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IAEE ENERGY FORUM

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PRESIDENT'S MESSAGE

Dear IAEE Members,

As we release the 3rd Quarter Issue of the *Energy Forum*, I am delighted to share important updates and new opportunities for engagement across our global community. I am pleased to announce the election of new IAEE Council members, whose terms will begin on January 1, 2026. These distinguished colleagues bring deep expertise and leadership to our association:

- President-elect: Professor Ying Fan, Ph.D. (China)
- Vice President for Publications: Professor Tooraj Jamasb, Ph.D. (Denmark)
- Vice President for Conferences: Cristian Stet, Ph.D. (Netherlands)

Earlier this month, IAEE held its Annual Meeting of Members in a fully virtual format for the first time. This successful event allowed a larger number of members to receive updates on our activities and exchange ideas on how to strengthen IAEE's impact—particularly through *The Energy Journal*.

The Call for Papers for the 47th IAEE International Conference – Santiago, Chile (July 2026) is now open. Chile, a global leader in renewable energy and sustainable development, offers the perfect setting to examine global energy challenges through a Latin American lens. We warmly encourage you to share your research and join this vibrant dialogue.

We also invite submissions for a special symposium hosted by *Economics of Energy & Environmental Policy (EEEP)*. This collection will focus on the critical role of sustainable energy infrastructure in Ukraine's reconstruction and its aspirations for EU membership. We welcome contributions from scholars, researchers, and policymakers to advance this timely discussion.

This issue of the *Energy Forum* explores one of the most urgent topics in today's energy landscape: the accelerating growth of global electricity demand. The International Energy Agency has described this transformation as the world's entry into the *"Age of Electricity."* With electrification expanding across industry, transport, and digital infrastructure, demand is outpacing global GDP growth and raising vital questions:

- Can renewable capacity scale fast enough to meet demand?
- What will the impacts be on electricity prices and energy equity?
- Could soaring demand jeopardize climate targets?

Several of our colleagues contribute valuable perspectives to this debate. We believe this issue makes a meaningful contribution to understanding the future of electricity demand and its implications for our field.

Thank you for your continued engagement and commitment to advancing energy economics. We look forward to your active participation in these initiatives and hope you enjoy this issue of the *Energy Forum*.

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Editor's Notes

Our sincere thanks for the insightful articles received on the topic of "**Understanding the Future of Electricity Demand and its Consequences.**"

The International Energy Agency (IEA) recently declared that the world is entering an "Age of Electricity," highlighting the accelerating electrification of economic activity. From replacing fossil fuels in industry and transport to powering emerging technologies like AI-driven data centers, electricity demand is now rising faster than global GDP. This rapid growth raises pressing questions for energy economists: How accurate are these projections, and what are the implications for both developed and developing nations? Key issues include whether financing and renewable capacity can keep pace, how soaring demand might influence electricity prices, and whether this surge could complicate global decarbonization efforts.

We are pleased to present you with a summary of plenary sessions from the 46th IAEE International Conference "Energy Solutions for a Sustainable and Inclusive Future", held in Paris, France June 15-18, 2025.

Xinya Hao and **Lin Zhang** examine the implications of rapid electrification of power demand and supply on energy sustainability, reliability, and accessibility. The upcoming Age of Electricity is generally positive for the Sustainable Energy Future, but there are potential threats that policymakers should be aware of.

Catarina Silva and **Inês Carrilho-Nunes** explore how self-consumption can support the next phase of electrification by complementing centralized supply, easing peaks, and stabilizing electricity prices. In addition, when paired with electric mobility, it offers a practical though partial route to meet rising demand more sustainably and strengthen progress toward decarbonization.

Manuel Frondel and **Colin Vance** state that to achieve its ambitious goal of becoming climate neutral in 2045, Germany has set an even more ambitious goal for its electricity sector: Already by 2035, Germany strives to cover its electricity consumption almost entirely by renewable technologies. With a current share of renewables in electricity consumption of about 55%, we argue that the 2035 goal would be both overly ambitious and a suboptimal outcome.

Joachim Geske, Boris Ortega, Laura Andolfi, and Rawan Akkouch simulate realistic cross- sector prosumage flexibility for 2040 in Luxembourg at the distribution grid level. They find that the increase in electricity demand requires higher electrification efforts, but it is the timing of this demand that causes the main infrastructure overload: the duck curve evolves into a turtle- like one. Thus, operators need to consider this evolution of demand to avoid grid overload or unsustainable investment.

Hiroaki Onodera posits that rising electricity demand calls for new adaptation strategies. Beyond expanding supply capacity, integrated siting of demand and generation emerges as an overlooked solution. Some case studies have demonstrated renewable-energy- driven demand relocation can be mutually beneficial for end users and power systems.

Luis Renato Amórtegui Rodríguez analyzes how electricity is the secondary energy source that will support the global energy transition projected for the mid-21st century, especially that produced renewable energy on the path toward decarbonization, considering that the essence of these sources is electricity generation. This gained relevance with the 1973 oil embargo, as efforts were made to make solar and wind energy competitive with conventional sources of generation, ensuring energy security and national interests.

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Summaries of plenaries - 46th IAEE Conference in Paris: Energy solutions for a sustainable and inclusive future – June 15-18, 2025 - https://www.iaee2025paris.org/

Geopolitics, Energies, Climate change policies: what's up? - Opening Plenary Session

By Elias Zigah (PhD candidate, University Paris-Saclay, elias.zigah@centralesupelec.fr)

Session Chair:
Pr. Amy Myers Jaffe (New York University)

Speakers:
Dr Fatih Birol (Executive Director, International Energy Agency)
Pr Christian Gollier (Toulouse School of Economics)
M. Stéphane Michel (General Director Gas, Renewables & Power, TotalEnergies)

Keynote of Gala Dinner:
Ms. Claire Waysand (Executive Vice President, in charge of Corporate Secretariat, Strategy, Research & Innovation and Communication, Engie)

Abstract

The opening session of the 46th IAEE International Conference in Paris convened leading voices from policy, industry, and academia to address the critical challenges shaping the global energy landscape. Chaired by Professor Amy Myers Jaffe of New York University, the session underscored a world grappling with profound uncertainty. Keynotes and discussions navigated the escalating tension between energy security, affordability, and climate action, a trilemma intensified by geopolitical conflicts, economic shifts, and the immense energy demands of new technologies like artificial intelligence (AI). A consensus emerged on several key points: the energy transition is advancing, demonstrated by a historic pivot in investment toward clean energy; however, it is imperilled by grid infrastructure bottlenecks, critical mineral scarcities, the high cost of decarbonisation, and a growing political backlash in Western nations. Speakers issued a call to action for economists to develop integrated, system-level solutions and robust market designs to ensure the transition is resilient, affordable, and socially acceptable.

1. Context and Welcome: Ambition Anchored in Pragmatism

The conference commenced in Paris, a city symbolic of global climate ambition as the home of the Paris Agreement and the International Energy Agency (IEA). In a welcome video, the Minister of State for France underscored the conference's theme, "Energy solutions for a sustainable and inclusive future," and affirmed France's commitment to a pragmatic energy transition. The address paid homage to the legacy of economists like Marcel Boiteux, former CEO of EDF, whose vision shaped France's energy policy, stressing the vital role of high-quality, evidence-based research in navigating the current complex environment. The minister's remarks clearly show the host nation's strategy, which integrates industrial and energy policy to bolster national resilience and security. France's strategy involves significant investment in six new EPR2 nuclear reactors and small modular designs, coupled with an aggressive expansion of renewables, particularly offshore wind, to secure a reliable and affordable energy supply as a prerequisite for a strong industrial base. This introduction established the session's core premise: climate ambition must be anchored in pragmatic, system-level thinking that integrates energy security and economic competitiveness.

Disclaimer: All these summaries have been prepared by non-expert economists to reflect their possible understanding of the plenary discussions for a global audience. It does not claim to provide a comprehensive or fully accurate account of the content. The document has been produced under the supervision of Pr. Cédric Clastres and Dr Christophe Bonnery.

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2. Keynote — "The Age of Electricity": Investment Pivot, Demand Drivers, and New Exposures

Dr. Fatih Birol, Executive Director of the IEA, delivered a data-centric keynote address, asserting his guiding principle that "data always wins." He declared that a historic structural shift is underway. Global energy investment has reached $3.2 trillion, with investment in clean energy $2.2 trillion now double that of fossil fuels $1.1 trillion. This 2:1 ratio marks a dramatic acceleration from parity in 2015. It has placed global electricity investment 50% higher than that for oil, gas, and coal combined, with China accounting for nearly 30% of the total. Dr. Birol identified this as the dawn of the "Age of Electricity," with demand projected to grow six times faster than overall energy demand in the coming decade. This surge is propelled by three powerful new drivers: electric vehicles, which have soared from 5% to over 25% of global car sales in just four years; air conditioning, now the single largest source of incremental electricity demand; and artificial intelligence, whose data centres depend on reliable 24/7 load profile, with a medium-sized data centre consuming as much electricity as 100,000 households.

However, Dr. Birol warned that this new era brings a formidable set of new exposures. The geopolitics of energy has expanded from a focus on fuel supply to the security of power networks, undersea cables, and cyber risk, as evidenced by recent suspicious incidents in the Baltic Sea. He pointed to recent events, such as NATO being forced to patrol undersea cables in the Baltic, as evidence that electricity networks are becoming critical geopolitical targets. Physical bottlenecks loom in critical minerals, especially copper, where the 17-year average lead time for a new mine creates a significant supply risk. While he confirmed that the "golden age" of gas is fading, he noted that a massive expansion of LNG capacity of 300 bcm is still expected by 2030, reshaping market dynamics.

Dr. Birol concluded with a powerful reminder of the profound energy injustices that persist, noting that 600 million people in Sub-Saharan Africa still lack access to electricity, and over 500,000 women die prematurely each year from the lack of clean cooking facilities, a crisis he termed the "number one gender issue" globally.

3. Market Reality Check: Insecurity, Affordability, and Systemic Failures

The subsequent panel discussion grounded these structural shifts in the stark realities of the current market. Professor Christian Gollier of the Toulouse School of Economics described the landscape as "deep uncertainty," a sentiment echoed by Stéphane Michel, President of Gas, Renewables & Power at TotalEnergies. Mr. Michel argued that a new era of geopolitical conflict, supply-chain fragmentation, and the end of near-zero interest rates has fundamentally redefined the investment calculus for capital-intensive decarbonisation, forcing a rebalancing of the energy trilemma with a renewed focus on security of supply.

This new macro-environment has exposed affordability and public acceptance as binding constraints on the energy transition. As articulated by Claire Waysand, EVP at ENGIE, the transition risks failure without public support, which is contingent on affordability and reliability. Professor Gollier detailed a growing political "backlash" in advanced economies, driven by a public awakening to the high implicit costs of many decarbonisation measures, such as synthetic aviation fuels, far exceeding current carbon prices. Mr. Michel reinforced this point, stating bluntly that customers are unwilling to pay a green premium and that demand for expensive solutions like green hydrogen is almost entirely compliance-driven.

