role in adopting cutting-edge technologies. This study surveyed Luxembourgish households to characterize early adopters of smart energy technology. The findings show a strong positive correlation among technology awareness, adoption, energy literacy, and some household characteristics. Nevertheless, technology awareness is relatively low, highlighting the need for energy education and increased visibility of smart energy products to encourage adoption.

Introduction

The ongoing renewable energy transition heavily relies on supporting policies and technological innovations. The rapid evolution of technology has positioned digitalization as a crucial factor in ensuring the success of this transition (Veskioja et al., 2022; Xu et al., 2022). Countries like Germany, France, the U.S., and Luxembourg have actively promoted digital technologies due to their numerous social benefits, including increased energy efficiency (Lange et al., 2020; Lin & Huang, 2023), a higher flexibility potential (Baidya et al., 2021; Li et al., 2023), and improved information sharing (Stermieri et al., 2023).

While the potential social benefits of a digitalized energy market are significant, several challenges remain to be solved to fully realize this potential. One key challenge is the uneven adoption of new technologies, which risks exacerbating existing socioeconomic inequalities.[1] The rate of household-level technology adoption is particularly inconsistent. This highlights the need to identify and learn from early adopters to catalyze broader acceptance across the population.

This paper surveys Luxembourgish households to shed light on the demographic profile of early smart technology adopters and suggests possible next steps towards a more widespread adoption.

Context

Luxembourg is undergoing an ambitious digitalization strategy that began with the replacement of all traditional electricity and gas meters with smart meters (European Commission, 2019; Government of the Grand Duchy of Luxembourg, 2020). By 2021, Luxembourg had equipped 95% of its households with smart meters (ACER, 2022), enabling customers to access detailed information about their energy consumption and costs. In addition, in 2021, the main distribution system operator (DSO), Creos, launched Smarty+, a new digital technology and the focus of this study. The Smarty+ dongle, costing 40€, provides households with detailed real-time insights into their energy data.

When the Smarty+ dongle is connected to the smart meter, households can consult their energy data in real time via the Smarty+ application on a tablet or smartphone. Additionally, they have the option to share their data with Creos, contributing to enhanced management of electricity distribution grids and supporting the energy transition. To date, around 1500 households have adopted the Smarty+ device. However, despite the initial campaign's goal of widespread adoption, little is known about the demographics of the actual adopters, making it difficult to assess the campaign's success and determine future strategies for increasing technology uptake. To address these challenges, this paper performs a household-level survey targeting a sample of the Luxembourgish population.

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Survey Design

The survey analyzed in this paper is part of the data collection for FlexBeAn, which aims to study the energy flexibility potential in Luxembourg. Specifically, the survey focuses on the relations between personal characteristics and the intention to provide flexibility with different appliances in households.

The survey was conducted online through three distinct channels: an email outreach to Creos customers, social media platforms, and the personal networks of Creos employees. The email outreach targeted 3,959 customers who requested a power connection upgrade, such as for installing an EV charger or solar panels at their home. To broaden participation, a social media campaign promoted the survey on X and LinkedIn. Additionally, Creos encouraged its employees and their families to participate in the survey.

A total of 544 respondents completed the survey, with 472 from the email campaign, 57 from social media, and 14 from Creos internal campaign. After reviewing the responses, 461 surveys were deemed valid for analysis (395 from the email campaign, 52 for the social media campaign, 14 from Creos internal campaign).

Table 1 summarizes the main characteristics studied in this paper. The variable Smarty+ Adoption only considers households that are familiar with the device. Among those households, approximately 42% have adopted it. However, nearly half of the sample is unaware of this new technology, highlighting a significant gap in awareness. Approximately 88% of the households report a net household income above 5,000€ a month. The majority of participants are homeowners, and a substantial portion owns electric vehicles (49%) and solar panels (43%).

Energy literacy measures the understanding of the nature and role of energy in the world and daily lives accompanied by the ability to apply this understanding to answer questions and solve problems (U.S. Department of Energy, 2017). To assess energy literacy, we developed an index based on a comprehensive review of existing literature and incorporated questions from widely used energy literacy surveys. This index evaluates respondents' general knowledge related to energy consumption, generation, and transmission. Scores range from 1 to 13, with higher scores indicating greater energy literacy.

Table 1: Summary Statistics

Variable	Mean	Obs.
Smarty+ Adoption	41.8%	232
Unaware	49.7%	461
Income > 5,000	87.5%	368
Age	48	461
Has Bachelor's Degree or Higher	65.2%	461
Home Owner	92.8%	461
Electric Vehicle	49.2%	461
Solar Panels	43.1%	461
Home Members	2.5	456
Detached Home	46.6%	461
Energy Literacy	7.7	461

Notes: energy literacy represents the average score from 1 to 13. Income is presented in net household income per month.

To mitigate response bias, participants were assured of the anonymity of their answers and test scores (Podsakoff et al., 2003). This anonymity helped encourage honest and uninfluenced responses.

It is important to note that the population sample primarily consists of customers who requested an upgrade of their power connection from Creos. As a result, caution is warranted when generalizing these findings to the broader population.

The Early Adopters

The correlation analysis, illustrated in Figure 1, shows distinct characteristics of early adopters of the Smarty+ device. These adopters are typically older homeowners with higher incomes, residing in detached houses. The analysis also indicates a higher adoption rate among households that own electric vehicles and solar panels, likely because these households perceive greater benefits from using the Smarty+ device. Furthermore, there is a positive correlation between the number of household members and the likelihood of adopting the technology, suggesting that larger households might find the real-time energy insights more valuable for managing their consumption effectively.

Exploring the Awareness Gap

A surprising finding from our survey is that about half of the households reported being unaware of the Smarty+ device (which differs from households that are aware but decide not to adopt it). This low awareness raises several questions, such as whether marketing campaigns where ineffective or if the unaware households were not initially part of the target group. To explore these questions, Figure 2 highlights the main characteristics of households that are unaware of Smarty+.

On average, unaware households present slightly lower levels of income and education. Younger respondents and women show lower awareness rates compared to their counterparts. Additionally, larger families living in detached homes are less likely to be unaware of the technology. Finally, households that own electric vehicles and solar panels are generally more knowledgeable about the new technology, likely because they are more engaged with advanced energy technologies.

The Role of Energy Literacy

Figure 3 illustrates the correlation among the energy literacy score, SMARTY+ adoption, and unawareness. Among households familiar with Smarty+, higher energy literacy scores are linked to a greater adoption rate of the technology. Additionally, comparing households familiar with Smarty+ to those unaware of it reveals that higher energy literacy scores correspond to increased awareness of this digital innovation. These results suggest a new venue for policymakers and private companies to boost the adoption of these new digital technologies.

Figure 1: Early Adopters of Smarty+

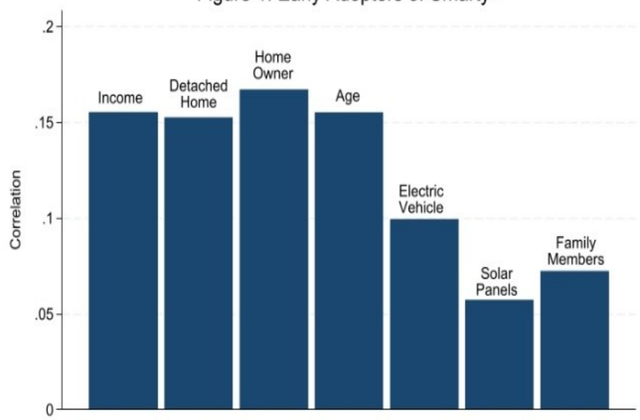


Figure 2: Technology Awareness

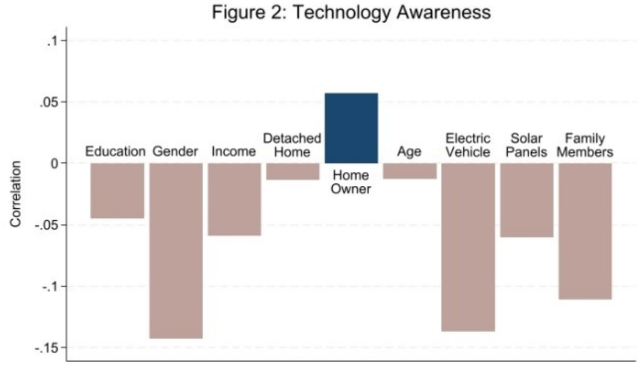
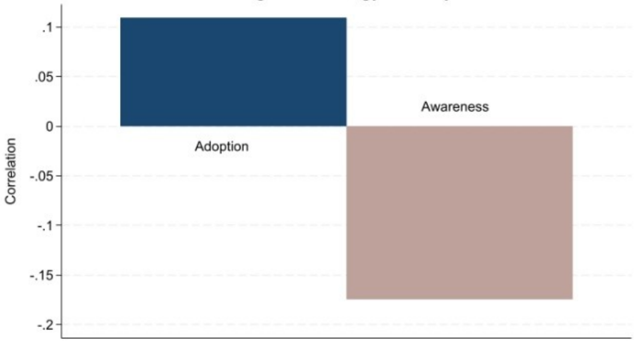


Figure 3: Energy Literacy



Discussion and Implications

The results suggest that relatively wealthier and larger households, particularly those with electric vehicles and solar panels who own their homes, are more inclined to adopt Smarty+. Intuitively, these characteristics increase the potential benefits obtained by a digital technology that allows to optimize consumption patterns. However, these findings also highlight a concerning trend: less wealthy households might be falling behind in profiting from technological advancements. To be able to harvest the full social benefits of such technology, targeted policies should be put in place to mitigate possible undesirable distributional effects. For instance, offering a subsidized version of the Smarty+ dongle may boost adoption rates among lower-income households.

Additionally, this study reveals that technological awareness is low, with only around half of the sample being familiar with Smarty+. This is particularly relevant as awareness serves as the initial step for households to consider adopting new technologies. Moreover, the data reveals that the lack of awareness is disproportionately concentrated among relatively less wealthy and educated households, exacerbating the potential undesirable distributional effects mentioned earlier. Therefore, increasing the visibility of emerging digital technologies like Smarty+ should be a central focus for policymakers and private firms alike. By implementing targeted awareness campaigns and educational initiatives, stakeholders can ensure that all households have equitable access to information about these technologies, thereby fostering more inclusive and sustainable adoption patterns.

Another important factor influencing adoption decisions and technology awareness is energy literacy. The results show a strong positive correlation among these variables, highlighting the importance of energy education in the successful widespread adoption of digital technologies. Intuitively, more energy literate households are more likely to be more aware of the potential benefits of new technologies, increasing the likelihood of adoption. In addition, energy literate households may be inclined to actively seek out innovative ways to save money and contribute to environmental sustainability, enhancing their awareness of digital tools like Smarty+. Consequently, regulators, policymakers, and private companies may find value in investing in energy education as an additional mechanism to promote the adoption of new digital technologies.

Conclusion and Future Research

Digitalization has become an integral part of today's energy system, with households slowly taking on a more proactive role in adopting cutting-edge technologies. This paper provides a first glimpse at the profile of early adopters of a new digital energy technology in Luxembourg. Additionally, the paper presents new insights on the widespread low awareness of this type of technology and the role of energy literacy. However, some limitations need to be acknowledged.

Firstly, the survey sample may not be fully representative of the Luxembourgish population, potentially limiting the generalizability of the findings. Future research should include a bigger, more representative sample to be able to draw conclusions at the country level. Nevertheless, we anticipate that the results will be robust to a bigger sample size.

Secondly, while this paper considers key demographic characteristics, other factors may influence technology adoption and awareness, such as peer and network effects. Future research could expand on our work by exploring additional relevant factors in greater detail.

Finally, while the results are expected to be robust across developed countries, they may vary in developing country contexts or regions with differing levels of technological penetration (e.g., lower adoption of smart meters). It is anticipated that some factors like income and energy literacy will have an even more prominent role, while others like house ownership, might become less relevant. Consequently, replicating this study in different contexts to test its robustness could be explored in future research.