The panellists converged on diagnosing systemic failure, identifying grid infrastructure as a primary bottleneck. The discussion revealed that piecemeal rules and a lack of system-level thinking have led to market distortions, such as negative power prices and long grid connection queues, which signal a misallocation of capital. Professor Jaffe delivered a sharp critique of mainstream energy-economy models, challenging the academic community to integrate the macro-risk feedback, such as the significant GDP losses at high warming levels projected by the reinsurance industry, currently absent from most forecasts.

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4. Proposed Solutions: Coalitions, Carbon Architecture, and Market Design

The panel proposed concrete solutions centred on better policy architecture and market design in response to these systemic challenges. To counter the problem of free-riding among nations, Professor Gollier advocated for a "coalition of the willing." This bloc of ambitious countries would align on a meaningful internal carbon price and enforce it externally via a carbon border adjustment mechanism (CBAM). To ensure equity and encourage broader participation, he suggested that revenues from the CBAM could be used to capitalise a climate fund for adaptation and mitigation in developing economies.

Concurrently, Mr. Michel directly challenged the economists in the room to move beyond theory and focus on the practical design of power markets. He framed the division of labour clearly: while engineers are developing technological solutions like batteries, it is the job of economists to design market structures that can explicitly procure and remunerate the system services flexibility, adequacy, and resilience that a renewable-heavy grid needs to function reliably. This requires moving toward market designs that internalise intermittency costs and turn today's negative prices and grid backlogs into investible signals for the resources the system truly needs.

5. Analytical Conclusion — The Core Conflict and the Mandate for Economics

The opening session exposed a fundamental credibility gap between stated net-zero trajectories and observed market signals. This core conflict emerges from two perspectives that shed light on different sides of the same problem. For firms, as Mr. Michel argued, halting fossil investment while demand persists would spike prices and erode public support for the transition. Meanwhile, as Professor Gollier noted, persistently high oil prices and risk premia signal investor doubts about the durability of long-term climate policy. Together, these views expose the chasm between policy promises and investible rules, the central challenge of the transition. Resolving this challenge is the explicit mandate for the energy economics community.

The session concluded that closing the pledge-performance gap requires stable, predictable institutions, carbon prices that travel across borders, border adjustments that reduce leakage, and power-market designs that pay for reliability. The charge given to economists was to design these market architectures and reform analytical models to internalise reliability, affordability, and risk, making the energy transition financeable, politically viable, and socially legitimate.

The lingering question, posed by Dr. Birol and Professor Jaffe, of whether there will be enough electricity to power the AI revolution, served as a stark reminder of the monumental scale of the challenge ahead.

Climate Policies: Delivering a fair, efficient and timely energy transition - Dual Plenary Session 1.1

By Hayeon NAM (MSc Sustainable Impact Analysis, Paris School of Economics, hayeon.kate@gmail.com)

Session Chair:
Aude Pommeret (University of Savoie Mont Blanc)

Speakers:
Katheline Schubert (Paris School of Economics)
Ying Fan (Beihang University)
Mark Jaccard (Simon Fraser University)

Aude Pommeret, professor at University Savoie Mont Blanc, chaired the session. In her opening speech, she highlighted the strong political opposition to efficient carbon pricing. As a result, climate policy often relies on alternatives like green subsidies. However, considering that the effectiveness and cost of energy transitions depend on policy and mechanism design, relying primarily on subsidies may not be the wisest approach. At the same time, policies must be perceived as fair to ensure a successful transition. In such a context, designing fair instruments without compromising efficiency becomes a key concern. Three experts joined as keynote speakers to discuss possible approaches: Kathline Schubert of Paris School of Economics on the cost of politically acceptable instruments in a general equilibrium model of the power sector; Ying Fan of Beihang University, on applying this question to China's low-carbon transition; and Mark Jaccard of Simon Fraser University on sector-specific policy effectiveness in Canada.

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The first speaker, Kathline Schubert focused on the political difficulty of implementing carbon pricing. Economists generally view it as the optimal instrument for internalizing CO2 externalities. It directly incentivizes households to cut emissions, generates revenues for redistribution, and stimulates green innovation. However, public resistance remains strong as the French Yellow Vest movement illustrated. To many citizens, carbon pricing appears unfair and regressive, while subsidies seem less costly and more equitable. This leads to a central issue of policy acceptability: why do societies favor command-and-control instruments and subsidies over carbon pricing, and what are the welfare costs of such preferences?

To address this issue, Schubert's joint work with Aude Pommeret and Francesco Ricci, investigates the "costs of acceptability." The paper models an economy where governments, unable to implement the optimal increasing carbon pricing, opt for constant or low carbon pricing combined with subsidies for renewable energy. Using both analytical modeling and its application to the European energy transition, the authors estimate the welfare and fiscal costs of the second-best strategy compared to the first-best carbon pricing. The results showed that if carbon prices are set at sufficiently high levels, the costs of relying on subsidies are moderate. On the other hand, when carbon pricing remains low, subsidies must be maintained permanently, leading to substantial welfare losses and heavy fiscal burdens. The findings suggest that although subsidies may be more politically acceptable, depending on them can substantially increase the overall cost of the transition.

Building on the discussion of policy acceptability, Ying Fan turned to China's energy transition, highlighting the power system as the core sector for achieving the country's carbon neutrality target by 2060. Since 2015, the share of non-fossil energy in power generation has increased from 27% to 41% in 2024, with wind and solar driving this rapid expansion. This growth has intensified the flexibility challenge, requiring coordination across generation, transmission, storage, and market mechanisms.

To study these challenges, Fan presented a transition model combining short-term economic dispatch with long-term capacity expansion planning of the power system. This model incorporates renewable uncertainty and an exogenous carbon price trajectory reaching about $115 per ton of CO_2 in 2050. Simulations demonstrated that wind and solar dominate, coal declines only after 2030, and transmission capacity increases significantly, particularly from northern resource-rich regions to the rest of China.

Fan then analyzed several policy instruments. Combining an environmental tax with carbon pricing reduces coal's share, promotes interprovincial transmission and health benefits. Storage policies are also important with solar dependent much more heavily on storage than wind. Last, demand-side measures such as time-of-use EV charging to support valley-filling can improve flexibility, though consumer willingness to shift charging differs between home and public locations.

Achieving China's 2060 carbon neutrality target will require a long, complex, and costly power system transition. Technological advancement provides the foundation, policy and market design serve as the key to guiding the process, and active demand-side participation unlocks additional potential to manage economic, social, and operational hurdles.

The final speaker, Mark Jaccard, opened his presentation by quoting James Buchanan, the 1986 Nobel Prize winner in economics, who urged economists to consider the political context and constraints under which policy decisions are made. Using this quote, Jaccard emphasized that economists often overstate the role of carbon pricing without accounting for the real-world limitations faced by elected officials. In Canada, he noted, the plurality electoral system makes opposition in swing ridings particularly decisive, so even a relatively small share of strongly opposed voters can determine electoral outcomes.

Jaccard categorized policy instruments into three broad types: carbon pricing (taxes or cap-and-trade), regulations, and subsidies. He centered his talk on Flexible Regulations (FlexRegs), which set performance standards but allow firms to trade compliance, pay penalties, or choose technology-neutral approaches. He explained that such flexibility reduces compliance costs and lets firms realize low-cost reductions first. Evidence from California's Air Resources

Board revealed that most greenhouse gas reductions were achieved through various types of regulations, many of which were flexible, rather than through carbon pricing systems.

Other Canadian case studies demonstrated these dynamics in practice. In British Columbia, the serious carbon tax was implemented alongside low carbon fuel standards and clean electricity standards that prevented new fossil fuel plants. Modeling results to 2030 showed that the carbon tax achieved relatively modest emission reductions at low cost, whereas flexible regulations achieved larger reductions at higher cost. Surveys revealed that public support for carbon taxes was far lower than for FlexRegs, even when respondents were informed that the latter were more expensive.

At the federal level, Jaccard's team modeled scenarios to 2050 comparing efficient carbon tax, efficient FlexRegs, and politically constrained carbon tax implementations with lump-sum payment. They found that both efficiently designed carbon tax and FlexReg produced similar GDP outcomes, but politically constrained carbon tax underperformed in terms of GDP growth over time. He stressed that economists must integrate political constraints into their advice and consider a range of instruments, including FlexRegs and subsidies. Jaccard concluded that providing policy recommendations as if advising a benevolent despot is unrealistic and that economists should work with policy analysts and public opinion experts to help politicians balance economic efficiency with political acceptability.

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Conclusion

Designing climate policy is never just about economic efficiency. Schubert showed that even well-intentioned subsidies can come with significant welfare and fiscal costs, despite its higher acceptance to the public than carbon pricing. Fan illustrated how these challenges play out in China, where achieving carbon neutrality by 2060 requires careful planning across technology, markets, and consumer behavior. Jaccard reminded us that political realities like electoral constraints in Canada, could make FlexRegs and subsidies more effective in practice than carbon pricing alone. Taken together, successful climate policy must reconcile economic, political, and social considerations, indicating that efficiency, equity, and acceptability all play a role in the transition to a low-carbon future.

Energy Poverty in the World: Improvement or Increasing Gap? - Dual Plenary Session 1.2

By Laura Natalia Beltran Genera (MsC, ln.beltrang@gmail.com) and Alice Mevel (MSc Paris School of Economics, alice.mevel@psemail.eu)

Session Chair:
Pr Anna Creti (Paris Dauphine PSL University)

Speakers:
Pr Anna Alberini (University of Maryland)
Dr Stuti Khemani (World Bank)
Pr Roula Inglesi-Lotz (University of Pretoria)

This plenary explored global energy poverty and its relationship with widening economic disparities and the just energy transition. Speakers addressed three dimensions: definitions and measurement (Pr Alberini), policy design and institutional constraints (Dr Khemani), and the social justice implications (Pr Inglesi-Lotz).

Anna Alberini opened the discussion with a survey of how energy poverty is defined and measured across contexts. In high-income countries, energy poverty typically refers to households unable to afford adequate heating or cooling, or those facing high energy cost burdens relative to income. In low-income and developing countries, the concept broadens to include complete lack of access to electricity, dependence on unsafe fuels for cooking, and infrastructure unreliability.

Pr Alberini noted the absence of a single agreed-upon metric. Common measures include the "10% rule" (households spending more than 10% of income on energy), arrears on utility bills, and inability to keep homes at a safe temperature. But these are typically self-reported, irregular, and fail to capture seasonal effects or persistence over time. She pointed out that data is often cross-sectional rather than longitudinal, making it difficult to trace causality or long-term trajectories.

Energy poverty is the result of a combination of structural, economic and environmental factors that tend to occur alongside broader income poverty. However, unlike income poverty, energy poverty can be triggered by external shocks over short periods, such as unpredictable spikes in energy prices caused by global crises like the pandemic or the war in Ukraine. These events cause fluctuations in supply. Energy poverty can also be triggered by policy reforms, such as the removal of energy subsidies or the liberalisation of tariffs, which reduce the affordability of energy for the poorest. Furthermore, climate change exacerbates the issue by increasing energy demand due to more frequent and severe extreme temperatures.

Pr Alberini pointed out that the transition to electricity systems could exacerbate energy poverty for the most vulnerable people if policies are not well defined. She gave the example of shifting to electricity, particularly through carbon pricing channels, which may initially increase costs before long-term benefits are realised, putting further short-term pressure on vulnerable people. Moreover, poor housing, particularly poorly insulated homes, increases energy demand, requiring additional energy to cool or warm residential spaces and resulting in higher costs. She concluded by emphasising that these diverse and often co-occurring causes must be identified in order to create effective policies to support the most vulnerable people.

On the other hand, Stuti Khemani challenged the assumption that direct subsidies and progressive tariffs necessarily alleviate energy poverty. Drawing on World Bank research, she argued that these approaches can produce counterproductive general equilibrium effects. In South Asia, for example, subsidies have distorted electricity pricing, discouraged infrastructure investment, and entrenched political patronage systems.

Dr Khemani emphasized that energy poverty in regions like sub-Saharan Africa is fundamentally tied to institutional capacity. Without improving state capacity, revenue collection, and local governance, scaling up access will not be sustainable. Her framework treats energy poverty as a constrained optimization problem—balancing SDG7 goals with tight fiscal and political limits.

She pointed to East Asia, particularly China, as a case where rural electrification was successfully embedded in broader local economic strategies. In contrast, countries that rely solely on subsidies without institutional reform tend to see stagnation or regression. She also noted the importance of local governance: evidence from India shows local politicians were less inclined to support free electricity than national-level counterparts, possibly because they face more direct accountability.

Her recommendations emphasized the importance of solid policies to reduce energy costs and encourage investment in infrastructure, particularly renewable energy. Delinking tariff setting from welfare policy is an essential part of this. This would give utilities, whether private or public, greater freedom and reduce the threat of political intervention. Utilities must also be reformed to create incentives for innovation, lower costs and increase service reliability, while keeping tariff structures financially acceptable and consumer-friendly.

Alongside these reforms, local governments must become more effective in directing public spending towards poverty reduction through targeted welfare transfers, investment in roads and infrastructure, and access to credit markets. Local institutions must also be strengthened. Local institutional changes can enhance legitimacy, provide subsidy reforms more effectively, and improve fiscal ability. As electrification spurs local economies, increased property values can be leveraged through taxation to support ongoing infrastructure needs. Together, these policies can create a sustainable and equitable framework for expanding energy access and overcoming structural barriers to productive electricity use.

Roula Inglesi-Lotz extended the discussion to justice and inequality. She began by pointing out how subjective the concept of energy poverty is—many people in rural areas may not consider themselves "poor" in energy terms simply because they've never had access or alternatives. This highlights a key issue: energy poverty is not only a question of access, but of affordability, quality, reliability, and consumer agency.

She presented global data that confirms progress in reducing energy poverty has been regionally uneven. Sub-Saharan Africa stands out as the only region where the number of people without electricity has increased, driven by population growth. Access to clean cooking fuels remains particularly low in both Africa and parts of Asia.

Pr Inglesi-Lotz distinguished between Global South and Global North experiences: while the former struggles with basic access and reliability, the latter faces affordability and hidden energy poverty. She cautioned against blanket policies, pointing to intra-country disparities and the risk of poorly targeted subsidies reinforcing inequalities.

She also problematized the notion of a "just" energy transition. For many in sub-Saharan Africa, the urgency is not about decarbonization but about securing basic access. The transition risks widening the access gap unless carefully managed. For instance, South Africa's solar panel subsidy disproportionately benefited wealthier households who could afford the up-front investment, excluding the poor and destabilizing the grid.

Pr Inglesi-Lotz added that the energy transition can be a powerful tool for tackling energy poverty if it is planned and implemented with equity, security and sustainability in mind. Targeting infrastructure investments at the specific needs of vulnerable individuals can provide access to modern, secure and clean energy services, which also improves health and wellbeing and creates new jobs that can lift communities out of economic poverty.

To prevent energy poverty from being exacerbated, the forthcoming challenges must be anticipated, such as job losses in the fossil fuel sector, stranded assets and higher energy prices resulting from the introduction of new technologies. Unless these transformations are managed effectively, they are likely to affect poor households disproportionately. Pr Inglesi-Lotz also noted that resilient and responsive institutions are key to mitigating these risks. She mentioned that corruption-free, high-quality regulation and good governance can facilitate targeted investment and ensure that energy transformation policies are inclusive, resilient, and maximally transformative for all.

Conclusion

The panel converged on a few core themes: energy poverty is multifaceted and context-dependent; solving it requires more than subsidies or technical fixes—it demands coherent, long-term policy grounded in local institutions and economic development. Global disparities are likely to widen unless energy access is integrated into broader strategies for fiscal reform, state-building, and equitable development.

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Sustainable Electricity Generation: Enabling Electrified Uses - Plenary Session 2

By Alice Mével (MSc Paris School of Economics, alice.mevel@psemail.eu) and Shruti Gupta (MSc Sustainable Impact Analysis, Paris School of Economics, shruti.25gupta@gmail.com)

Session Chair:
Dr Yukari Yamashita (Executive Director, Institute of Energy Economics)

Speakers:
M. Marc Benayoun (Group Senior Executive Vice-President, Customers & Energy Services, EDF)
Pr Catherine Wolfram (MIT Sloan School of Management)
Dr Christian Zinglersen (Director of European Union Agency for the Cooperation of Energy Regulators)

This plenary session examined how the main constraints of decarbonisation have shifted away from technology towards economics and governance. Renewable electricity is increasingly abundant, but its integration depends on flexible, price-responsive demand, credible carbon pricing and strong institutional frameworks. The three contributions focused on Europe's stagnant demand, the global spillovers of carbon pricing, and the governance gaps in power markets and grids.

Marc Benayoun argued that Europe has entered a "post-growth" demand regime. In France, electricity consumption in 2024 remained around 8 per cent below the 2018–2019 average, returning to levels last seen in 2003–2004. The trend is continental: in the United Kingdom, industrial load has fallen by more than 30 per cent since the early 2000s.

He explained this decline through three mechanisms: (1) de-industrialisation, as high energy prices and weak policy coordination pushed heavy industry abroad; (2) corporate efficiency contracts, exemplified by La Poste's retrofit of one million square metres of buildings, which saves more than 20 GWh annually; and (3) residential behavioural change, as households reduced their usage after the 2022 price shock and maintained these habits with the help of EDF's EDF & Moi/Écowatt application, which now has over 50 million users and smart meters connected to monitoring tools.

The combination of stagnant demand and fast renewable deployment has created oversupply. France recorded more than 400 hours of negative wholesale prices in 2024, compared with 180 in 2023 and none in 2022. This erodes merchant revenues and even EDF's integrated margins. At the same time, electrification has slowed: sales of heat pumps fell by 35 per cent when subsidies were paused, electric-vehicle registrations declined after changes to bonus–malus rules, and hydrogen offtakers remain cautious while contract-for-difference schemes await EU approval.

M. Benayoun warned that demand-side electrification is not self-sustaining and requires policy support to be effective. He proposed three levers: (1) durable capital incentives for technologies such as heat pumps and electric vehicles; (2) integrated programmes that link efficiency with electrification to absorb surplus renewable generation; and (3) expanded capacity and flexibility markets to monetise demand response and storage. He also pointed out that policy asymmetry across EU member states is economically incoherent, as countries have heterogeneous starting points and face different challenges.

Catherine Wolfram turned the discussion to the global geopolitics of carbon pricing. She argued that carbon markets are now the main engine of climate policy, with 17 of the G-20 economies applying some form of carbon price. Russia, Saudi Arabia and the United States remain the main exceptions. In the U.S., she explained, three factors block progress: (1) the country's status as a leading oil and gas exporter, (2) the reserve-currency privilege that shields it from external pressure, and (3) deep political polarisation that leaves both left and right sceptical of carbon markets. Ironically, she noted that a further U.S. retreat from climate leadership could accelerate reforms in other blocs.

The EU's Carbon Border Adjustment Mechanism (CBAM), due to take effect in January 2026, will apply the EU carbon price to imports of steel, cement, aluminium, fertilisers, hydrogen and electricity, adjusted for any levy paid in the country of origin. Anticipating this, Turkey, Brazil and China are expanding their emissions trading systems to ensure charges are collected domestically. The EU and the UK are also exploring market linkage, signalling the emergence of a more interconnected global carbon-pricing web.

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Pr Wolfram illustrated these dynamics with Mozambique's Mozal aluminium smelter, which runs largely on hydropower. Today, Mozal sits around the 20th percentile of the global cost curve. Once coal-based competitors face a €90 per tonne CBAM levy, Mozal could move up to the 5th percentile, securing a competitive advantage. If Mozambique introduced a €50 per tonne domestic carbon tax that was credited against EU charges, it could generate revenue worth about 1 per cent of GDP without undermining the smelter's position. Exporting aluminium in this way effectively embeds renewable electricity at around €2 per exported MWh, far cheaper than exporting electrons directly or in the form of liquefied hydrogen, which costs €180–220 per MWh.

She concluded that carbon pricing can reward countries with clean electricity resources, provided they invest in robust grids and credible monitoring and verification systems. Far from being a form of regulatory colonialism, CBAM can create opportunities for African economies to pursue green industrialisation while capturing new fiscal revenues.

Christian Zinglersen focused on the mismatch between Europe's rapid renewable build-out and its lagging market and grid frameworks, which he described as a "plumbing crisis." Although average prices have eased since 2022, volatility remains severe. Intraday swings of more than €50 per MWh occur on 70 per cent of trading days, and Spain saw a spread of €180 per MWh in April 2024. Negative-price hours have increased more than tenfold since 2021. Meanwhile, imported liquefied natural gas (LNG) still sets the seasonal margin, meaning global gas shocks continue to shape European power bills.

He identified three governance gaps: (1) cross-border bottlenecks, as only 17 out of 27 EU countries comply with the rule to offer at least 70 per cent of interconnector capacity to the market, leaving renewable surpluses stranded while neighbouring states pay peak prices; (2) locked-out flexibility, since nine countries lack legal frameworks for aggregators, and most consumers remain on flat tariffs that provide no incentive to shift demand, excluding batteries, electric vehicles and smart-home devices from system balancing; and (3) unchecked grid spending, as transmission system operators plan €500–800 billion of investment through 2030, often without first optimising existing assets through digitalisation and dynamic pricing.

Dr Zinglersen argued that Europe should (1) reward flexibility before adding new grid infrastructure, (2) finance interconnectors on a benefit-sharing basis, and (3) give ACER sanctioning powers to ensure compliance. Using a humorous The Simpsons clip, he illustrated that adding imperfect policy fixes—such as subsidising electrolysers to absorb excess supply—only worsens distortions. For him, only market and governance reforms can turn renewable abundance into a reliable supply, stable prices and competitiveness.

For concluding remarks as moderator, Yukari Yamashita framed the debate within the "twin pressures" of decarbonisation and energy security. She cautioned that Asia should not assume electricity demand will rise in a straight line as devices proliferate, underlined that ASEAN steel exporters to Europe will need credible carbon data, and warned that without regional regulators, Asia's grid upgrades could prove costlier and less flexible.