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For the purpose of open access, and in fulfillment of the obligations arising from the grant agreement, the author has applied a Creative Commons Attribution 4.0 International (CC BY 4.0) license to any Author Accepted Manuscript version arising from this submission.

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Footnotes

[1] See (Castaneda et al., 2017) for an overview of increased socioeconomic inequalities due to solar PV adoption (i.e., the death spiral).

Challenges of Digit(al)ization to Energy Policy: A Role for Big Data Analytics

BY TIMOTHY C. COBURN AND RONALD D. RIPPLE

Abstract

This essay discusses challenges facing energy policy makers in the Big Data analytics era, including how best to promote new approaches to energy delivery arising from the industry's embrace of digitalization, and how to reconcile differences in resource reporting arising from disparate rates of digitization and inconsistent data handling.

Introduction

The transition to greater digitization and reliance on Big Data analytics across the global energy landscape has led to a range of policy challenges, particularly with regard to the regularization of data access and availability, data quality, information alignment, and uncertainty reduction. Various options exist to address these situations and to inform policy makers of the role Big Data analytics may play.

Big Data analytics rely on large volumes of data, and the ownership of the available data is, and will continue to be, a further situation requiring resolution (Chase and Berzina 2018). It has been suggested that, at least in the energy space, the data may actually become more valuable than the electricity, oil, or other energy resources being produced and sold (Toonders 2014; The Economist 2017, Bhageshpur 2019, Sadowski 2019, Tiwari 2019). How data ownership, security, quality, and privacy should be formalized or regulated to facilitate inter-economy collaboration are additional policy issues that must be addressed. However, given different approaches to legal ownership and access to data among companies and countries, there will likely not be a one-size-fits-all policy prescription that can be relied upon. Furthermore, consistent access to data—particularly data that are equivalent—will also be required in order for policy makers to both understand what is being done across the energy sector and to better analyze markets to provide stronger foundations for policy prescriptions (U.N. 2018).

This brief exposé identifies some of the energy data and digitization challenges encountered across the globe and suggests policy initiatives that can be used to resolve barriers to data sharing that result from a lack of standardized analytical and management approaches. It also addresses some of the terminology disparities that energy policy actors must navigate, and it describes the role of Big Data analytics in making future evidence-based policy decisions for the energy industry.

Digitization, Digitalization, and Digital Transformation

As is the case in most disciplines, the terms digitization and digitalization are often used interchangeably in conversations about energy policy and economics. However, they actually have very different meanings. Digitization is essentially the conversion of data and information that exists in analog (e.g., paper) files to digital (electronic) format; i.e., bits and bytes that can be interpreted, and acted upon, by computers. Digitalization, on the other hand, is the process of using digitized data and information to simplify established workflows and/or make them more efficient. In this sense, digitalization facilitates the migration of established systems and processes from a human orientation to one that is software-driven. Kahn et al. (2015) discuss the impact of digitization on economies and economic activity, while Brennen and Kreiss (2016) note that digitalization also pertains to the way in which social domains are restructured around digital communication and media.

While digitalization does not actually result in a changed workflow – just a more efficient one – digital transformation uses digitalization and digitized data to alter the way organizations and political jurisdictions conduct their activities, encouraging them to reconsider or reimagine the ways that things get done. At its core, digital transformation is the integration of digital technologies into all aspects of the entity's activities. Various authors have addressed the concept of a digital economy as an outgrowth of digital transformation (Deloitte n.d., OECD 2014; Ahmad and Mokal 2023).

Digitalization is rapidly transforming the delivery of energy and the deployment of energy technologies around the world. Both the International Energy Agency (IEA 2023) and the European Union (European

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Commission 2024) describe the impact of digitalization on all sectors of the energy economy, as well as their policies to further advance the energy transition through digitalization. Nazari and Musilek (2023) review the overall impact of digitalization on energy, and Jaffe (2021), in particular, makes the case that the digitalization of energy is a primary mechanism with which to harness innovation and promote resilience and national security in the United States.

Big Data and Big Data Analytics

Digitization is the movement and activity that gives rise to Big Data. While there are many definitions, forms, and dimensions of Big Data, it is essentially the largest, or most complex, compilation of information that cannot be managed or processed using more-traditional data management principles and techniques. Admittedly though, what is "big" to one group or entity may not be "big" to others. Perhaps better described as an information ecosystem consisting of elements extracted from disparate sources, the concept and reality of Big Data has emerged due to (1) the rapid growth of information storage capacity and computing power, (2) an ever-expanding number of artifacts delivered through social media, telecommunications, and Internet streaming, and (3) the rise of physical data capture devices and advanced instrumentation (e.g., sensors, quick response (QR) codes, radio frequency identification (RFID), supervisory control and data acquisition (SCADA) systems, and other "smart" tracking/recording devices). This change in the way that data and information present themselves has come to be known as the variety-volume-velocity data paradigm (Lee 2020).

The rise of Big Data has become nowhere more apparent than in the energy industry. The value and importance of Big Data has spawned an ever-expanding and always-enlightening conversation across all segments of the industry (Feblowitz 2012, Ferguson and Catterson 2014, Schuelke-Leech et al. 2015, Akhavan-Hejazi and Mohsenian-Rad 2018, Shobol et al. 2019, Kozman et al. 2024). Perhaps first championed in upstream oil and gas, it is now embraced all across the energy landscape; from wind, solar, biomass, and geothermal energy in the renewables space, to coal mining and coalbed methane extraction, carbon capture-utilization-sequestration, refining, production and transportation of liquefied natural gas (LNG), smart grids, battery storage, and beyond.

Though sometimes conflated with Big Data, Big Data analytics is the discovery, interpretation, and communication of meaningful patterns and trends within these large data sets. However, as some have said, it is not really about more data … it is about a deeper look which the increasing variety and volume of data facilitates. Big Data analytics may involve well-known statistical or computational tools, or, because of the complexity of the information, it may involve the application of newer generation computing architectures and algorithms more commonly associated with artificial intelligence (AI) and machine learning (ML). However, the technical aspects of Big Data analytics are not all that new, much of the computational theory having been known for some time. It is the application of such tools to larger and more-complex data sets that can yield insights not extractable from small sample data scenarios.

Policy Challenges

Virtually all sectors of the energy industry are fully pursuing digitalization and employing Big Data analytics to improve operations (Eissa 2020, Mohammadpoor and Torabi 2020, Bist et al. 2021, Asthana et al. 2022, Turetskyy 2022, Patel et al. 2020, Thomas et al. 2023). This transformation presents new and evolving policy challenges. The challenges have to do not only with advancing the ways in which energy gets delivered, but also with the manner in which the data themselves concerning energy resources and delivery get synthesized and reported. An important aspect of the digitization challenge is that the rate of digitization varies across different sectors of the energy industry, as well as in different countries, around the world. Further, data differences, particularly with regard to aggregation and the processing of unstructured data, frequently present policy makers with difficult choices as they try to reconcile data sets and sources to construct meaningful comparisons. The same or similar data may not be collected, values may be obtained from sources about which uncertainty persists, some data may be combined whereas others are not, and the combination approaches or weightings may not be the same. This is not a new situation, but it is one that is exacerbated by the variety and volume of data employed. Finally, the various algorithms associated with Big Data analytics do not produce unique solutions. Unless the exact same data set is used and the exact same algorithm is applied, the resulting predicted values are guaranteed to be different and/or to be more uncertain. This non-uniqueness of solutions makes the development of energy policy across sectors and/or political jurisdictions a very difficult proposition.

Finally, energy policy makers and economists have heretofore largely relied on the scientific method to produce estimates and projections, an approach that for decades has depended on the theory surrounding traditional small-sample statistics that is probabilistic in nature. However, with the advent of Big Data and Big Data analytics, there is very little reason to rely on t-tests, F-tests, and the like, since the availability of Big Data essentially implies that the entire population is known (Anderson 2008, Kitchen 2014). Big Data analytics, data mining, artificial intelligence, and machine learning are purely data-driven ventures that rarely rely on theory, allowing the data themselves to tell a story apart from more-conventional probabilistic statements.

The challenge for all economies, then, is two-fold. First, private and public sector players across all energy sectors are already adopting Big Data analytics – but perhaps in different ways – to improve their bottom lines and efficiency of operations; so, policy makers and regulators will need to understand how this shift may affect their decisions. Second, the same policy makers and regulators may well find that the adoption of Big Data analytics in their own workflows enhances their specific decision-making processes. A change in emphasis of this nature could improve the fact-based decisions that will allow policy makers to more effectively, and efficiently, meet domestic and international aspirations, such as those presented in Sustainable Development Goal 7 (SDG7) (U.N. 2023).

Proposed Actions

Harmonizing the quality and flow of energy data, incorporating improved transparency and more consistent and rapid accessibility, are needed in order to take full advantage of the power and benefits of Big Data analytics and digitization in the energy policy arena. At a minimum, this requires development of a full understanding of the current focus on Big Data and digitization across all energy sectors within all economies. To establish this baseline knowledge, the United Nations (U.N.) or similar high-level organization should initiate, coordinate, and fund one or more information-gathering fora, with the goal of publishing a database and report summarizing various approaches over the next two to five years. Academic institutions, government agencies, and national research organizations/laboratories can help. Such information can be critical to the decision-making efforts of the private sector involved in creating the energy capacity growth that will support global economic development. An initiative of this nature would also help enhance and standardize in-house governmental capabilities in digitization techniques and Big Data analytics sufficient to properly interpret the information being developed by the private sector and presented to government policy makers. This effort would ultimately lead to more effective government decision-making regarding the allocation and development of energy capacity and resources, as well as a more efficient global energy system.

Conclusion

The energy digitization transition is already occurring around the world, reaching into the energy sectors of each and every country. As such, each country is, and will continue to be, faced with the challenges of addressing the issues raised by digitization and how these may affect economic development. In addition, digitization will likely influence the paths each country takes to meet SDG7 goals of "ensuring access to affordable, reliable, sustainable and modern energy for all." Finally, digitization particularly impacts resource estimation, data synthesis, and reporting. Without some degree of consistency and standardization, along with a commitment to data quality and equivalency, the ability to formulate and sustain coherent energy policy may be elusive for the foreseeable future.

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Economics of Data Interoperability in a Data-driven Energy Sector

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ABSTRACT

A market-based energy transition requires active customers, which means they offer their energy flexibility through data-driven services. Implementing these services requires data interoperability standards and processes, and single common front doors. In economic terms, data interoperability lowers the barriers to participate in those services and improves their liquidity and efficiency.

1. Introduction

In the past decade, the massive connection of Renewable Energy Sources (RES) has changed the characteristics of the generation mix, which has become more random, variable and highly correlated with weather conditions, e.g., sun or wind, varying at fine geospatial levels (ESMAP 2020, Davies et al. 2023, Zardo et al. 2022). Inevitably, traditional rigid consumption profiles must become flexible to adapt their consumption to the available RES production at each time. In this regard, hourly electricity markets play a key role when allocating RES generation and consumption schedules, and two opposite outcomes are seen in countries with high volumes of RES: electricity prices become negative when there is a surplus of RES, or electricity prices peak when there is a deficit of RES production and costly pollutant technologies must be called on.

Customers must adapt their consumption profiles and become flexible through implicit flexibility which is expressed by their reaction to price signals. This form of flexibility opens the door to implementing Time of Use (ToU) tariffs, differentiated by hours, days of the week or seasons. However, this is not straightforward and requires the massive installation of smart meters that are able to record hourly consumption of energy in households. This transforms the role of the different stakeholders in the power system, enables frequent data exchanges and communications between them and adds to the complexity of interactions between the different agents. Figure 1 provides an overview of this transformation and contrasts the corresponding data flows in power systems with passive consumers vs. emerging systems with active consumers equipped with smart meters.