Overall, the plenary underscored that the challenge of sustainable electricity generation no longer lies in technology but in governance, economics and institutions. Without stronger demand-side support, coordinated markets and effective regional cooperation, abundant renewable capacity risks becoming stranded rather than powering the next wave of electrified growth.

Key Takeaways

- Decarbonisation challenges lie more in economics, governance and institutions than in technology.
- Europe's electricity demand is stagnating while renewable capacity continues to grow, creating oversupply and price volatility.
- Carbon pricing, especially CBAM, is reshaping global markets and may enable green industrialisation in countries with clean power resources.
- Europe's market and grid frameworks are lagging behind renewable deployment, leading to volatility and stranded capacity.
- Stronger policy support for electrification, coordinated carbon pricing and robust governance reforms are essential to ensure renewables drive sustainable growth.

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Dual Plenary Session 2.1 - Gas based solutions for sustainable future? perspectives on Hydrogen, Biogas and CCS

By Laura Natalia Beltran Gerena (MSc Sustainable Impact Analysis, Paris School of Economics, ln.beltrang@gmail.com) and Hayeon NAM (MSc Sustainable Impact Analysis, Paris School of Economics, hayeon.kate@gmail.com)

Session Chair:
Pr Olivier Massol (Université Paris Saclay)

Speakers:
Pr Christian Von Hirschhausen (DIW Berlin),
Dr Yukari Yamashita (Institute of Energy Economics)
Ms Marie-Claire Aoun (Director of Strategy and institutional relationships, Teréga)

Olivier Massol, who holds the position of professor at Centrale Supélec et University Paris Saclay, chaired the session. In his opening speech, he emphasized that recent shocks have exposed vulnerabilities in global gas markets, particularly in Europe, resulting in profound shifts. This turbulence has dispelled the idea of gas as a simple "transition fuel", necessitating a careful balance between affordability, security, and decarbonisation. In response to these challenges, the session aimed to critically reassess a range of technologies both old and new. Three experts joined as keynote speakers: Christian Von Hirschhausen of TU Berlin et DIW Berlin; Yukari Yamashita of Institute of Energy Economics; and Marie-Claire Aoun of Teréga. Each of them proposed a combination of solutions that included low-carbon hydrogen, biomethane, and Carbon Capture Storage (CSS). They also highlighted the challenges associated with them, such as high costs, inconsistent policies, and integration into existing systems.

Energy transformation should be approached from a long-term perspective. The first speaker of the event, Christian Von Hirschhausen, opened the discussion by introducing Cesare Marchetti, who originated the concept of CCS. M. Marchetti was an Italian physicist and systems analyst who in the 1960s first introduced the concept of energy transition in the form of energy substitution theory. He defined energy transition as the long term technical substitution of wood by other fuels such as coal, oil, natural gas and hydrogen. Although his ideas do not fully explain the dynamics of today's energy transitions, his work continues to influence current thinking.

After, Pr Von Hirschhausen turned his focus to more recent developments, and discussed his recent work which focuses on the need for a voltaic pipeline and a Europe without Russian exports. His research shows that if the infrastructure is used efficiently, Europe can survive without Russian gas — highlighting the importance of more flexible and adaptive infrastructure use. He also identified two main challenges in the current hydrogen market: first, its structural design and second, the balance between centralized and decentralized production and consumption. The latter issue is particularly problematic because localized production, the logical offshoot of decentralization, requires the supply of specialized pipelines and the optimal functioning of local industrial clusters, which are currently insufficient.

In the final part of his presentation, Pr Von Hirschhausen gave a historical overview of CCS technology and its more recent iterations. CCS was originally discussed in the 1920s, when CO2 was first separated in the US. Despite its long history, CCS suffers from a mismatch of projected use and widespread adoption. A more contemporary version of this technology, Direct Air Capture (DAC), is even less known to the public. Among its mechanisms, chemical absorption and electrochemical methods are similarly competitive in technology and comparable in market share. The key question is how these approaches will evolve over the coming decades, and how much time will need to reach maturity. The future is uncertain, and many energy and climate scenarios in the IPCC and elsewhere tend to repeat familiar social and technological patterns. Efficient use of existing infrastructure, improved market design, localized hydrogen solutions, and technological innovation in CCS and DAC will be crucial for ensuring a sustainable and resilient energy future.

The second speaker Yukari Yamashita begins the discussion on hydrogen by noting that achieving carbon neutrality requires a multi-pronged approach, incorporating energy efficiency measures, widespread electrification and innovative solutions for sectors where electricity is not sufficient. Hydrogen can indeed play a pivotal role in the energy transition era, as it is a versatile, low-carbon fuel capable of addressing current gaps in the transition. Unlike electricity, it can decarbonise "hard-to-abate" sectors such as industrial heat and heavy transport. Its ability to store energy also makes it invaluable for balancing the intermittent nature of renewable sources. She points out, for instance, that surplus wind or solar power can be used to produce hydrogen via electrolysis, which can then be stored and used during periods of low renewable generation. Moreover, ammonia and synthetic fuels (e-methanol) further expand hydrogen's utility by serving as transportable carriers, though questions linger about their lifecycle emissions.

Nevertheless, Dr Yamashita noted that economic and political challenges must be taken into account. Electrolysis and CCS remain costly, and hydrogen's low energy density requires expensive infrastructure upgrades. Import-dependent nations such as Japan also face logistical complexities, such as converting hydrogen to ammonia for transport and back again. Furthermore, cross-border standards for hydrogen trade and carbon accounting are lacking, creating market uncertainty. Lastly, price volatility and shifting export policies make long-term planning difficult.

Dr Yamashita emphasized the need for rapid technological advancements, particularly in reducing the cost of green hydrogen, as well as stronger international collaboration to establish standards and secure demand. While Japan's feasibility studies and CCS projects represent progress, scaling up hydrogen production to meet net-zero targets will require unparalleled public-private sector collaboration. In her closing remarks, Yamashita struck a cautious yet optimistic tone, stating that hydrogen is not a magic solution, but that with targeted innovation and cooperation, it could form the foundation of a clean energy future.

The third speaker of the event was Marie-Claire Aoun of Teréga. Teréga is the French gas transmission system operator and storage operator, representing 14% and 25% of the French gas pipeline network and gas storage capacity. Ms Aoun emphasized Teréga's commitment to expand its business portfolio beyond gas transmission, to include a new role as an operator of "infrastructure molecules," transporting hydrogen and CO2.

Global gas consumption is declining, but renewable gas, in particular biomethane from methanation, is increasing in France. Under French law, the country must meet 15% of its gas consumption from renewable gas by 2030. The production cost of biomethane remains high compared to natural gas, but this price gap can be bridged by valorizing the other positive externalities that biomethane provides. For example, it supports agriculture, creates jobs, and contributes to the circular economy. In addition, as biomethane fits into existing gas networks without new infrastructure investments, it allows an easier transition to renewable energy compared to other sources.

Alongside renewable gases, electrification is essential to achieving carbon neutrality. Nevertheless, not all uses can be electrified. In this context, hydrogen offers a promising solution. European countries aim to expand hydrogen production through electrolysis, prioritizing decentralized infrastructure by building electrolyzers and encouraging local consumption until centralized models are in place. High-demand regions like Germany and the Iberian Peninsula, including Portugal and Spain with strong solar potential, are main targets.

The BarMar project, which plans to create a hydrogen corridor from Portugal and Spain, through France, to Germany, exemplifies this strategy. To reduce capital expenditures of the project, existing gas pipelines were repurposed by replacing compressors where feasible and redundant lines that were freed up due to declining natural gas demand were used. Despite these efforts, implementing hydrogen infrastructure presents difficulties, particularly regarding the economic model and business plan. Securing regulatory visibility is therefore vital to secure long-term market commitment.

As for Carbon Capture, Utilization and Storage (CCUS), Ms Aoun emphasized the importance of the "utilization" part. This is because there is potential for biogenic CO2 from biomass in the southwest region of France, which could be used for power-to-gas or e-fuels. Like hydrogen, several projects are in progress, pipelines transporting CO2 to storage sites. CCUS is also seen as a promising avenue for industrial emitters constrained by the EU ETS, since they are expected to lose access to free quotas in the near future.

Conclusion

The energy transition for a sustainable future requires diversified and integrated approaches. No one solution alone can fully address the triple challenge of affordability, energy security, and decarbonization. Technologies that have been debated from hydrogen and biogas to CCS and DAC, are all promising but each of them also faces economic, technological, and regulatory issues. From the discussions, it is very clear that there is a need for smarter use of infrastructure, adaptive market design, and stronger international cooperation to enable these solutions to be deployed at scale and become affordable.

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Energy decentralised markets and environmental policies in territories: an efficient bottom up scheme - Dual Plenary Session 2.2

By Rowena Mathew (PhD Candidate, University of Savoie-Mont-Blanc, rowena.mathew@univ-smb.fr)

Session Chair:
Pr Yannick Perez (University Paris-Saclay)

Speakers:
Pr Michael Caramanis (Boston University)
Pr Ricardo Ranieri (Pontifical Catholic University)
Pr Laurens de Vries (Delft University of Technology)

Dr. Caramanis mentioned that uncertainty from wind and solar generation is increasingly evident in operational planning, from day-ahead and week-ahead markets all the way to real-time balancing and transmission management. Market clearing processes are evolving to address these challenges, with robust LMP (Locational Marginal Pricing) and adaptive DLMP (Distributed Locational Marginal Pricing) methods being developed.

Both individual assets and the system as a whole face risk. For renewable generation, this includes uncertainty in available capacity at the asset level and correlated impacts at the system level. Demand, meanwhile, often exhibits price inelasticity, especially in areas such as EV charging and HVAC usage. Storage is expected to play a key adaptive role in the day-ahead market and in SCED (Security Constrained Economic Dispatch). Congestion management and contingency planning are also critical, particularly as transmission constraints can amplify risk.

On the demand side, certain loads effectively behave like storage at scale, especially at the wholesale level. California's "duck curve" highlights the challenge: solar generation creates steep net load peaks that require costly catch-up in dispatchable generation. Wind forecasting is another important tool; specialized companies in the U.S. now provide forecasts ranging from 5 minutes to 50 hours ahead, using granular models at 5x5 km resolution to capture the risks of uncertain wind generation.

The newRAMP (Risk Assessment Management Paradigm) framework has emerged as a way to integrate risk into energy market operations. Market-based reserve planning is becoming essential under conditions of highly uncertain renewable generation. Since total generation is distributed differently across time and space, location awareness is critical: reserves must be deployed effectively to alleviate transmission congestion and reduce short-term marginal costs across locations. Reconfiguring transmission and distribution networks can also help improve reliability and efficiency.

Studies have been carried out in the U.S., such as modeling the Southwest Power Pool (SPP) in PSO and benchmarking performance. One of the key findings is that socially optimal scheduling requires acceptable pricing mechanisms that support distributed decision-making. However, achieving this under non-convex market conditions remains an emerging challenge.

Uncertainty in both net demand and centralized renewable generation is proving to be a game-changer. Power flows often move from high-supply to high-demand regions, which risks overloading transmission paths. Once capacity limits are reached, electricity cannot be moved further, making line congestion avoidance crucial. On the edges of the transmission and distribution system, radial substations with no interconnection raise concerns about power quality and end-user supply reliability.

Cost structures show that generation accounts for about 50% of total costs, transmission for 5%, and distribution for 45%. This suggests that both centralized transmission-level management and decentralized, interactive, adaptive distribution-level management must be considered. Overloading risks are also growing eg. widespread EV charging can overload service transformers and drastically reduce their lifespan. Case studies, such as DLMP-based equilibrium pricing in upstate New York on sunny days, further demonstrate how renewable variability and localized conditions shape cost outcomes.

Dr. Ranieri started his address with some history about Chile's electricity markets, mentioning that Chile was the first country to liberalize its electricity markets in the 1970s, setting an influential example for others in the region. The country introduced straightforward energy laws and implemented a central dispatch system. Its electricity sector was restructured into separate markets for generation, transmission, and distribution. While transmission operated as a mix of monopoly and open access, generation was fully liberalized. A significant portion of output, nearly one-third, was consumed directly by mining companies, with electricity sold to them under direct contracts.

In recent years, energy systems worldwide have been shifting away from traditional top-down centralized planning toward more decentralized, bottom-up approaches. These new schemes allow generation and demand to be managed at the local, municipal, or prosumer level, often through distributed energy resources (DERs) such as rooftop solar, microgrids, and PMGDs (Pequeños Medios de Generación Distribuida). Policy and governance frameworks are increasingly designed to respond to local needs, embedding projects within communities.

This bottom-up approach has important social and political implications. It transforms opposition into support by moving beyond "Not In My Backyard" resistance. Participation, legitimacy, and fairness are fostered through economic inclusion, community ownership, and resource localization. However, the model also introduces challenges. Coordination gaps, system fragmentation, balancing difficulties, and the lack of standardization can limit effectiveness. In some cases, local projects are invisible to system operators, provide no frequency control, and disconnect automatically during disturbances.

Governance and implementation risks add further complexity. Technical constraints, knowledge gaps, and misalignments between system operations, grid services, policy objectives, market signals, social movements, and cybersecurity concerns all contribute to vulnerabilities. For instance, Chile's power system grew from 240 power plants in 2010 (60 of which were small-scale under 9 MW) to more than 1,000 by 2025, including over 100 small-scale plants. Managing such a diversified and distributed system presents a significant challenge.

Hybrid governance frameworks are therefore emerging as a solution. By combining bottom-up participation with top-down oversight, they provide clearer regulatory boundaries, equitable access mechanisms, and stronger balancing arrangements. Without such mechanisms, decentralized systems are exposed to serious risks. Spain and Chile have both experienced blackouts that illustrate these vulnerabilities. In Chile, a transmission line failure in 2025 disconnected the northern and southern grids. Around 10% of the system, comprising small solar plants, automatically disconnected when frequency dropped below the safety threshold. The blackout began at 3 p.m. and cascaded through the system, taking nearly nine hours to restore.

These events underscore the need for a strong digital foundation to support bottom-up energy systems. Intelligent forecasting, smart grids with two-way communication, and real-time monitoring are essential to ensure resilience and stability. Without such infrastructure, bottom-up approaches risk becoming "bottom-out" failures, undermining both system reliability and public confidence.

Dr. De Vries believes that skepticism remains around the long-term role of local renewable energy in Europe's urban areas. Even net zero cities will continue to rely on the grid, particularly in winter months when local generation potential is insufficient. Most European cities lack the spatial capacity for significant renewable deployment, although cooling demand often aligns better with local generation. As a result, the strongest economic rationale for local energy markets lies in alleviating network congestion. Beyond this, distributed renewable energy (DRE) integration is supported primarily as a means to stimulate local flexibility and resilience.

Designing effective market structures remains complex. Nodal pricing is one approach, but it must be complemented by additional tariffs to recover the fixed costs of grid infrastructure. Incentives for network users are therefore not yet fully optimal, mirroring challenges also seen in the U.S. and Europe has adopted a combination of connection charges, network tariffs, and congestion management tools. Nonetheless, longer-term studies consistently show that full decarbonization and electrification will require massive new investments in the electricity grid. Local flexibility markets can help reduce these costs by 10–20%, but they are not a complete substitute for network reinforcement.

Price formation is shaped by renewable penetration and demand elasticity. With limited renewable generation, inelastic demand amplifies price volatility. With ample renewable supply, downward pressure can drive prices to zero or even negative levels. However, simulations suggest that zero-price events occur only 10–20% of the time, indicating that demand-side participation is essential in smoothing outcomes.

The DEMOSES project, led by Dr. De Vries as a PI, is addressing these barriers to flexibility. It aims to assess regulatory and market constraints, while coupling partner models to express flexibility without requiring confidential data exchange. Yet a persistent "chicken-and-egg" problem remains: to model the future electricity system, analysts need data on the flexibility of large consumers, but those consumers require clearer price signals to justify investing in flexibility.

Several additional issues complicate the transition. In Europe, network charges remain the primary barrier to flexibility. In the Netherlands, net metering for solar has become problematic, while time-of-use (TOU) tariffs offer a more promising solution. Another challenge is enabling multi-day flexibility: while electricity storage remains costly, heat can be stored more cheaply, making it a priority for market design. European wholesale markets may therefore need to incorporate "micro-forward" structures to capture these opportunities.

Hydrogen is now a formal policy priority in the Netherlands, where it is positioned as a centralized green energy source. However, regulators face uncertainty regarding industrial demand for hydrogen and the scalability of electrolysis. Alternative pathways to decarbonization, such as heat networks and geothermal systems, may offer more immediate efficiency gains, especially since 40% of electricity demand in the Netherlands is related to heating.

Overall, local markets represent only part of the broader solution. Even in well-insulated, net zero cities, the central grid will remain indispensable. While the long-term contribution of local markets is limited, they provide valuable complementary flexibility, helping to reduce costs, support integration of renewables, and enhance system resilience. Coherent market design remains the critical challenge to ensure that both centralized and decentralized elements work together effectively

Energy networks, decentralization and connected consumers: a new role for grids - Dual Plenary Session 3.1

By Laura Natalia Beltran Gerena (MSc Sustainable Impact Analysis, Paris School of Economics, ln.beltrang@gmail.com) and Hayeon NAM (MSc Sustainable Impact Analysis, Paris School of Economics, hayeon.kate@gmail.com)

Session Chair:
Chloé Le Coq (Université Paris Panthéon-Assas)

Speakers:
Pr Paul L. Joskow (MIT)
Pr Chiara Lo Prete (Penn State University)
M. Thomas Veyrenc (Member of the Executive Board, Managing Director in charge of Economy, Strategy and Finance, RTE)

The traditional model of large, centralized power plants delivering electricity to passive consumers is evolving. Chloé Le Coq of Université Paris Panthéon-Assas chaired the session and highlighted how consumers are becoming more active in the energy system through solar panels, electric vehicles, and smart devices. The grid itself is also evolving: neighbors are forming microgrids, and the boundary between producers and consumers is becoming blurred. Supply and demand are now more dynamically connected than ever. This dual plenary session explored key questions, including how to manage increasingly complex electricity networks, what being truly connected means for consumers, and whether decentralization can lead to a more efficient, resilient, and accessible energy system. Three experts joined as keynote speakers: Paul L.Joskow of MIT; Chiara Lo Prete of Penn State University; and Thomas Veyrenc of RTE.

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The first speaker of the event, Paul L.Joskow opened the discussion by pointing out that economic research has mostly focused on generation and transmission, while distribution has been neglected. L.Joskow argued that as decarbonization progresses, distribution network economics deserves more attention. The increasing use of electrification, such as electric vehicles (EV), electrical heat pumps, rooftop PV, batteries, and storage, offers limited flexibility but has a significant impact on distribution networks. These changes are making electricity demand more diverse in terms of peak times and load profiles.

Massive investments are being proposed to accommodate these new applications. An example from Massachusetts shows that around one-third of substations will need expansion to support future EV and heat pump penetration. Consumer electricity bills also reflect this shift. Delivery charges are rising faster than energy supply costs, which are actually declining. L.Joskow emphasized that this is a common phenomenon across the US. Public policy goals are being funded through electricity bills rather than general taxation, as this approach is more implicit and less visible to the public.

Facing these issues, Time Of Use (TOU) pricing has been proposed to shift electricity demand away from peak hours. However, a study by MIT found that poorly designed TOU schemes can cause unintended new demand spikes immediately after prices go down. These sudden surges trigger reliability issues on the distribution network and require substantial investments to maintain system reliability. In response, a Canadian field experiment suggested that pairing TOU pricing with utility-managed charging, where the utility controls the EV charging schedule, effectively shifted load without this issue. Although heat pump usage patterns create less pronounced peaks than EVs, combining new loads add significant complexity. This means that, even with utility-managed charging, distribution companies may still face challenges in balancing demand across a wide range of devices.

Consequently, distribution economics must be prioritized in energy transition planning, and field experiments are essential for understanding actual consumer behavior. Providing price signals and allowing consumers to self-manage their usage may offer a more effective approach. Yet consumers are not fully rational, which underscores the need for innovative pricing schemes that were originally designed for the collective generation network but are now implicitly applied to the semi-individual network.

Chiara Lo Prete followed the discussion by addressing the growing interdependence between natural gas and electricity systems in the U.S., particularly during winter storms, which have caused over $100+ billion in damages and 1,400 deaths since 1980. These extreme weather events reveal fundamental vulnerabilities in energy infrastructure as demand spikes simultaneously for both heating and electricity generation.

Their research revealed several systemic flaws in the current energy market. A key issue is that natural gas serves two critical roles: it heats 45% of U.S. households and generates 42% of the nation's electricity (up dramatically from just 17% in 1980). This dual dependence creates competing demands that intensify during winter emergencies. Three structural problems exacerbate this situation: (1) rigid long-term gas contracts that penalise power plants for necessary flow variations; (2) day-ahead gas markets that close too early (by 9:30 am) to accommodate real-time generator needs; and (3) local distribution companies (LDCs) withholding reserves due to misaligned incentives that prioritise regulatory compliance over overall system efficiency. As Lo Prete emphasized, these interconnected issues collectively undermine the resilience of the energy system during critical periods.

Pr Lo Prete proposed several policy solutions, including implementing "shaped flow" contracts with volumetric pricing to better match power plant needs, creating day-ahead reallocation mechanisms for gas reserves, and adjusting regulatory frameworks to encourage LDCs to release unused gas during emergencies. Australia's successful implementation of day-ahead auctions was highlighted as a potential model for improving system resilience while maintaining affordability and reliability. She emphasized the urgency of reforming gas markets to match electricity's flexibility needs, ensuring reliability amid escalating climate risks. Lastly, Lo Prete emphasized that significant research continues to model their potential impacts and implementation pathways.

The last speaker, Thomas Veyrenc, on the other hand, presented RTE's analysis, which highlighted the complex evolution of Europe's energy markets. These markets initially prioritized market integration and depoliticization in the early 2000s, but have since seen renewed government intervention, particularly in setting decarbonization targets. This shift has necessitated comprehensive planning, as demonstrated by RTE's 2050 energy study. This study moved beyond narrow cost comparisons, such as LCOE, to evaluate the full cost of the system, including flexibility, grid investments and the need for cross-border interconnection. The study revealed that the cost of grid modernization would triple to match generation investments, providing a crucial insight that had previously been missing from public debate.