As is shown in Case A of Figure 1, prior to the deployment of smart meters, customers had mechanical meters that recorded the accumulated monthly (or bimonthly) electricity consumption, and the possibility of differentiating the time of consumption was limited, at best, to peak and off-peak periods. In Case B, the possibility to record hourly consumption of energy opens the door to implement hourly electricity prices, which has the potential to transform passive customers into active customers, while enabling the suppliers to offer complex dynamic price schedules. These might play a clear role in incentivizing consumption in some hours over others, which increases efficiency and RES integration. However, the possibility of introducing new dynamic pricing strategies will necessarily also impact on the competitive nature of the markets. The net effect of such an impact needs to be carefully considered by considering how static efficiency, i.e., better matching dynamically changing demand and supply, and dynamic market efficiency, that includes the impact on contestability, entry conditions, market power and the speed of innovations, are affected.

The transformation of the energy system made by smart meters goes beyond the implementation of hourly economic incentives to customers. Smart meters have the potential of transitioning the traditional energy sector into a data-driven energy sector. Energy data becomes the core of many system operator processes and new roles such as metered operator, metered data administrator or data access provider, among others, are created (European Commission, 2023a). In this new scenario, the interaction between customers and system operators grows. As defined in the European Commission (2019), smart meters should

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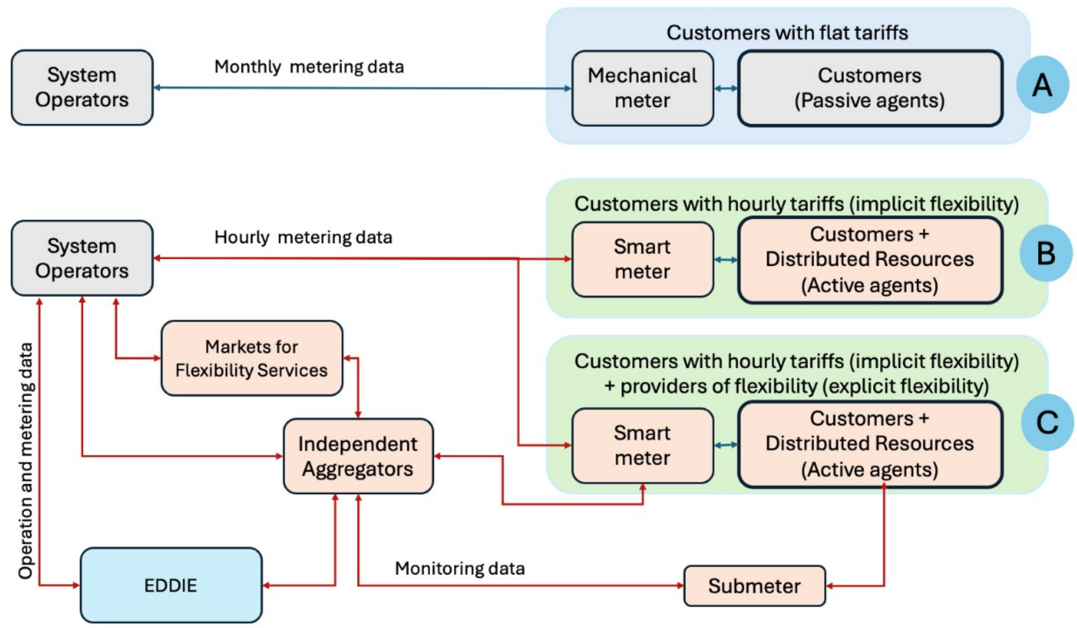

Figure 1. Data flows in the power system: Case A represents the system before implementation of smart meters, Case B represents the current system with smart meters, and Case C represents the future system with providers of flexibility and data exchanges with other sectors through EDDIE platform as described in section 2. Note: black arrows correspond to past data flows, red arrows represent data flows in the new paradigm.

also provide real-time data to the customers to allow them to react to the real-time price signals.

2. Economic considerations

Poletti, (2022) from Octopus, a key European supplier, has defined this transition as an historic shift, that moves from the traditional Demand Side Response (DSR), to one of Intelligent Demand. Indeed, historically, energy systems always focused on adjusting energy supply to meet the demand. For instance, DSR was incorporated into the 2005 Energy Policy Act in the United States. In the United Kingdom, the *Economy 7* tariff, utilizing base-load generation to offer cost-effective electricity during off-peak hours, commenced in October 1978 (Hamidi et al., 2009). Moreover, since the 1950s, New Zealand and South Africa have been managing peaks in electricity demand using 'ripple control', first introduced in France, back in 1927 (Poletti, 2022). This method widely used already by 1948 (Ross, and Smith, R., 1948), worked by transmitting a high-frequency signal (ripple) at the substation with the standard 50 Hz power supply over the existing power lines while also having specific receivers installed at the consumer's premises detecting the ripple control signals to activate or deactivate connected devices accordingly (Kwon, 2009). Ripple control helped in grid load management by turning on or off water heaters or streetlights, during peak and off-peak hours balancing the load and preventing grid overloads. It was contextually beneficial for consumers with different electricity tariffs for different times of the day, as it could be used to switch devices to operate during cheaper tariff periods, optimizing energy costs. As a result, Ripple control could be used to support demand response programs where consumers reduce their electricity usage during peak demand periods in response to signals sent by the utility company (Poletti, 2022).

However, DSR techniques arose from the need to optimize a system based on coal fueled and nuclear power plants, matching electricity usage based on systems that could be anticipated with little uncertainty. As the energy system incorporates intermittent RES in the power grid, Poletti (2022) advocated replacing traditional DSR with the data-based energy management concept of 'Intelligent Demand.' This becomes essential, since, not only integrating RES supplies have an intermittent nature, but also the demand for electricity is changing drastically. For instance, the diffusion of Electric Vehicle (EV) home chargers and heat pumps, all necessary tools towards net zero, due to their intermittent timings, could add to the traditional 1kW household demand winter peak an additional 9-12kW load.

An example of "Intelligent demand strategy" is shown in Figure 2, superimposing wholesale electricity prices (grey bars) with "Intelligent Octopus Charging" (red line), between 30th of December 2021 and the 2nd of January 2022, whereby the key (intelligence) element is shown in the almost perfectly symmetric dynamics between the two curves, whereby any decrease in wholesale electricity prices (in p/kWh) is matched with an increase in *Intelligent Octopus Charging* (in MW). Even more interestingly, the spiking of charging in response to negative wholesale electricity prices when wholesale prices go down, can be matched to the instances when *Intelligent Octopus* tariffs send a command to the EVs to start charging.

The interaction between intermittent supply and intermittent demands is what allows data-driven systems

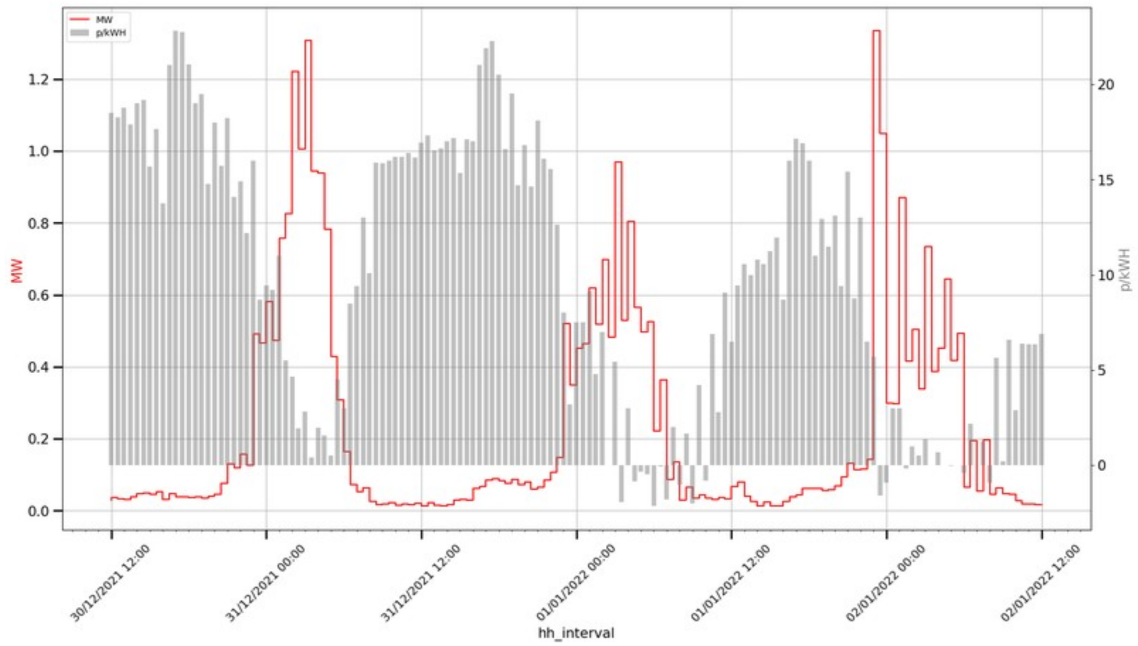

Figure 2 Intelligent Demand and wholesale energy prices with "Intelligent Octopus"
Source: Poletti, (2022) https://octoenergy-production-media.s3.amazonaws.com/images/fig2021-12-30.width-800.png.

and algorithms to achieve the necessary efficiency. However, as these key economic components of demand and supply are transformed, price signals also move to reflect these changes. In this case, it becomes unavoidable to address the potential economic consequences of these new intelligent tariffs that are transforming what economists call market fundamentals. Moreover, in non-monopolistic markets, the strategic implications of these dynamic pricing strategies will also shape the resulting competitive dynamics, market prices, demand and efficiencies in the short term and, in the longer term, innovation rates.

Finally, users might have different cognitive abilities and willingness to invest their time in understanding and comparing alternative complex intelligent tariffs. These differences might be related to socio-demographic factors, or to the level and composition of energy consumption of a household, depending, for example, on whether the household has a home charger, an EV or a heat pump. Each retailer might then find an incentive in using *intelligent* dynamic pricing tariffs, as strategic devices, possibly to soften competition, or discourage entry, due to the potential increase these tariffs might induce on the asymmetry in the switching costs among consumers (Giovannetti and Siciliani, 2023). Hence, it is important to consider the concerns that such tariffs, while necessary in incentivizing intelligent demand, might not be used to segment an incumber retailer's customers, based on their differentiated willingness to switch between intelligent and more rigid tariffs, either within those on offer by the same retailer, or between those offered by competing ones.

3. Operational Considerations

The impacts of RES go beyond the hourly electricity prices and affects the operation of the power system. Grids have limited capacity and grid constraints (congestions or operational constraints) might occur more frequently in highly decarbonized power systems, especially at the distribution grids where many RES and most of the Distributed Resources are connected. These Distributed Resources include in-home devices (electric boilers or heating devices), small generators behind the meter, storage devices or EVs and their charging points. However, the same Distributed Resources can and should be part of the solution for grid constraints as they evolve into active Flexible Resources that respond to the needs of System Operators through the new data-driven services such as flexibility services.

In this model, independent aggregators pool a group of Flexible Resources and offer to the new markets for flexibility services the possibility to modify the consumption or generation patterns of Distributed Resources on request of System Operators to solve their grid constraints. The implementation of this new paradigm requires establishing new data exchange processes between all the involved parties as is shown in Figure 1 (case C). First, System Operators use energy operation data to forecast and anticipate in-advance grid constraints to be later solved by Flexible Resources. This also includes sharing energy operational data from other System Operators to coordinate. Second, Independent Aggregators use energy data from Flexible Resources collected through submeters to assess its potential flexibility to be offered to System Operators. In the European Reform of the Electricity Market Design, submeters are also known as dedicated measurement devices (DMD). Third, System Operators send operational setpoints to the Independent Aggregator to request the activation of its Flexible Resources. Independent Aggregators also implement cross-sectorial data exchanges (e.g., electricity, gas, transportation or heat, among others) as there are many links between energy sectors and electricity flows can be modified through changes in other sectors. In the data exchange processes, submeters play a key role. They are additional smart meters used to monitor energy flows of individual Flexible Resources, which are also needed to validate the activation of Flexible Resources by Independent Aggregators or System Operators (Chaves-Avila et al., 2024).