The study outlined three core pillars for France's grid strategy: (1) replacing aging infrastructure while adapting to climate change, (2) integrating new low-carbon generation (renewables and nuclear) and demand-side solutions, and (3) reinforcing high-voltage transmission to accommodate shifting generation patterns, such as westward wind and nuclear expansion. These measures are crucial for France to meet its net-zero targets, especially given that industrial consumers still rely on fossil fuels and the importance of cross-border coordination is growing.

A key challenge lies in balancing political, technical and market-driven priorities. For instance, the nuclear versus renewables debate hinges on capital costs and technological progress, while grid investments must align with long-term generation shifts. RTE's work highlights that achieving decarbonization requires more than just new generation capacity, since it also requires a fundamental rethink of grid planning that integrates climate resilience, flexibility, and European cooperation.

Conclusion

This session emphasized the urgent need to modernize energy grids to facilitate decentralization and climate resilience. Joskow emphasized the importance of better distribution planning for electrification, while Lo Prete proposed gas market reforms to prevent winter crises. Veyrenc, meanwhile, outlined France's grid overhaul for renewables and nuclear power. They all agree that successful energy transitions require integrated technical, economic and policy solutions. As grids evolve, collaboration between all stakeholders will be essential in building reliable, affordable and sustainable systems.

Energy Access in Developing Countries: Renewables or Fossil Fuels? - Dual Plenary Session 3.2

By Shruti Gupta (MSc Sustainable Impact Analysis, Paris School of Economics, shruti.25gupta@gmail.com) and Alice Mével (MsC, alice.mevel@psemail.eu)

Session Chair:
Ricardo Raineri (*Pontifical Catholic University*)

Speakers:
Dr Axel Pierru (Vice President, Knowledge & Analysis, KAPSARC)
Dr Vibha Dhawan (Director General, TERI)
Pr Ujjayant Chakravorty (Tufts University)

This session addressed the core development dilemma facing the Global South: how to expand energy access equitably while transitioning toward cleaner energy sources.

Axel Pierru argued from the perspectives of fuel importer and exporter that energy access in developing nations cannot be reduced to "renewables versus fossil fuels." He showed—using cross-country data—that electrification strongly bi-directionally correlates with GDP per capita but also depends on policy decisions, import dependency, and institutional capacity.

Countries fall into two broad groups: (1) those with high access but dependent on energy imports and (2) those with low access but resource-rich. Within this context, many have expanded electricity access primarily through fossil-based infrastructure, including coal and diesel generators.

He examined the trade-offs:

- Fossil generators: low upfront cost, high running costs and emissions.
- Renewables + battery storage: low operating costs, low emissions, but capital-intensive and intermittent.

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On clean cooking energy, Dr Pierru presented case studies from East Africa and West Asia where biomass dependence incurs massive social costs—from non-renewable deforestation to women's lost labor time. He suggested LPG as a practical clean alternative but stressed that affordability, financing, and infrastructure are key.

Gulf states (GCC) are building out local renewables supply chains to:

- Capture high-value jobs and diversify away from oil & gas economies, and
- Hedge against transition risks: (e.g. future carbon border taxes and import-reliance shocks). This may entail, at least in the short run, paying a small premium over China's cost advantage.

He warned against "low-access equilibrium traps" caused by subsidized electricity pricing that distorts investment signals and degrades grid reliability, citing examples from South Africa and Nigeria.

Way Forward: Low countries need assistance to adapt to decarbonization. Pragmatic approaches are needed from global institutions to balance low-carbon transitions with energy access, particularly by reconsidering restrictions on financing natural gas projects in resource-rich regions like Africa.

Vibha Dhawan provided an overview of India's transition. While village-level electrification is complete, supply quality remains uneven—especially in rural and agricultural regions. With 300+ sunny days per year, solar energy has emerged as a low-cost, decentralized option for both households and farms. Agrivoltaics and solar irrigation are central to this strategy, along with a push for rooftop solar through subsidies and free electricity schemes.

She discussed how India's energy policy increasingly blends renewables with rural development. Innovations like Agrivoltovics, solar irrigation systems, solar-powered cold storage chains, distributed food processing, and successful programs such as "pay-as-you-go" mini-grids and "Light a Billion Lives, are being piloted as income multipliers.

Yet clean cooking fuel adoption lags despite LPG subsidies. Capital investment for solar and storage remains a barrier. Dr Dhawan called for better-designed carbon markets and skilling programs to ensure transitions are inclusive. She also noted institutional innovation, including India's National Green Hydrogen Mission and solar-powered transport infrastructure, as long-term enablers.

Ujjayant Chakravorty provided micro-level evidence from India and long-run econometric analysis from the Philippines. In India, his research revealed that rural biomass collection is not just subsistence-driven, it's also commercial. Households farther from forests often collect and sell more fuelwood, drawn by higher scarcity prices, locking communities into environmentally degrading cycles.

In the Philippines, Pr Chakravorty exploited a historical electrification policy that prioritized municipalities above 100,000 residents. Forty-five years later, those municipalities have significantly more infrastructure and lower electricity prices, but no measurable income gains. Instead, the main long-run effect was population migration—people moved toward cheaper, better energy.

These findings challenge conventional metrics. Short-term studies might overlook transformational outcomes like demographic shifts or infrastructure buildout. Chakravorty stressed that reliable, affordable energy does not automatically translate to economic growth—it often requires complementary assets like skills, capital, and market access. He also highlighted that rural households often have low willingness to pay, making cost recovery for energy programs difficult. Yet, improving energy access in developing countries presents a highly cost-effective strategy for CO_2 abatement—significantly cheaper than mitigation efforts in wealthier nations.

Conclusion

Across all speakers, a common message seemed to be that energy access must be viewed as context-driven. Technology choice matters, but not as much as affordability, governance, infrastructure, and social inclusion. Fossil fuels may have a role in transitional strategies, especially where natural gas is locally available, while renewables are essential for long-term sustainability.

Capital costs, financing models, and regulatory systems will determine whether solutions are accessible at scale. Equally, energy transitions cannot be delinked from local development strategies, especially in rural and agricultural areas.

Policy frameworks will need to balance the imperatives of access, equity, and decarbonization, while remaining tailored to local constraints. Perhaps most importantly, these transitions require long time horizons, cross-sectoral coordination, and a willingness to prioritize real-world outcomes.

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The challenge: Energy solutions for a sustainable and inclusive future: Which recommendations? - Closing Session

By Elias Zigah (PhD candidate, University Paris-Saclay, elias.zigah@centralesupelec.fr)
and Shruti Gupta (MSc Sustainable Impact Analysis, Paris School of Economics, shruti.25gupta@gmail.com)

The Closing Ceremony of the 46th International Association for Energy Economics (IAEE) International Conference, held on 18 June 2025 at the Palais des Congrès in Paris, marked the culmination of three days of debate under the theme "Energy Solutions for a Sustainable and Inclusive Future." The session combined recognition of research excellence, a gesture of climate solidarity, and wide-ranging reflections on the future of energy economics. It also looked ahead to upcoming conferences and paid tribute to the organisers whose efforts made Paris 2025 such a success.

The awards segment opened with the Best Poster Award. Out of 59 posters submitted, four finalists were shortlisted. After careful deliberation, the jury awarded the prize to Jacob Thrän (Imperial College London) for "Levelised Cost of Demand Response: comparison of energy storage and demand response using the levelised cost framework." His study systematically compared technologies such as pumped hydro, lithium-ion batteries, hybrid heat pumps, and vehicle-to-grid schemes, breaking costs down into investment, operations, rebound effects, and end-of-life. The jury highlighted its policy relevance, noting how demand-side flexibility can mitigate price volatility in renewable-rich power systems.

The Best PhD Student Paper Award followed. Seven papers were eligible, of which four were shortlisted. The prize was awarded to Maureen Kizza Lugolobi for her research on "Policy advancement for the interpretation of Indigenous knowledge and biogas-based clean cooking in Uganda: a pathway to climate resilience." Combining quantitative regressions with qualitative field analysis, her research showed how Indigenous knowledge can be integrated into modern energy strategies. The jury praised its clear message, methodological depth, and direct applicability to policy, pointing to lessons that extend well beyond Uganda.

A symbolic act of climate solidarity came next. Cédric Clastres, Chair of the Organising Committee, presented a donation to Geres, represented by its President Marie-Noëlle Reboulet. This French NGO supports sustainable development and energy access projects worldwide. The contribution, made possible by participants' voluntary carbon-offset payments, embodied the conference's commitment to match intellectual debate with tangible climate action.

The centrepiece of the closing session was a round-table of former IAEE presidents, invited to reflect on the plenary themes and draw lessons for the future. Peter Hartley (Rice University), Gürkan Kumbaroğlu (Boğaziçi University), Ricardo Raineri (Pontificia Universidad Católica de Chile), Yukari Yamashita (Institute of Energy Economics, Japan), and Edmar de Almeida (Federal University of Rio de Janeiro) offered perspectives shaped by diverse academic and regional experiences.

Reflections: While all stressed the difficulty of ranking such a broad programme, several plenaries stood out. The session on sustainable electricity generation and enabling electrified uses was praised for balancing academic rigour with business insight, highlighting Europe's paradox of flat demand alongside expanding renewables. The debate on gas-based solutions for a sustainable future was deemed crucial for hard-to-abate sectors, examining hydrogen, biomethane, and carbon capture. The discussion on energy access in developing countries resonated as a reminder that poverty and inequality remain central to the transition. Other reflections pointed to the importance of geopolitics, carbon pricing, and energy networks, confirming the breadth of issues confronting energy economists.

From these sessions, several themes emerged. Electrification remains central but depends on robust grids, flexibility markets, and institutional reform. Gas-based solutions, though costly, are unavoidable for industries where electrification alone cannot suffice. Energy access continues to expose the tension between development needs and climate goals, particularly in countries like India, where renewable ambitions coexist with coal expansion. The geopolitics of energy now centres as much on critical minerals and supply chains as on oil and gas. And climate policy must reconcile efficiency with acceptability: while carbon pricing is most effective, public preference often lies with subsidies and direct controls.

Gaps: The panel also identified gaps. Financing the transition was described as under-addressed, with calls for future conferences to devote plenary attention to investment models and subsidy design. Institutional bottlenecks, such as protracted permitting and fragmented regulation, were seen as equally binding. Regional perspectives reinforced these points: Texas and Australia illustrated how electricity and gas markets can destabilise each other during crises; South America faces a choice between becoming a fossil exporter or a renewable hub, depending on finance and policy clarity; and Asia struggles to balance surging demand with sustainability under weak institutional frameworks.

Looking forward, the ceremony announced the IAEE Mediterranean and Central Asia Conference to be held in Antalya, Turkey, on 4–6 December 2025, with abstract and paper deadlines in August and October. The 47th IAEE International Conference was confirmed for Santiago, Chile, on 19–22 July 2026, under the theme "Bridging Continents, Fueling Progress: Energy Development in a Global Context." The Chilean organisers highlighted the country's unique position as both an importer of hydrocarbons and a potential exporter of green hydrogen and renewable electricity.

The final moments were dedicated to acknowledgments. Cédric Clastres thanked speakers, participants, and especially student volunteers, stressing that their contributions were essential to the success of Paris 2025. A special tribute was then paid to Christophe Bonnery, who after fifteen years leading the French affiliate and decades of service to IAEE, is stepping into retirement. On behalf of the IAEE Council, Edmar de Almeida presented him with a recognition of his career. With emotion, Bonnery remarked that "this is not finished for me," signalling his ongoing commitment to the association. The French affiliate was hailed as a "stronghold of IAEE," and many participants described Paris 2025 as "the best IAEE conference I have ever attended." The presence of a large number of young scholars and students was also widely praised as a sign of renewal for the association. Volunteers and staff, including Olga and her team, were warmly applauded for their dedication.

IAEE Paris 2025 closed, then, with both celebration and reflection: recognition of research excellence, a tangible act of climate solidarity, and candid dialogue about the challenges of financing, governance, and geopolitics. The community left Paris not only with memories of an exceptionally successful meeting, but also with a collective mandate: to deepen analysis, broaden representation, and ensure that energy economics remains at the heart of the transition—next in Antalya, and then in Santiago.

The Sustainability Future of the Age of Electricity

BY XINYA HAO AND LIN ZHANG

Xinya Hao: School of Energy and Environment, City University of Hong Kong. **Lin Zhang:** Corresponding author, School of Energy and Environment, and Department of Public and International Affairs, City University of Hong Kong.

Abstract

This article examines the implications of rapid electrification of power demand and supply on energy sustainability, reliability, and accessibility. The upcoming Age of Electricity is generally positive for the Sustainable Energy Future, but there are potential threats that policymakers should be aware of.

The IEA's *World Energy Outlook 2024* report indicates a rapid global transition into the "Age of Electricity," driven by soaring power demand. Substantial new electricity requirements emerge across lighting, cooling, data centers, electrical appliances, and transportation sectors. From 2010 to 2024, electricity consumption grew annually at approximately 2.7%—nearly twice the rate of overall energy demand (IEA, 2024). Scenario analysis projects that unabated fossil fuels will be substantially replaced by clean electricity generation across nearly all sectors and regions. How will the electrification of energy demand and supply affect pathways toward a sustainable energy future? This article discusses potential opportunities and threats, following a "Sustainability, Reliability, and Accessibility" framework.

1. Sustainability

Electrification shapes the renewable energy revolution profoundly. By shifting end-use consumption from fossil fuels to electricity, electrification establishes a foundation for incorporating renewable options like wind, solar, and hydro power. Despite the reliance on coal and oil for power generation in many countries, end-use electrification is a crucial first step. This is why, even though China primarily depends on coal for electricity, promoting the penetration of electric vehicles is still regarded as an important strategy for energy transition. The economic logic, or assumption, behind this is that the demand-side electrification can motivate the supply-side transition. Market outlook and prospects shaped by the demand-side electrification, instead of policy incentives, are the most critical drivers for renewable energy investments and applications. This surge in electricity demand also sparks green technological and managerial innovation.

However, a potential threat is that the rapid increase in electricity demand may widen the supply gap, leading to greater dependence on fossil fuels in the energy structure. This demand-driven "lock-in effect" has three potential mechanisms. First, new coal or gas power generation infrastructure may be built to mitigate the energy gap. Once established, these facilities could continue to emit carbon for 30 years or even more, posing a significant threat to the decarbonization goal (Davis and Socolow, 2014). Second, the retirement of old non-renewable facilities may be delayed. Aging units typically exhibit lower thermal and carbon efficiency (Tong et al., 2018). If demand surges outpace new infrastructure deployment, average fleet age could increase. Third, the integration of a large number of variable renewable energy (VRE) units raises the demand for flexible generation. If ramping services are primarily provided by coal or gas units, the carbon emissions from these flexible plants could offset the environmental benefits of VRE integration.

Although renewable generation expansion hasn't fully met rising electrification needs, renewable capacity continues to accelerate rapidly. Global electricity demand increased by approximately 5,400 TWh from 2010 to 2020, representing an average annual growth rate of about 2.3%[1]. During this period, newly installed renewable electricity generation grew by roughly 3,312 TWh, achieving an average annual growth rate of approximately 6.0%[2]. Between 2010 and 2024, global solar photovoltaic capacity expanded 45-fold while wind power capacity grew sixfold.

While renewable energy growth globally is narrowing the electricity demand gap, regional heterogeneity requires careful assessment. Developing Asian nations like China and India are leading global energy transitions despite simultaneously building significant new coal-fired capacity (Wang et al., 2023). Conversely, geopolitical conflicts and volatile international energy prices have pushed Europe toward resurrecting coal power. These back-and-forths underscore significant uncertainties on the path toward a sustainable energy future. For instance, government-mandated energy policies and subsidies are essential for renewable energy's swift advancement. Yet this reliance implies that subsidy reductions could severely disrupt new energy investments and construction (Droste et al., 2024). Whether related technological innovation and diffusion advance rapidly enough to achieve market-competitive prices remains essential (Bretschger et al., 2017).

2. Reliability

The upcoming electrification era has significant implications for energy reliability and security. Electrifying both power generation and consumption increases socio-economic dependence on grid stability. The intermittency of VRE poses a key challenge for grid management. In April 2025, widespread areas in Spain and Portugal experienced an 11-hour power outage, severely disrupting business operations and daily activities. While investigations are ongoing to assess VRE's potential role in this incident, the event has cast a shadow across the renewable energy sector.

The rapid electrification amplifies the vulnerabilities of the power system. Existing software and hardware

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for electricity dispatch and voltage management may require modernization to address next-generation load challenges. Cascading risks in power networks indicate that localized disruptions, like sudden voltage loss, can rapidly escalate into system-wide crises. This is not exaggerated concern but a documented hazard: transient, unpredictable extreme weather events could disturb the delicate balance between electricity supply and demand on the grid (Liang et al., 2025). Within current technical frameworks, as increasing proportions of renewable generation connect to grids, matching scales of flexible units are needed for delivering ramping services. Thus, developing resilient grid systems through innovations and advancing clean flexibility solutions are core policy priorities.

Compared to rapidly expanding renewable capacity, the shortfall in clean flexibility provision solutions is more concerning. Grid-scale storage refers to technologies linked to power grid that store electricity for later use, which are urgently needed to handle hourly and seasonal fluctuations in renewable generation while maintaining network stability. The most widely used technologies are pumped-storage hydropower and batteries. Battery manufacturing costs have fallen sharply in recent years due to economies of scale from the electric vehicle boom. BloombergNEF data indicates that the global average turnkey storage system price in 2024 was US$165/kWh, approaching economic viability for large-scale commercial applications. However, the escalating geopolitical rivalries are intensifying competition for critical resources, particularly lithium, which may increase the costs of grid-scale storage in the future.

Building a resilient power system appears more urgent and challenging in developed economies for two reasons. First, developing nations' younger grid infrastructure allows lower-cost adoption of new resilience technologies, whereas developed countries face higher upgrade expenses and sunk costs. Second, liberalized electricity markets in some advanced economies complicate grid management with increased uncertainties, though developing countries are rapidly introducing similar market reforms. Currently, the relationship between electricity market structures and system resilience remains poorly understood, requiring further empirical investigation.

3. Accessibility

Electrification and growing power demand signify improved energy accessibility. Electricity-based low-cost appliances and infrastructure have substantially enhanced modern energy availability and affordability in the least developed and economically challenged nations and communities (Li et al., 2024). World Bank data indicate the population share with electricity access increased from 87% in 2015 to 92% by 2023. Even traditionally isolated regions now have electricity access opportunities thanks to leapfrog developments in off-grid technologies, distributed solar power, and modular systems.

There is a concern about whether swiftly increasing electricity demand could elevate electricity prices, compromising energy affordability. However, precisely answering this question is exceptionally difficult. Electricity markets and regulatory frameworks differ substantially across nations and regions. In countries and regions with advanced electricity markets like the United States and Europe, rising electricity demand may induce capacity shortages, increasing end-user electricity prices. Conversely, transitioning and emerging economies are typically featured by government-directed electricity market structures. In developing countries, cross-sector subsidies (industrial users subsidizing the residential sector) and other subsidies in different forms are widespread. For instance, in China, electricity prices are heavily regulated by the government. The government sets end-user electricity prices based on the generating costs (primarily influenced by coal prices) (Xiang et al., 2023). Therefore, even if demand growth influences electricity prices, the direct burden falls mainly on industrial users rather than households. Certainly, these costs would be passed on to consumers at the end of the day, but in a more gradual way. Institutional and policy shifts, such as electricity market liberalization and phase-outs of renewable energy subsidies, likely exert greater influence than demand expansion alone.

Heightened attention should target vulnerable economies and low-income communities. Electricity price adjustments could profoundly impact energy poverty and equitable energy access, where electricity expenditure growth outpaces household disposable income growth. Electrification presents an opportunity for achieving "universal modern energy accessibility" under the UN's SDG 7 framework. However, related progress may be jeopardized if inappropriate policy choices lead to soaring electricity prices, making power accessible but not affordable. This reflects a dilemma in governments' energy policy practice, particularly in economies reliant on fossil fuels. A rapid phase-out of coal and gas power systems could result in increases in electricity prices (Greenstone, 2024). Whether borne by businesses or households, these utility costs may ultimately have a negative impact on overall resident welfare, even when environmental benefits are considered.

4. Conclusion and discussion

Overall, electrification has a positive impact on energy sustainability and accessibility. It is important to note that there remains a significant gap in clean electricity, although this gap is narrowing. Thus, fossil fuel electricity sources, such as coal and gas, are still being constructed. For these new fossil fuel energy infrastructure, governments must balance the stranded asset costs of phasing out fossil fuel energy with committed emissions. More innovative insights are needed to optimize pathways for decarbonization. For example, recent research suggests that retrofitting coal-fired units for flexibility could reduce the costs of energy transition in coal-dependent countries (Wang et al., 2025).

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The increasing share of variable renewable energy in the energy supply mix may impact energy reliability and security. Technological innovation and investment in resilient grids, energy storage, and clean flexibility provisions should be prioritized. Demand-side management and market-based peak-shifting policies are also crucial to help achieve load balancing with minimal welfare loss, such as through time-of-use pricing (Di Cosmo et al., 2014; Pon, 2017). In extreme situations, such as heatwaves, rationing measures should be considered to avoid systemic blackouts (Hao et al., 2025). Institutional reforms and contingency plans are needed to address potential energy security risks and the impacts of transitory shocks.

Electrification benefits a just energy transition, particularly as the costs of off-grid and distributed energy systems decrease and their widespread adoption, ensuring greater accessibility and affordability. However, economically challenged communities remain highly vulnerable to energy poverty. Targeted subsidies or transfer payment policies may help alleviate specific concerns without sacrificing the overall market efficiency.

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Notes

[1] Based on IPCC SSP2 scenario estimates.

[2] Data sourced from Energy Institute's Statistical Review of World Energy 2025.