In all these processes, the need to set data interoperability requirements between system operators, metering administrators, customers and manufacturers of their home devices become relevant. As defined in European Commission (2019), interoperability means the "ability of two or more energy or communication networks, systems, devices, applications or components to interwork to exchange and use information to perform required functions". The same Directive sets the need to further develop "interoperability requirements and non-discriminatory and transparent procedures for access to metering data, consumption data, as well as data required for customer switching, demand response and other services."

The definition of the data interoperability provisions for the red data arrows in the Case C (Figure 1) have relevant economic implications on the performance of markets for the new data-driven services: a lack of interoperability in the data exchanges might require a manual data processing or implementing additional costly software and hardware solutions Thus, data interoperability requirements set the entrance costs to participate in these markets and the economically feasible minimum bid unit to recover all the operating costs associated to the data communication flows. This data interoperability also includes the home devices that should react to the request of the aggregators, i.e., manufacturers must include data interoperability solutions to their devices.

In consequence, interoperability requirements constraint the number of potential participants in these markets, which in turn impacts the liquidity that sets the efficient performance of new data-driven flexibility markets. Thus, power system costs are reduced, and consumer surplus is maximized. However, such requirements might also open new channels for leveraging market power and information rent between data and energy platforms.

4. A European Distributed Data Infrastructure for Energy (EDDIE)

A complementary solution to improve data interoperability is setting national common-front doors, where Independent Aggregators can access all the energy data with a single communication link and regardless of who generates this hourly data. In this context, the European EDDIE (European Distributed Data Infrastructure for Energy) introduces a decentralized, distributed, open-source Data Space as these challenges have broad implications on an industrial, economic, and social level in Europe and beyond.[1]

Solutions tested in EDDIE also open the discussion about the adoption of centralized, decentralized or hybrid data architecture. Centralized corresponds to a single data platform that hosts all the information, while a decentralized corresponds to a group of platforms interconnected between them with a common front door as defined in EDDIE. In the middle, hybrid architecture corresponds to a combination of centralized and decentralized solutions. The adoption of an architecture model also has relevant economic implications. Decentralized solutions can make better use of existing data platforms and reduce their implementation time and cost, accelerating the implementation of flexibility services. However, this requires data interoperability requirements between them, as well as a common front door to access all the data. Centralized solutions can be more feasible solutions when any energy data platform is implemented from scratch. Additionally, their implementation costs might be higher than decentralized solutions.

Potential economic benefits of data interoperability go beyond the processes related to energy consumption and flexibility services. Recently approved European Data Act aims for a fair and innovative data economy based on the sharing of data of multiple connected objects or the Internet of Things (European Commission, 2023b). Data Act seeks to harmonise the access and use of data across Europe, which includes the development of interoperability standards for data-sharing and for data processing services. In economic terms, the European Commission estimates that 80% of the industrial data is not currently exploited and could create an additional GDP of EUR 270 billion by 2028 and increase competitivity.[2] Data interoperability also overcomes potential vendor lock-in or switching between data processing services, which means removing barriers to entry and exit, main characteristics of markets in perfect competition. Information asymmetry is another shortcoming that will be significantly mitigated by making data interoperable between different sectors. It will facilitate the emergence of new cross-sectoral innovative data-driven solutions (European Commission, 2020). For instance, facilitating seamless data exchanges between the mobility and the energy sectors removes entry barriers, streamlines access to information and, leads to optimized usage of EVs while increasing competition and lowering costs for consumers/users in both sectors. For manufacturers of home devices, data interoperability requirements are essential to enable third parties (beyond the manufacturers) to activate these devices. Otherwise, independent aggregators must install additional costly communication solutions.

Finally, defining data interoperability standards is critical and might become inefficient when incumbents lobby to impose their interoperability standards on the rest. This would provide a competitive advantage for the incumbent over the rest and would create entry barriers for some providers, limiting the number of providers. Thus, ending with markets in non-perfect competition.

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Footnotes

[1] https://eddie.energy

[2] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1113

Digital Transformation of the Oil and Gas Sector Towards Decarbonizing the Energy System for Net Zero Emissions in the Gulf Region: Trends, Applications, Challenges and Enablers

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Abstract

This article explores digital transformation in the oil and gas sector within the context of the Gulf countries. It highlights the latest trends in Industry 4.0 technologies, along with other advances related to renewable energy, alternative fuels, carbon removal, methane abatement and flaring control. The article highlights the transformative abilities of these technologies in revolutionizing oil and gas operations and sculpting the forthcoming narrative of the Gulf region and beyond. The discussion also delves into the opportunities, applications, and real-world use cases highlighting how technologies are driving the clean energy transition. The challenges in transforming the sector are then examined, followed by recommendations of critical success factors as enablers for governments and national oil companies to decarbonize the energy system in the region in pursuit of accelerating the realization of the net zero emissions agenda.

1. The Net Zero Emissions Agenda

In 2016, the historic Paris Agreement adopted at COP21, was enacted with the main goal of combating climate change and accelerating the global response to its threats. The Paris treaty brought together 195 nations in a collective effort to limit global warming to < 2°C above pre-industrial levels, with an aspiration to further limit the increase to 1.5°C. To remain within the latter limit, global carbon dioxide (CO_2) emissions must be reduced by an estimated 45% by 2030 (relative to 2010 levels) and eventually reach net zero emissions (NZE) by 2050 [1]. NZE refers to a state where the amount of greenhouse gases (GHG) released into the atmosphere is balanced by an equivalent amount removed, effectively reducing the net impact on the climate to zero. Currently, a total of 148 countries pledged to achieve NZE with the majority targeting mid-century [2], necessitating an extensive transformation across various sectors of the energy system including power, buildings, transport, industry and agriculture. Hard-to-abate sectors have a vital role in meeting the Paris goals, and are particularly challenging to decarbonize due to their high energy intensity, reliance on fossil fuels, and limited availability of practical low-carbon alternatives or proven technologies [3]. Specifically, the clean energy transition implies the restructuring of production processes on the supply side of the energy system which are responsible for the bulk of emissions. As the backbone of the global energy landscape and the main source of primary energy, the oil and gas (O&G) sector is a major source of GHG emissions from combustion processes and methane leaks during extraction, processing, and transportation for final use. Today, O&G operations are responsible for around 15% of total energy-related emissions globally, the equivalent of 5.1 billion tonnes of GHG [4].

2. The Case of the Gulf Countries

The Gulf[1] is the historic heartland of the global O&G sector as it holds almost half of the world's proven hydrocarbon reserves [5] and, in 2022, it produced nearly one-third of the world's oil [6], making the region a critical hub for global energy supplies. The Gulf countries, shown in Figure 1, contribute ~5.2% of global energy-related CO_2 emissions mainly from the burning of fossil fuels for power generation, with natural gas accounting for 56.4%, oil 42.6% and coal 1% [7]. Figure 2 illustrates the proven O&G reserves over the past two decades in this region compared to the rest of the world. Saudi Arabia holds the largest proven oil reserves, accounting for an average annual of 264.12 billion barrels, with the giant Ghawar Field being the world's most productive. Following that, Iran and Iraq, with annual oil reserves averaging 138.27 and 127.75 billion barrels respectively, play crucial roles in the region's energy dynamics despite geopolitical challenges. Kuwait and the United Arab Emirates (UAE) also boast substantial oil reserves contributing to their economies with averages of 100.47 and 97.8 billion barrels per year, respectively. Qatar, although smaller in oil reserves with an average of 20.09 billion barrels per year, is a leading global exporter of liquefied natural gas (LNG). Oman and Bahrain, while possessing smaller reserves compared to their neighbors with annual oil reserves of 5.41 and 0.13 billion barrels respectively, are essential players in regional energy markets. When considering natural gas reserves, Iran leads with an annual average of 1046.42 tcf, followed by Qatar with 799.25. Saudi Arabia and the UAE with significant reserves as well averaging an annual 267.55 and 214.69 tcf, respectively. Iraq holds 115.02 tcf, while Kuwait at 59.62 tcf, Oman 27.47 tcf and Bahrain 3.63 tcf.

Collectively, these countries hold a substantial portion of the world's O&G resources, heavily influencing global energy market and policies. Noteworthy, the O&G sector is characterized by a value chain segmented into upstream, midstream, and downstream operations. Each segment plays a critical role in ensur-

Figure 1: Geographical boundaries of the Gulf countries (Source: Data from Net Zero Tracker [2]).

ing the efficient extraction, transportation, and conversion of O&G into usable products, considering the following main operations and corresponding sub-operations:

Upstream – (1) **Discovery/Exploration:** This initial phase involves seismic surveys, gravity and magnetic surveys, and exploration drilling to locate potential O&G reserves. (2) **Field Development/Drilling:** Once a viable reserve is identified, development drilling begins which includes onshore and offshore drilling and vertical and horizontal drilling, utilizing various rigs such as land-based rigs, offshore rigs, and subsea rigs. (3) **Production/Extraction:** The extraction process begins with primary extraction using the reservoir's inherent pressure, followed by secondary methods like water or gas injection, and tertiary retrieval such as steam injection to maximize recovery.

Midstream – (4) **Processing:** Processing plants and refineries treat and refine O&G to prepare them for further processing. (5) **Transportation:** The transportation of O&G is primarily conducted through pipelines (the most common method), tankers for water transport, and/or trucks for short-distance land transport. (6) **Storage and Trading:** The processed O&G is stored in facilities like tank farms, underground storage, and/or trading hubs where these resources are bought and sold through distribution terminals.

Downstream – (7) **Conversion/Refining/Manufacturing:** O&G are refined into finished products such as gasoline, diesel, jet fuel, petrochemicals, and lubricants. (8) **Sales and Marketing:** Marketing and selling of refined products to wholesalers (industrial or commercial entities), retailers, and end consumers. (9) **Distribution:** The final phase includes the distribution of refined products through pipelines, tankers, and trucks reaching end consumers via gas stations, convenience stores, and other retail outlets.

3. Decarbonization Mechanisms

The O&G industry is now on the cusp of a new era for the decarbonization of the energy system. To accelerate the transition, governments and energy companies of the Gulf countries must harness the full potential of digitalization and energy efficiency in the O&G sector. Digitalization refers to the increasing use of information and communications technology (ICT) across the economy, particularly within energy systems. It involves the convergence of the physical and digital worlds and is composed of three fundamental elements: data, which is the digital information; analytics, which involves using data to gain valuable insights; and connectivity, which refers to the exchange of data between people, machines (including machine-to-machine communication), and devices via communication networks [9]. Digitalization can revolutionize O&G operations and significantly support the shift towards a more sustainable energy landscape across the Gulf countries given the following opportunities:

- ***Environmental:*** Increase the operational efficiency and reliability of relevant processes, Improve equipment longevity, Optimize energy production across the various processes, Mitigate risks through more informed data-driven decisions, Reduce energy consumption and minimize the carbon footprint/emissions of the industry, Enhance exploration accuracy and better manage supply chains.
- ***Economic:*** Better resource and asset management, Increase market competitiveness, Reduce downtime, inspection times, and maintenance costs while ensuring continuous operations, Reduce the

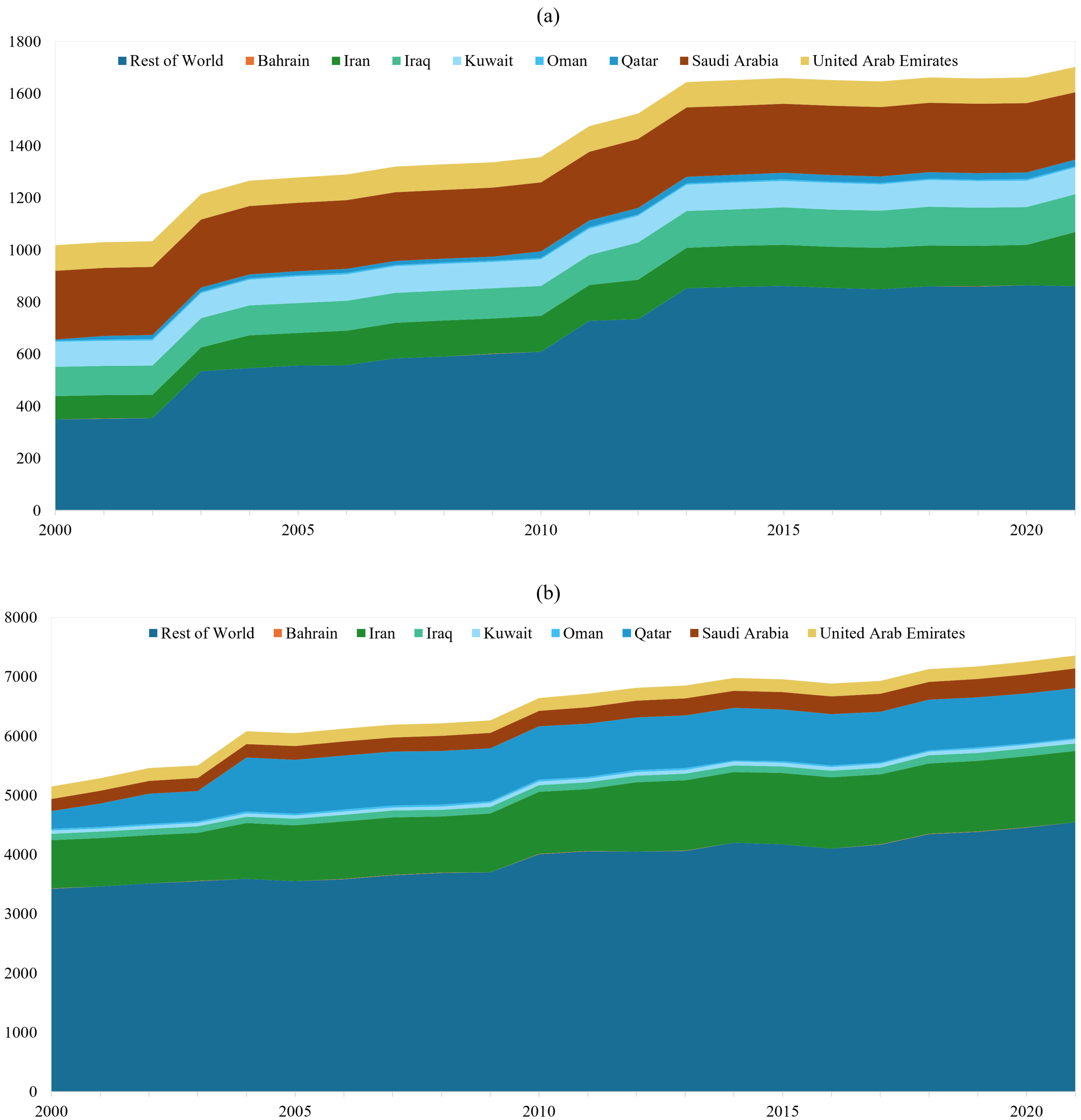

Figure 2: Gulf countries (a) oil reserves in billion barrels (billion b) and (b) natural gas reserves in trillion cubic feet (tcf) (Source: Data from U.S. Energy Information Administration [8]).

impact of price volatility, Evolve business models per global standards and best practices.

—***Social:*** Improve workplace safety by detecting leaks or other anomalies promptly, Provide better experiences for customers and partners, Improve workforce skill and knowledge development.

This section explores the role of different strategies and interventions in facilitating the clean energy transition for the O&G sector by delving into several key areas leveraging advanced technologies.

3.1 Digital Technology

Following the steam engine era of Industry 1.0, the electrification era of Industry 2.0, and the information era of Industry 3.0, Industry 4.0 represents the technological advancements of the 21st century. Also known as the Fourth Industrial Revolution (4IR), Industry 4.0 ushers in an “intelligence era” through the integration of information technologies that blur the boundaries between physical, digital, and biological realms driving profound industrial transformation [10]. These digital

Table 1: Summary of key 4IR technologies for the digital transformation of the O&G sector.

Digital Technology	Description	Reference(s)
Blockchain	Decentralized digital ledger to record transactions across multiple computers securely.	[9][11][12]
Mobile technology	Advanced smartphones and tablets for field data collection, remote monitoring, and real-time communication.	[9]
Digital twin	Virtual replica of physical assets, processes, or systems.	[11][13][14]
Cloud computing	Scalable and flexible storage and computing resources over the internet.	[13][14]
Cognitive computing	Simulate human thought processes using computerized models.	[13]
Edge computing	Data processing near the data generation source rather than in a centralized data-processing warehouse to improve response times and reduce bandwidth usage.	[15]
Internet of Things (IoT) and Industrial Internet of Things (IIoT)	Interconnected sensors and devices that collect and transmit data in real-time.	[9][11][13][14]
Robotics and automation	Automated machines and robots to perform tasks traditionally done by humans.	[9][11][13]
Drones and unmanned vehicles	Autonomous devices used for aerial and subsea inspections, environmental monitoring, data collection, and access to hard-to-reach areas.	[13]
Virtual/Augmented reality and wearable devices	Immersive experiences for training, simulation, and maintenance activities, while providing real-time information and hands-free communication.	[11][14]
3D printing and additive manufacturing	Three-dimensional objects from digital models by adding material layer by layer.	[11][13][14]
Big data analytics	Analyze large volumes of data to uncover patterns, trends, and insights.	[9][11][13][14]
Machine learning and Artificial intelligence (AI)	Mathematical algorithms to analyze data and make predictions or decisions, and computer models to replicate real-world processes and systems.	[13], [14], [16]–[19]
Wireless communication	Transmission of data over wireless networks.	[11]
Quantum computing	Highly complex computations and process information at unprecedented speeds much faster than traditional computers.	[14]
Digital marketing and sales	Online platforms and tools to promote products/services and facilitate transactions.	[9]

solutions are reshaping the global economy, including energy, to enable modern life and meet the world's growing energy demand. Table 1 outlines key 4IR technologies for the digital transformation of the O&G sector to decarbonize the energy system in pursuit of the NZE agenda.

3.2 Renewable Energy

As it is too soon to see a rapid decline in O&G, transformation must also happen in legacy energy assets that we have right now through shifting to renewable energy systems to reduce the industry's carbon footprint [15]. The natural conditions of hydrocarbon fields are highly suitable for integrating new clean energy sources, therefore, renewable energy can be integrated into O&G operations through the following [20]:

—***Solar:*** Solar oil recovery involves using thermal energy from sunlight collected by solar collectors to heat water and produce steam which is then injected into oil formations through injection wells, heating the heavy oil, increasing formation pressure, and forcing the crude oil out through production wells.

—***Wind:*** Wind energy for oil recovery involves installing on-site wind turbines which generate electricity from wind to drive pumps that produce O&G. The offshore industry has energy infrastructure capable of withstanding harsh weather, making it suitable for integrating wind energy.

—***Geothermal:*** Hot water oil recovery uses geothermal resources and water injection technology to transfer large amounts of heat into shallow oil formations by developing fluids (oil, gas, water and their mixtures) at high temperatures in deep layers, which thus reduces the oil viscosities and improves the oil flow capacities.

—***Biofuel:*** Biofuel production technology is a CO_2 recycling technology that decreases CO_2 emissions by reducing the use of oil. Advances in alcohol fuel production using nonfood crops as raw materials have gradually resolved issues related to raw material processing and production costs.

3.3 Alternative Fuels

As a clean fuel, hydrogen has a high combustion calorific value and its combustion byproduct is water meaning it does not emit GHG into the environment. It serves as a versatile energy carrier, capable of being transformed into and from other forms such as electricity, ammonia, methanol, and synthetic fuels, making it a crucial solution for industrial decarbonization where direct electrification is not viable. The strong connection between hydrogen and renewable, low-carbon energy sources promotes its use as an energy vector. Producing hydrogen from fossil fuels offers a transitional pathway from high-emission combustion processes to cleaner, lower-carbon alternatives. One of the most widely used methods is steam methane reforming (SMR), which accounts for nearly 50% of global hydrogen production. Currently, hydrogen production in the refining industry primarily relies on grey hydrogen technology, which uses coal and other fossil fuels. Moving forward, the focus should shift to advancing decarbonization strategies for hydrogen use including blue hydrogen technology which utilizes fossil fuels combined with storage systems, green hydrogen technology which generates electricity from renewable energy and biomass, and low-carbon hydrogen from nuclear energy-generated heat [20][21].

3.4 Carbon Removal

Carbon capture, utilization, and storage (CCUS) involves separating CO_2 from industrial processes, energy use, or the atmosphere, and then using it directly or injecting it into the ground for permanent emissions reduction. Approximately three-quarters of the 40 million tons (Mt) of CO_2 captured annually by large facilities come from O&G operations [20]. Using CCUS processes, CO_2 is captured using various capture systems such as pre-combustion, post-combustion and oxy-fuel combustion, then transported by tanker, ship, or pipeline for utilization or storage [21]. Uses include resource utilization by injecting CO_2 into the ground to increase O&G recovery rates or injecting into deep geological reservoirs for long-term isolation of CO_2 from the atmosphere. The O&G industry has the necessary technical capacity and expertise to handle large volumes of CO_2 and expand CCUS deployment [20]. There are three main processes to which CCUS can be applied to reduce the emissions intensity of O&G operations to help decarbonize the energy system [4]:

—***Gas processing:*** Natural gas extraction often involves removing impurities, including CO_2, which is typically vented into the atmosphere. Around 150 Mt of CO_2 are extracted annually from O&G operations, with 125 Mt being vented. The remaining 25 Mt of CO_2 is mostly used for enhanced oil recovery by injecting it into oil fields, with some being stored in inactive fields.

—***Refining and bitumen upgrading:*** Around 40 Mt of hydrogen are used annually for refining and upgrading oil globally, generating significant CO_2 emissions that can be captured. Hydrogen production units produce a relatively pure stream of CO_2, often vented, accounting for 60% of total CO_2 emissions from steam methane reformers which can be directly captured. Coal- and natural gas-based hydrogen units can be designed for up to 95% CO_2 capture to lower emissions intensity. CCUS can also reduce emissions from catalytic crackers, heat plants, and power generation at refinery sites.

—***Liquefied natural gas:*** Liquefying natural gas requires cooling to -162°C, an energy-intensive process typically powered by consuming a portion of the gas being processed, averaging around 9% of the gas globally. This process, combined with any venting of naturally occurring CO_2, results in the emission of approximately 2-3 tonnes of CO_2 for every ten tonnes of LNG produced. Currently, no projects utilize CCUS to mitigate these emissions, although implementing CCUS can potentially reduce emissions by around 90%.

3.5 Methane Abatement

Methane is the second largest global GHG after CO_2 [20], responsible for around 30% of the rise in global temperatures since the Industrial Revolution where the O&G sector is responsible for 80 Mt of methane emissions, equivalent to 2.4 giga tonnes CO_{2eq} [4]. As part of the Global Methane Pledge, 158 countries (including the Gulf countries except for Iran) representing over 50% of global anthropogenic methane emissions, have committed to work together to collectively reduce methane emissions by at least 30% by 2030 (relative to 2020 levels) [22]. The O&G industry can decrease methane emissions by approximately 75% by using existing technologies and measures, with approximately 40% of that methane achieving net zero cost reductions [20]. Examples include leak detection and repair campaigns, installing emissions control devices (vapor recovery units, blowdown capture, flares, plunger), and early replacement of existing components that emit methane by design (pumps, compressor seal or rod, air systems, electric motor) [4].

3.6 Flaring Control

Around 140 billion cubic meters of natural gas was flared in 2022 resulting in 500 Mt of CO_{2eq} emissions [4]. There are several efforts to cut down on flaring, including the Zero Routine Flaring by 2030, launched by the World Bank and the United Nations in 2015, which commits governments and companies to end routine flaring no later than 2030. Currently, the endorsers of the initiative include 36 governments including Bahrain, Oman, Saudi Arabia and Iraq [23]. There are many options for using natural gas that is currently flared, including bringing it to consumers/market via new pipeline connections or existing gas networks of transmission or distribution grids, reinjecting it to support reservoir pressure, or converting it to compressed natural gas (CNG) or LNG. Except for gas injection, the gas that is saved can be resold significantly lowering the net cost of abatement. New technologies have made it easier to monitor flares on a near real-time basis, helping companies to identify bottlenecks and opportunities in operated and non-operated assets. For example, mobile mini-LNG or CNG production equipment can reduce the need for flaring and venting during well-testing and other short-term operations [4].

4. Selected Real-World Use Cases

As the world's energy system is changing fundamentally, the region's position at the heart of the global O&G sector implies that the impact of the global decarbonization and clean energy transition agenda is likely to be felt more acutely over the coming years. In the wake of the 4IR, governments and national oil companies (NOCs) across the region are beginning to realize the shift globally towards digital and advanced technologies. These technologies, as presented in Section 3, can be integrated into O&G operations through a plethora of applications including monitoring of equipment health/performance, field surveillance, predictive maintenance, tracking environmental conditions, remote asset management, digital prototyping, real-time data collection and analysis, demand forecasting, operational automation and analytics, pricing optimization, logistics route management, and pipeline/refinery

Table 2: Existing or planned projects using digital and advanced technologies in NOCs in the Gulf countries.

Country, Company	Decarbonization Mechanisms	Applications	Reference(s)
United Arab Emirates, ADNOC	Digital Technology	Belbazem offshore block uses AI modelling and analysis tools to analyze reservoir data, manage reservoir operations and optimize production. Panorama Digital Command Center aggregates data from across operations providing real-time insights through smart predictive analytical models, AI, and big data. Hyperledger Fabric-based system for automated accounting and rapid transaction settlement in oil product sales. Digital twin in Taweelah gas compression plant.	[12][14][24][25]
	Carbon Removal	Projects include CO_2 storage hub (planned, 5 $MtCO_2$/year), Habshan-Bab gas plant (under construction, 1.5 $MtCO_2$/year), Hail and Gasha (under construction, 1.5 $MtCO_2$/year), ADNOC ENEOS Mitsui Ruwais Industrial Area (planned, 0.46 $MtCO_2$/year), Oxy/ADNOC Direct Air Capture (planned, 1 $MtCO_2$/year), Shah gas plant (planned, 2.3 $MtCO_2$/year), and TA'ZIZ blue ammonia (planned, 1.7 $MtCO_2$/year).	[26]
Saudi Arabia, Aramco	Digital Technology, Methane Abatement, Flaring Control	Shallow Water Inspection and Monitoring Robot for pipelines inspection in shallow waters. Uthmaniyah gas plant uses advanced analytics and drones to inspect pipelines/machinery. Khurais field uses 40,000 IoT sensors to monitor and forecast the behavior of more than 500 oil wells creating the world's first advanced process control for a conventional field. Abqaiq oil processing facility uses robots and smart drones, machine learning and AI algorithms, data analytics and predictive modeling to boost performance and efficiency. Yanbu oil refinery uses predictive maintenance, advanced data analytics, and automation to optimize processes and reduce downtime. Hasbah field uses digital twin for project design, construction planning, supply chain, materials handling, and facility operations and maintenance. Center AI hub leverages advanced analytics and machine learning solutions including unmanned aerial vehicles for operational uses of air, ground, and underwater robots that support flare stack inspection or methane gas detection, augmented and virtual reality to train operators on the plant experience from a simulation booth, and wearable technologies such as digital glasses and helmets to connect field workers to other employees for real-time interaction and collaboration. Additive manufacturing center that 3D prints a wide range of products for industrial uses. Cloud-based platform solution, eMarketPlace, to optimize supply chain processes. Smart Gas Detector to detect gas using electrochemical sensors using IIoT technology to deliver high-performing self-diagnostics compared to conventional detectors. Camera-Based Well Space Out system with smart high-resolution wireless cameras, and other sensors that use AI and machine learning to process the video and imagery captured to optimize the placement of the drillstring assembly a critical step in the process of drilling new hydrocarbon wells. Big Data Dammam-7, one of the world's most powerful supercomputers provides the vast computational power for running detailed 3D seismic models to recover and discover O&G. Supply Chain Control Center uses AI solutions and advanced analytics for real-time alerts to business disruption, live logistics tracking, and end-to-end visibility on supply chain. In-house reservoir and basin simulator, TeraPOWERS, using big data to simulate the Arabian Peninsula hydrocarbon system by updating models with new drilling and production data and employing algorithms to maximize access to hydrocarbon resources. In-house AI-powered i4Safety 2.0 Hazard & Incident Prediction tool using historical data to predict on-site incidents and hazards to increase safety and efficiency in operations.	[27][28]
	Carbon Removal	Projects include Jubail Hub agreement (planned, 9 $MtCO_2$/year) and Uthmaniyah CO_2 enhanced oil recovery demonstration (operational, 0.8 $MtCO_2$/year).	[26]

(continued)

Table 2: Existing or planned projects using digital and advanced technologies in NOCs in the Gulf countries. *(continued)*

Country, Company	Decarbonization Mechanisms	Applications	Reference(s)
Oman, Petroleum Development Oman	Digital Technology	Digital oil field connecting 2,000 wells where real-time data informs about electric submersible pump performance and auto-generates online well models.	[29]
	Renewable Energy	Miraah, one of the world's largest solar plants, harnesses solar energy to produce steam for oil production. The 330 megawatts solar thermal facility reduces natural gas used to generate steam for thermal enhanced oil recovery by generating an average of 2,000 tons of solar steam daily injected into the oil reservoir to heat the oil making it easier to pump to the surface and facilitating easier extraction at the Amal oilfield.	[30]
Kuwait, Kuwait Oil Company and Kuwait National Petroleum Company	Digital Technology	Sabriyah pilot comprises 49 wells each instrumented with state-of-the-art technology from subsurface to surface to acquire real-time data, upgrade power and communication infrastructure, and create collaborative decision centres to automate work processes. Private cloud in two data centres built on digital solutions using automation, big data, and smart applications to virtualize compute, storage, network, and security layers and automate lifecycle management of all software components across the organization's infrastructure.	[31][32]
Bahrain, Tatweer Petroleum	Digital Technology	Smart technology to monitor the wells with 500,000 IoT sensors fitted across the oil field to ensure that all wells are running as efficiently and safely as possible. Collaboration with UAE-based AI technology firm "AIQ" to integrate AI and digital solutions into upstream operations using advanced machine learning and data science to optimize field architecture, improve performance, and reduce operational risks.	[33][34]
	Renewable Energy	Solar power plant produces 3 megawatts of electricity, supplying around 6% of the company's total energy needs to reduce the use of natural gas for generating electricity and helping in the conservation of natural resources and the protection of the environment. The generated power is fed back into the power grid for use in oil field operations.	[35]
Qatar, QatarEnergy	Carbon Removal	Projects include Qatar LNG (operational, 1.23-2.1 MtCO_2/year) and Qatar North Field East Project (under construction, 2.9-4.3 MtCO_2/year).	[26]
	Renewable Energy	Al Kharsaah 800 megawatts photovoltaic power project applies the latest solar energy technologies to optimize electricity production and features automated systems for sun-tracking and robotic cleaning of solar panels, supplying 10% of the country's peak energy consumption and diversifying power sources by reducing the reliance on natural gas for power generation.	[36]
Iran, National Iranian Oil Company	Digital Technology	Strategic AI center to digitalize 15 O&G fields along with acquiring technology for drilling long multilateral horizontal wells by using homegrown rotary steerable system. A joint venture with Chinese tech companies to employ AI in the whole value chain including exploration, drilling, production and development.	[37][38]
Iraq, National government and authorities	Renewable Energy	1 gigawatts solar power plant to supply electricity to the Basrah regional grid to enhance the development of natural resources and improve electricity supply, and recover the flared gas on three oil fields to supply gas to power generation plants and the construction of a seawater treatment plant for pressure maintenance to increase regional oil production.	[39]

corrosion monitoring, among various others. Table 2 sheds light on applications of digital and advanced technologies in the Gulf countries showcasing trends that are becoming a key focus for investment as companies prepare for the future.

5. Challenges and Enablers

The above technologies and measures are radically restructuring the O&G sector, creating both opportunities and potential challenges for energy companies which include but are not limited to [9][21][40]:

- —***Lack of Technical Expertise****:* Implementing and maintaining digital technologies necessitate specialized workforce skills, yet there is often a shortage of qualified personnel who can manage and operate advanced systems.
- —***Cybersecurity Risks:*** Increased vulnerability to potential cyberattacks due to interconnected digital devices/systems with multiple access points.
- —***Siloed Systems:*** Drilling, completions, geosciences, production, and reserves systems in most O&G organizations are siloed as these systems are created, managed and stored using various software and databases and by numerous teams within the organization.
- —***Data Handling:*** Implementation of digital technologies generates large volumes of data.

—***Geological Uncertainty:*** The inherent variability in geological formations presents a significant challenge particularly for technologies such as CCUS.

—***Capital Intensity:*** High initial investment costs associated with the deployment of new technologies and infrastructure for renewable energy and clean fuels given budget constraints and uncertain economic benefits.

—***Resource Availability:*** The availability of necessary resources, such as water for hydrogen production or specific materials for renewable energy technologies, can be limited and geographically constrained.

—***Technological Obsolescence:*** The rapid pace of technological advancements can make new systems and tools obsolete quickly, necessitating continuous updates and investments.

—***Technological Maturity:*** Some clean technologies, like advanced biofuels and hydrogen, are still in the early stages of development and deployment and thus their commercial viability and scalability remain uncertain.

—***Ambient Settings:*** Deploying digital technologies in extremely high temperature and pressure environments of O&G operations impacts durability and accuracy, especially in hot climates typical of many oil-producing regions or environmentally sensitive or dangerous areas such as deserts and areas affected by war.

—***Market Dynamics:*** Adapting to changing market demands and competition from alternative energy sources while navigating complex regulatory frameworks.

—***Intellectual Property (IP) Forge and Contractual Risks:*** Implementing digital technologies involves complex IP and contractual challenges including protecting proprietary technologies, negotiating clear and fair contracts, and managing IP rights across stakeholders which can lead to disputes over ownership, licensing agreements, and data sharing, ultimately hindering collaboration and slowing digital transformation.

To successfully navigate potential challenges in transforming the O&G sector for the Gulf countries, NOCs must focus on key enablers which refer to "critical success factors" that present key areas in a business where positive results are crucial to ensure successful competitive advantage, and if results fall short, the organization's overall performance will suffer [41]. Suggestions to accelerate the clean energy transition of the O&G sector include [9][21][29][40][41]:

—***Workforce Development:*** Invest in training and awareness education to build a skilled workforce capable of handling new energy systems and digital technologies while adhering to safety measures from high-risk activities and hazardous materials through the use of personal protective equipment, the implementation of safety procedures, and the monitoring of equipment and processes.

—***Operational Resilience:*** Implement robust cybersecurity protocols and measures to protect computer systems, digital infrastructure, and connected networks from cyber threats.

—***System Integration:*** Ensure compatibility of new technologies with existing operations and legacy infrastructure to function as a coordinated whole through careful planning and retrofitting where needed to avoid systems interference and potential disruptions.

—***Data Management:*** Robust computing infrastructure and sophisticated algorithms are required to manage, store, and process data securely and efficiently.

—***Geotechnical Stability:*** Detailed geological surveys and continuous monitoring to understand the geological characteristics of storage sites and ensure the long-term integrity of carbon storage over extended periods.

—***Innovative Financing***: Explore financing mechanisms and incentives, such as green bonds, carbon trading tax breaks or subsidies, to fund energy transition projects while considering return on investment (ROI).

—***Stakeholder Cooperation:*** Foster public-private collaboration between government, industry, and academia to accelerate the deployment of new technologies and access to critical resources and raw materials residing in particular geographical regions.

—***Technological Adaptability:*** Establish partnerships with technology vendors and startups to gain early access to emerging technologies and invest in modular and scalable digital infrastructure that can be incrementally updated without significant disruptions to operations.

—***Pilot and Scale:*** Allocate funding for research and development (R&D) to accelerate the development of clean technologies with pilot demonstrations for performance data and viability assessment before full-scale deployment, and facilitate technology transfer from international partners to advance local capabilities.

—***Environmental Control:*** Conduct thorough testing and validation in simulated environments, implement regular calibration and maintenance protocols to guarantee the reliability of technology in extreme conditions and use high-quality durable materials and coatings for digital equipment for resistance to corrosion and wear.

—***Effective Governance:*** Align with international standards and best practices for O&G operations that encourage innovation and investment in digital technologies and clean energy.

—***IP and Contract Management Systems:*** Develop clear IP policies, ensure detailed and transparent contracts for new technologies, and create collaborative frameworks with predefined dispute resolution mechanisms. Engage legal experts and use advanced contract management software to streamline processes and maintain compliance.

In closure, we argue that a rapid and significant change in the pace and scale of industry actions is imperative to achieve the necessary transition. Government leaders and responsible corporations need to prioritize decarbonization strategies to make NZE a reality. The O&G sector is facing growing public concern over climate change, stricter government regulations, and a volatile global energy market. The ongoing drive to reduce emissions and the environmental damage caused by the energy industry will require innovative solutions from O&G companies that wish to flourish in this era of change. Enterprises may leverage free cash flow from resilient O&G assets to drive digital transformations and clean energy transitions. Management support and strong leadership are vital to fostering a cultural shift within organizations for commitment to a smooth transformation. Uncertainties remain about the future of the energy system, but those preparing today to meet anticipated demand trends and adopt appropriate technologies will fare better than those who neglect the need for change or investment in future-proof technologies. The strategic choices, policies, and plans made today by governments and operators in the region are likely to prove to be fundamental to their success or failure within the energy system in the coming decades to meet the objectives set forth by global climate agendas.

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Footnotes

[1] While it is referred to as the Persian Gulf in Iran, the Arab governments refer to it as the "Arabian Gulf" or the "Gulf". In this article, the Gulf is used.

Harnessing AI for Sustainable Energy Transition: A Dual Focus on Renewable Integration and Predictive Maintenance.

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Abstract

The sustainable energy transition is advancing with the integration of renewables, but challenges such as efficient renewable integration and the need for predictive maintenance remain significant. Harnessing AI can address these issues by optimizing energy systems and improving maintenance strategies, which is crucial for a reliable and sustainable energy future.

"This work explores the pivotal role of Artificial Intelligence (AI) in driving the transition towards sustainable energy solutions. It focuses on two key aspects: integrating renewable energy sources and enhancing system reliability through predictive maintenance. By leveraging advanced algorithms, AI optimizes the integration of intermittent renewable sources like solar and wind into the energy grid, ensuring a stable supply.

AI algorithms process sensor data to forecast potential equipment failures, enabling timely predictive maintenance and reducing downtime costs. This dual approach, which includes predictive maintenance and energy sustainability, addresses industry needs while aligning with public concerns about energy efficiency.

1. Introduction

The urgency of transitioning to sustainable energy sources cannot be overstated. It is a crucial step in our collective fight against climate change and ensuring a secure energy future. An evidence of this inevitable rapid transition is the global consensus (also called the UAE consensus) of tripling up on renewables to at least 11 TW installed capacity increase, with over 130 countries signing this agreement to reach this goal by the year 2030 (United Nations Climate Change). This shift necessitates replacing fossil fuels with renewable energy sources such as solar, wind, and hydropower. In the midst of this ambitious goal lies the underlying challenges of the existing energy system and infrastructure as well as a spectrum of innovative strategies to solve them. Artificial intelligence (AI) has been one of the cynosures of these strategies as the race to achieving a rapid transition intensifies.

The potential of AI and digitalization to revolutionize various industries, including the energy sector, is immense. The combination of these technologies can significantly enhance the efficiency and reliability of energy systems, which have historically been the central rationale of energy systems evolution and transition from the traditional energy sources to the current regime (Fouquel, 2016). These rationales are also not unconnected to taking advantage of energy prices, improving production efficiency, and providing support to overall socioeconomic development.

This article delves into the role of AI-driven digitalization, not just as pivotal but transformative for integrating renewable energy and maintaining system reliability through predictive maintenance. The central aim is to explore ways that artificial intelligence (AI) is being effectively utilized to facilitate the sustainable energy transition, with a particular emphasis on integrating renewable energy sources and implementing predictive maintenance strategies. By examining current advancements and future prospects, the article aims to highlight the potential of AI to further enhance the efficiency, reliability, and sustainability of energy systems.

2. Literature

Renewable energy sources, such as solar and wind, are inherently variable and intermittent, posing challenges for integration into existing power grids. AI technologies, including machine learning (ML) and neural networks, have been increasingly applied to address these challenges by improving forecasting accuracy and optimizing energy management.

The development of energy systems has undergone a significant transformation, progressing from the traditional power grid to the smart grid and now towards the concept of energy internet (Lee J et al. 2019). The power grid represents the traditional energy supply system, whereas the smart grid enhances it by integrating information gathering, control, and regulation, along with incorporating renewable energy sources (Breyer, C et al., 2022). However, the energy internet signifies a more advanced stage, marked by energy optimization decisions and extensive coordination enabled by the integration of smart grid technologies, AI, cloud computing, the Internet of Things, big data, and mobile internet. It represents a profound convergence of information, physical systems, and societal elements(Motlagh, N.H et al., 2020).

AI techniques have been widely used to enhance the accuracy of renewable energy forecasts. For example, Chen et al. (2019) demonstrated the effectiveness of deep learning models in predicting solar power output, significantly outperforming traditional statistical methods. Similarly, Zhang et al. (2020) applied machine learning algorithms to wind energy forecasting, achieving notable improvements in prediction accuracy and reliability.

AI can optimize the operation of power grids to accommodate the fluctuating nature of renewable energy. According to Du et al. (2019), reinforcement learning algorithms have been successfully implemented to balance supply and demand in smart grids, thereby enhancing the stability and efficiency of energy systems. Predictive maintenance leverages AI to predict equipment failures before they occur, allowing for timely maintenance and reducing downtime. This approach is particularly valuable in renewable energy systems, where equipment reliability is crucial for consistent energy production. AI-based condition monitoring systems utilize sensor data and machine learning algorithms to detect anomalies and predict failures in real time. A study by Li et al. (2018) showcased the application of neural networks in monitoring wind turbine health, achieving high accuracy in fault detection and prognosis.

Similarly, Zhang and Qin (2019) highlighted the use of AI for solar panel maintenance, where image recognition techniques were employed to identify defects and optimize cleaning schedules.

The adoption of AI-driven predictive maintenance can lead to significant cost savings and efficiency improvements. According to a report by McKinsey & Company (2020), AI-based maintenance strategies can reduce operational costs by up to 20% and increase equipment lifespan by 15-20%. This highlights the economic benefits of integrating AI into maintenance practices in the energy sector.

3. Method

The literature review was conducted using a systematic approach to identify relevant studies and articles related to the use of artificial intelligence (AI) in renewable energy integration and predictive maintenance. The primary databases used for the search included IEEE Xplore, ScienceDirect, Google Scholar, and PubMed. The search terms included combinations of the following keywords: “artificial intelligence,” “machine learning,” “renewable energy integration,” “predictive maintenance,” “solar energy,” “wind energy,” “smart grids,” and “condition monitoring.”

Inclusion and Exclusion Criteria

To ensure the relevance and quality of the reviewed articles, the following inclusion and exclusion criteria were applied:

Inclusion Criteria:

- Articles published in peer-reviewed journals or conference proceedings.
- Studies focusing on the application of AI in renewable energy systems.
- Research addressing predictive maintenance using AI techniques.
- Publications from the last ten years (2013-2023) to ensure contemporary relevance.
- Articles available in English.

Exclusion Criteria:

- Studies not directly related to AI applications in renewable energy or predictive maintenance.
- Non-peer-reviewed articles, including opinion pieces, editorials, and blog posts.
- Articles published before 2013.
- Publications not available in English.

4. Results and Analysis

AI technologies offer significant benefits in optimizing renewable energy integration and enhancing predictive maintenance within the energy sector. The following are some of the areas that AI have deployed significantly to shape the entrance of sustainable and clean energy systems.

4.1 Electricity generation

AI has significantly shaped the development of sustainable and clean energy systems in electricity generation. AI-driven predictive maintenance systems, such as those used by Siemens Gamesa and GE Renewable Energy, have reduced downtime and maintenance costs by forecasting equipment failures before they occur (GE Renewable Energy. (n.d.). “AI in Wind Power.”, Siemens Gamesa. (n.d.). “Digital Solutions and Predictive Maintenance.” 2024) . Additionally, AI-enhanced weather forecasting models have improved the predictability of renewable energy production, aiding grid operators in managing supply and demand fluctuations more effectively . These advancements enhance the efficiency and reliability of renewable energy sources, supporting their integration into the power grid and fostering a more resilient and sustainable energy system.

4.2 Smart grid development

AI deployment in smart grids addresses critical challenges like load forecasting, fault detection, and grid stability, which are essential for efficient renewable energy integration. AI techniques, such as machine learning and data analytics, accurately predict energy production and consumption patterns. Improved load forecasting through AI enables better demand response and energy distribution, resulting in efficient grid management and reduced reliance on non-renewable sources (Omitaomu & Niu, 2021).

AI-driven predictive maintenance enhances grid reliability by continuously monitoring components and analyzing sensor data to predict and prevent equipment failures, minimizing downtime and maintenance costs. This ensures reliable integration of renewable sources like wind and solar (Khosrojerdi et al., 2022).

Moreover, AI optimizes real-time energy storage and distribution, which is crucial for microgrids dependent on renewable energy. AI systems balance supply and demand within these smaller grids, enhancing overall resilience and sustainability (Mandal, 2017).

In summary, AI integration in smart grids supports the transition to renewable energy while improving grid efficiency, reliability, and sustainability, which are crucial for a resilient and eco-friendly energy infrastructure.

4.3 Transportation

AI, a key player in enhancing efficiency, optimization, and management in the transportation sector, is a vital component of the global energy transition. It optimizes energy consumption in electric vehicles (EVs) by analyzing driving patterns, traffic data, and battery health. This not only extends battery life but also significantly reduces emissions, providing reassurance about the positive environmental impact of AI (Necula, 2023).

AI also integrates renewable energy into transportation networks, managing charging stations by predicting peak usage and balancing load distribution to prevent grid overloads, thus ensuring a stable renewable energy supply (World Economic Forum, 2021).

In the realm of predictive maintenance, AI takes a proactive role in monitoring and analyzing transportation infrastructure, such as electric buses and trains. By predicting failures and scheduling proactive maintenance, it minimizes downtime and costs, ensuring reliable operation and instilling confidence in the audience about the cost-effectiveness and reliability of the infrastructure (MDPI, 2024).

Furthermore, AI facilitates intelligent transportation networks by integrating IoT devices and data analytics to adjust operations, improving efficiency and reducing energy waste dynamically. For example, AI optimizes traffic signals to reduce idling and manages autonomous vehicle flow, lowering energy consumption and emissions (Energy Informatics, 2023).

In summary, AI transforms transportation by optimizing energy use, integrating renewable energy, enabling predictive maintenance, and developing smart networks, which are crucial for a sustainable energy future (World Economic Forum, 2021; MDPI, 2024).

4.4 Energy efficiency

AI technologies have revolutionized energy efficiency in buildings and industrial applications by optimizing energy use, enhancing performance, and improving resource management. Despite the initial complexity in setting up AI systems, their benefits are substantial. In smart buildings, AI dynamically adjusts heating, ventilation, and air-conditioning (HVAC) systems by analyzing sensor data to optimize temperatures and airflow, maintaining indoor environmental quality while reducing energy use by up to 30% (Ogundiran et al., 2024; Bejan et al., 2021).

In industrial settings, AI-integrated energy management systems (EMS) with Internet of Things (IoT) devices monitor real-time energy consumption, identify inefficiencies, and suggest corrective actions. This real-time optimization not only saves energy but also reduces operational costs significantly (Okamoto, 2022).

Furthermore, AI enhances energy efficiency through demand-side management (DSM) and demand response programs (DRPs). By predicting energy demand and adjusting consumption patterns, AI helps balance grid load and prevent energy waste, particularly during peak periods. This reduces the strain on the grid and lowers greenhouse gas emissions (MDPI, 2021).

In summary, AI significantly optimizes energy use in buildings and industrial systems, manages HVAC systems, and improves energy management through real-time data analysis and predictive maintenance, promoting sustainable energy practices and reducing environmental impact.

By using machine learning models to analyze historical and real-time data, AI can accurately forecast energy generation from sources like solar panels and wind turbines, improving energy storage and distribution and ensuring a stable supply. Additionally, AI-driven predictive maintenance helps detect early signs of equipment failure, reducing downtime and operational costs while extending the lifespan of the equipment and improving overall energy infrastructure reliability.

However, the implementation of AI in the energy sector faces several challenges. Technical limitations, such as the need for high-quality data and the complexity and cost of integrating AI systems with existing infrastructure, pose significant barriers.

Furthermore, a shortage of skilled professionals and resistance to change within traditional energy companies hinder the adoption of AI technologies. Despite these challenges, advancements in AI and digitalization, along with supportive government policies and incentives, present significant opportunities for innovation and investment in clean energy solutions. Nonetheless, regulatory and compliance issues and external risks like technological failures and economic volatility underscore the need for robust risk management strategies.

5. Conclusion

Integrating AI, digitalization, and energy is not just a concept, but a crucial and proven strategy for a sustainable energy transition. The energy sector can achieve greater efficiency, reliability, and sustainability by leveraging AI for renewable integration and predictive maintenance. For example, AI has already demonstrated its ability to optimize energy distribution, reducing wastage and carbon emissions.

The journey towards sustainable energy is indeed complex and multifaceted, but with AI as a powerful ally, the path becomes clearer and more attainable.

Harnessing AI-driven solutions will not only turbocharge the shift to renewable energy but also lay the foundation for a more efficient, reliable, and sustainable energy future.

Government policies and financing play a pivotal role in supporting innovative AI-driven technologies that can better support all the value chains of the energy systems - generation, transmission, and distribution. Countries like the U.S., China, Germany, France and a few other European countries are leading in innovative AI research and development spending to boost their national energy and economic development outlook. In the U.S. for instance, the department of energy (DOE) is committing significant funding for initiatives to build AI-powered tools to support critical infrastructure in improving permitting and siting of clean energy adoption. This underscores the importance of enabling government policies and investments in AI, and other countries can take a cue from these jurisdictions.

The private sector, including EV companies like Ford, Tesla, General Motors, etc., and those developing smart home energy devices, are not just playing a key role, but are the driving force behind the rapid clean energy transition that is supported by AI. Their innovations have been instrumental to the successes achieved so far in our global energy landscape, and they continue to pave the way for others to follow.

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What is in Red AI? Scoping the Energy and Environmental Impacts of Artificial Intelligence

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The energy consumed in training generative and other computationally-intensive forms of artificial intelligence (AI) is attracting increasing attention from computer scientists, energy modelers, policy makers, and the public. However, the development and use of AI has other potential energy and environmental impacts. Building on bibliometric analysis, this article describes impacts that are the focus of current research—energy use in training AI—those starting to be characterized in the research literature—energy use in inference—and those impacts that exist or are hypothesized to exist but have drawn little attention from researchers—including indirect impacts from the use of AI, rebound effects, and misleading inferences in environmental management and policy relying on the use of AI.

Artificial intelligence (AI) has the potential to enable increases in energy efficiency and other improvements in the energy system (Donti and Kolter, 2021; Rolnick *et al.*, 2022). Researchers and AI developers are keen to propose ways to use digital technology for environmental improvement. Scans of the literature on AI and the environment suggest that research on environmentally beneficial applications are legion (Mosavi *et al.*, 2019; Haupt *et al.*, 2022; He *et al.*, 2022).

In 2020, Schwartz et al. published "Green AI" in the *Proceedings of the Association for Computing Machinery* arguing that the AI research community "needed to make efficiency an evaluation criterion for research alongside accuracy and related measures in the development of AI". They dubbed AI research that is more environmentally friendly and inclusive as "Green AI" and that which is not as "Red AI." That paper along with seminal work in the same period, such as that by Strubell et al. (2019), prompted attention and efforts by computer scientists to address energy consumption in AI.

The potential negative energy and environmental impacts, however, are not limited to the direct energy consumed and the resulting greenhouse gas (GHG) emissions from the development of AI. Those impacts can include indirect impacts arising from the use of AI, impacts other than energy consumption and attendant emissions, and environmentally harmful changes in production and consumption. This short piece draws on an ongoing bibliometric analysis to develop search algorithms to identify research on Red AI (Porter, Lifset and Lee, 2024). For brevity, we adopt and stretch the term "Red AI," using it as shorthand for diverse potential energy and environmental impacts of AI.

Here, we describe the scope of potential environmental impacts—some of which are the focus of current research and others which have not drawn much or any attention. This is not a literature review, a synthesis of current quantitative findings, nor a bibliometric analysis, but an effort to draw attention to the range of potential impacts that can benefit from the attention of energy and environmental researchers. The references provided are not comprehensive but rather are intended as an entrée to literature.

There are many different types of AI, but here we focus primarily on generative AI, the approach that underlies the now familiar chatbots. Generative AI can create new data—such as text, images, video, code, and audio—rather than, as with other types of AI, making a prediction about a specific dataset. Development of generative AI requires training, a process where the AI model is fed very large amounts of data, asked to make decisions based on the information, and then adjusted based on the AI output's accuracy. Because it is computationally intensive, generative AI models are typically energy intensive.

Direct Energy and Environmental Impacts

In response to calls for Green AI, computer scientists are increasingly looking for ways to reduce energy and GHG impacts of AI compute, that is, the development and use of software and hardware used in AI (OECD, 2022). This includes proposing ways to make training more computationally efficient (e.g., Treviso *et al.*, 2023); devising tools to measure energy consumption or emissions from AI models (e.g., Bannour *et al.*, 2021; Lannelongue and Inouye, 2023); and, debating likely trajectories of energy in AI development (Bender *et al.*, 2021; Patterson *et al.*, 2022; Luccioni, Jernite and Strubell, 2023; Castro, 2024). Much of the growing computer science literature focuses on methods to reduce the computational intensity of AI (Verdecchia, Sallou and Cruz, 2023).

Less common are analyses of energy consumed in the use of AI, known in computer science as "inference" (Luccioni, Jernite and Strubell, 2023). In part, this is because, while training typically occurs in data centers, inference may be disbursed among sites, equipment, and devices. While individual instances of inference typically consume little energy, inference has the potential to be a much greater consumer of energy because of the scale of usage (Kaack *et al.*, 2022; Vries, 2023). Research on energy consumed in specific uses of AI is limited. Some research on the carbon footprint of medical uses of AI is emerging (e.g., Yu *et al.*, 2022; Doo *et al.*, 2024) Energy consumed by AIs in the serving of digital advertising, a ubiquitous phenomenon, has attracted little research (Pärssinen *et al.*, 2018; Wu *et al.*, 2022; Pesari, Lagioia and Paiano, 2023).

Analysis of other instances of direct energy use by AI raises conceptual issues of causality, responsibility, and boundaries. The issue of causality can be illustrated through the examples of robots and autonomous vehicles. If use of a robot results in environmental damage and the robot employs AI in its functions, it is not clear whether the damage should be deemed an impact of the AI—no more than the material of which the robot is composed would be viewed as causing the damage.[1] Autonomous vehicles (AVs) present another conundrum in defining Red AI. The environmental impact of AVs may arise primarily from the increases in transportation and emissions that they engender, but AVs, unlike some other technologies, conspicuously would not exist at all without AI. A substantial literature exists on energy use by AVs, focusing efforts to estimate likely types and extent of use (Taiebat *et al.*, 2018). A literature on the footprint of data processing and transmission including AI in autonomous vehicles is emerging (Sudhakar, Sze and Karaman, 2023).

Other Direct Environmental Impacts of AI

Data centers where much AI compute occurs face issues in addition to energy use. Water use is drawing increased public concern, especially in places where data centers are concentrated or water supplies are constrained (Doorn, 2021; Mytton, 2021; Lei *et al.*, 2024). In a review of research needs on the environmental impacts of AI, the Organisation for Economic Cooperation and Development has called for more attention to non-energy impacts of AI including biodiversity (OECD, 2022).

Embodied Energy and Carbon

As operational energy use in computation improves, the relative importance of the impacts of producing the equipment used in AI grows. Embodied energy and carbon are attracting increasing attention (Gupta *et al.*, 2022; Wu *et al.*, 2022).

Generation of e-waste arising from AI

In some domains of the digital economy, changes in technology cause digital equipment to become obsolete. For example, in the mining of cryptocurrency, competition pressure has led to the rapid evolution of mining rigs with resulting turnover of equipment and generation of e-waste (de Vries and Stoll, 2021). Changes in the hardware used for AI could also increase the generation of e-waste.

Indirect Energy and Environmental Impacts of AI

Indirect energy and environmental impacts of AI are diverse and potentially legion with little systematic treatment. A modest but growing research literature on the indirect environmental impacts of digitization (Horner, Shehabi and Azevedo, 2016; Bieser and Hilty, 2018; Vaddadi *et al.*, 2020) does not address AI specifically. Such impacts include both shifts in consumer and producer behavior in response to changes in capabilities and costs, and broader structural changes in the economy and society. Among the indirect impacts are increases in energy consumption arising from functionality, availability, or costs of digital platforms enabled by AI and internet search (Wu *et al.*, 2022).

An important, but understated, indirect impact is increased production or consumption arising from efficiencies generated by AI. Such rebound effects are well known to and studied by energy economists (e.g., Herring and Sorrell, 2009), but, to our knowledge, only a small number of analyses of rebound effects from digitization have been conducted (e.g., Coroama and Pargman 2020; Gossart 2015). Very few papers have been published examining rebound arising from AI (Ertel, 2019; Adha and Hong, 2021; Willenbacher, 2021; Willenbacher, Hornauer and Wohlgemuth, 2022).

Other Research on Red AI

Incorrect or misleading algorithms

Algorithms developed for environmental research or management could produce misleading guidance or damaging outcomes (Rillig *et al.*, 2023). AI models can also incorporate racial or social bias or hallucinate, i.e., create false information, including nonexistent scientific references (Zhu *et al.*, 2023).

Infrastructure risk, security risk, and cascading failures

Reliance on artificial intelligence could lead to risk to infrastructure if algorithms are faulty (Nishant, Kennedy and Corbett, 2020; Galaz *et al.*, 2021; Robbins and van Wynsberghe, 2022). While this risk appears to be little different than risk arising from other forms of digitally-based management systems, AI could lead to greater autonomy of digital management or the problem of the inability to understand the basis for decisions produced through AI (Vinuesa and Sirmacek, 2021; Islam *et al.*, 2022). Similarly, increased reliance on digital management, because of the capabilities of AI, could lead to security risks if the AI applications are vulnerable.

Other Environmental Concerns

There are other environmentally related concerns voiced in the research literature that have varying degrees of connection to energy issues. These include ethical critiques (e.g., Dauvergne, 2021), discussions of potential negative impacts of smart cities (e.g., Colding and Barthel, 2017), and the likely impact of AI on the sustainable development goals (SDGs) (Vinuesa *et al.*, 2020).

Much is unknown about Red AI. As noted above, the likely magnitude of the impacts arising from the growth of AI such as training AI models—currently a focus of study—is contested. The character and significance of other potential impacts such as misleading algorithms or increases in e-waste remain largely unexplored.

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Footnotes

[1] Note, however, that embodied carbon in the robot, that is, the GHG emissions generated in the production of the materials used in the robot could be considered as arising from the use of the robot when taking a life cycle perspective.

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