How Self-Consumption Can Contribute to the Next Phase of Electrification

BY CATARINA SILVA AND INÊS CARRILHO-NUNES

Abstract

This article examines how self-consumption can support the next phase of electrification by complementing centralized supply, easing peaks, and stabilizing electricity prices. In addition, when paired with electric mobility, it offers a practical though partial route to meet rising demand more sustainably and strengthen progress toward decarbonization.

Introduction

The world is moving fast into the "Age of Electricity". Over the last decade, electricity use grew at twice the pace of total energy demand. From now until 2035, it is set to grow six times faster, driven by the uptake of electric vehicles (EVs), air conditioning, chips, artificial intelligence, and other electrified end uses[1]. This is not a marginal shift, it is the demand side reality of the next stage of the transition.

That acceleration raises climate concerns. Energy is responsible for more than three-quarters of global greenhouse gas emissions (GHG), primarily from the burning of fossil fuels. Current carbon dioxide (CO_2) trends still run above what is required to avoid the worst impacts of climate change. The transition will only succeed if electrification advances with a rapid decarbonization of supply. Renewable energy is pointed out as one solution to the growing energy challenges (Asif & Muneer, 2007). Renewable resources such as solar, wind, biomass, waves, and tidal energy are abundant, inexhaustible, and environmentally friendly.

However, a key question remains. Can available renewable resources and the networks that deliver them keep pace with such rapid growth in electricity use? Self-consumption is a possible way to support and complement that effort. Self-consumption means generating renewable power where it is used and consuming it on-site (Gautier et al., 2019). It is a way of decentralizing energy production. In practice, there are two main forms. First, all electricity is used or stored at the premises, so nothing flows back to the grid. Second, any surplus can be exported and paid for, depending on national rules and local grid capacity. This second form introduces the prosumer, a renewable self-consumer who generates, consumes, stores, and sells power, taking part in the market (Gallego-Castillo et al., 2021). In both cases, households and firms move from passive users to active participants in the energy transition. As a result, self-consumption can democratize access to clean energy by allowing households and firms to produce part of what they use, supporting a more inclusive and fair energy transition.

Centralization vs decentralization of production

Large central renewable plants remain essential for scale and for cutting emissions. They have delivered real gains, yet they often need heavy new infrastructure and face losses when production and use are not aligned (Kabeyi & Olanrewaju, 2025). Decentralized power systems can substitute for central supply, where generators are placed closer to demand, which mitigates transmission losses. In these settings, solar installations are often more economically viable (Javid et al., 2021). Decentralization also changes who participates. Households and communities can generate and store electricity and share surplus within local schemes. Consumers move from passive price takers to active price makers and engage directly with energy markets (Hasan & Yousefi, 2023; Mansouri et al., 2022). The system becomes more integrated, vertically from supply through to demand, and horizontally across power, heat, and gas. The result is a system that is more secure and more competitive, where exposure to supply shocks is reduced.

Catarina Silva is a student in the Innovation and Entrepreneurship Master's program at Instituto Superior Técnico, Universidade de Lisboa. **Inês Carrilho-Nunes** is Assistant Professor of Economics at Instituto Superior Técnico, Universidade de Lisboa, and a Research Fellow at CEGIST. Corresponding author **Inês Carrilho-Nunes** can be reached at ines.c.nunes@tecnico.ulisboa.pt.

Self-consumption is often realized through rooftop solar photovoltaics (PV) installed on residential buildings. It has a clear impact on household energy use, from domestic tasks and lighting to water heating and charging EVs. This local clean generation helps meet growing electricity demand, reduces reliance on the grid during peak periods, and supports greater energy independence. When combined with energy storage, the contribution of solar energy to the resilience of the energy system becomes even more powerful. Batteries allow solar systems to supply electricity even at night or during grid disruptions.

Taking these factors into account, increasing self-consumption is a vital step toward meeting rising electricity demand. Outcomes will not follow from infrastructure alone. Progress requires innovation in technology and in policy that aligns local generation with use and supports decarbonization. It also requires a clear view of the drivers of adoption for households and firms. Because individuals are at the center of these choices, understanding what lowers barriers and lifts uptake is essential.

Price dynamics and market design

Self-consumption can potentially influence electricity price stability by shifting demand toward on-site

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renewable generation and storage. Using data from a pilot with 39 households, van der Stelt et al. (2018) show that household and community energy storage combined with demand-side management can significantly increase PV self-consumption and reduce grid imbalance between supply and demand. By aligning local generation with household use, these systems lower reliance on grid imports during peak hours, which reduces exposure to high tariffs and supports a smoother load profile. At a broader scale, peer-to-peer trading mechanisms can channel surplus self-generated electricity to nearby consumers, creating local market equilibria that benefit both prosumers and consumers. Indeed, An et al. (2022) demonstrate that by defining optimal trading prices between consumers and prosumers, peer-to-peer exchanges can provide competitive pricing that improves the match of local supply and demand, contributing to more efficient and stable energy markets.

At the system level, self-consumption's impact on household electricity prices depends strongly on regulatory design. Fett et al. (2019) find that in Germany, less than one-third of the potential increase in household electricity prices is attributable to self-consumption itself, while feed-in remuneration and the reallocation of grid levies play a larger role. Their simulations show that tariff structures (whether based on consumption, capacity, or fixed charges) determine whether self-consumption moderates or amplifies overall price pressures. Importantly, they highlight that policy choices, such as self-consumption charge or revised allocation of grid costs, can limit price increases while still encouraging adoption of rooftop PV and storage. Thus, while self-consumption can contribute to stabilizing prices at both the household and market level, its effectiveness depends on supportive regulatory and market frameworks.

Self-consumption and transport decarbonization

Transport accounts for about 15 percent of total GHG emissions and roughly 23 percent of global energy-related CO_2[2]. Decarbonizing this sector is unavoidable, and electric mobility is the central pathway because it replaces fossil fuels with electricity. Yet climate gain is conditional. An EV charged with electricity produced from fossil sources delivers only part of the environmental benefit and generates new concerns regarding electrification.

Self-consumption can address both concerns. It lowers emissions and helps manage the extra electricity required by transport. When households or firms pair an EV with PV installed on-site, the vehicle is charged with clean power produced where it is used. Charging from on-site generation lowers the carbon intensity of every kilometer driven (Khan et al., 2018). In practical terms, this new energy demand is met with a clean supply. Decentralized renewable energy can therefore not only reduce emissions from household energy use, for example, air conditioning, but also decrease the emissions associated with charging, which accelerates the decarbonization of transport.

In terms of demand response capacity, solar-powered EV charging can reduce reliance on the traditional grid and help avoid overloads at peak times. Local generation shortens the delivery path of electricity and can lower transmission losses, which improves grid performance and strengthens energy security (Maghami, 2025). Yet, this magnitude is context dependent and rests on sizing, timing, and operation, including the alignment of charging with daytime PV output. As EV numbers grow, higher PV penetration helps to moderate the added stress by matching local generation with local load.

The interaction extends beyond technological integration. Self-consumption can impact the adoption dynamics of road transport choices. There is evidence that decentralized renewable energy can accelerate EV uptake. Early PV adopters are more likely to consider EV because both purchases fit within a broader home plan that reshapes electricity use and can influence perceived home value. In practice, PV and EV can act as complements, both in purchase decisions and in day-to-day operation (Rai et al., 2016).

Yet, one should note that electric mobility will raise electricity demand. Self-consumption does not remove that fact. It can offset part of the increase with the new cleaning generation created by adopters themselves. This is why a co-diffusion lens matters. PV can raise EV adoption and, at the same time, supply the electricity those vehicles require. Importantly, there is a lack of empirical analysis that jointly examines EV and self-consumption adoption within a spatial and temporal framework (Wen et al., 2023). These technologies have synergies, and consumers play a growing role in sustainable technology uptake. However, identification of the relationships and spillovers is still limited. A co-adoption perspective is needed that considers integration in the electricity network and the way adoption diffuses across space.

Policymakers and researchers should further explore this co-diffusion pathway. First, understanding which factors drive joint adoption and how local conditions shape outcomes, then designing interventions that recognize households and firms as system actors in the transition. It is also necessary to establish the direction of causality and to assess whether self-consumption is a causal factor or whether simultaneity is present. If PV and EV adoption move together mainly because of socio-economic drivers, preferences, or local infrastructure, support for pairing has low additionality. Clear identification helps design policies that foster co-adoption, manage the rise in electricity demand from EVs, and decarbonize that extra need for energy at the least cost. In the "Age of Electricity", self-consumption paired with electric mobility presents a practical route to decarbonize demand partially while meeting it.

Conclusion

Electricity demand is set to rise sharply, raising concerns about costs, infrastructure, and the ability to decarbonize supply fast enough. Self-consumption offers a practical complement to centralized generation by easing stress during peak hours, moderating household exposure to high tariffs, and channeling local surplus through peer-to-peer exchanges that foster more competitive pricing. Self-consumption also supports progress in road transport. Electric mobility remains central to decarbonization, but its benefits depend on the carbon intensity of electricity and its added load on networks. Pairing EVs with on-site renewables lowers the carbon intensity of charging, reduces local stress at peak hours, and can accelerate adoption when households view PV and EVs as complementary. The next step is to examine these interactions in practice and to clarify the drivers of co-adoption across households and firms. With robust evidence, policy can encourage this pathway as a pragmatic contribution to meeting rising demand while advancing decarbonization at lower cost. Co-adoption is not a panacea, but when supported by the right conditions, it can play a meaningful role in shaping a more resilient and sustainable electricity system.

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100 % Renewables in Germany's Electricity Mix by 2035? Neither a Realistic, nor a Desirable Outcome

BY MANUEL FRONDEL AND COLIN VANCE

To achieve its ambitious goal of becoming climate neutral in 2045, Germany has set an even more ambitious goal for its electricity sector: Already by 2035, Germany strives to cover its electricity consumption almost entirely by renewable technologies. With a current share of renewables in electricity consumption of about 55%, we argue that the 2035 goal would be both overly ambitious and a suboptimal outcome.

When economists or engineers talk about mathematical optimization problems, they mean systematic ways of finding the "best possible" solution under real-world constraints—such as minimizing costs or maximizing welfare while ensuring reliability of supply. In such problems, the best solution rarely lies at the extreme, referred to as a *corner solution*. Applied to electricity, this means that a 100 % renewable share is unlikely to be optimal. As the renewable share grows, each additional percentage point becomes harder and more expensive to achieve: balancing intermittent wind and solar requires ever more backup capacity, storage, and grid expansion. These integration costs rise steeply at very high shares. Therefore, the welfare-maximizing outcome is much more likely to be an *inner solution*—a mix in which renewables play a role, but are complemented by other technologies that ensure reliability and flexibility at reasonable cost.

This intuition is supported by Hirth's (2015) work on optimal renewable shares in Northwestern Europe, published in *The Energy Journal*. Even under the unrealistic assumption of constant winds, he finds the optimal share to be only 60%. Under the more realistic assumption of intermittent wind, the share drops to as low as 20%, illustrating the dramatic impact of wind variability on the results. Moreover, today's actual costs for electricity production from onshore wind power in Germany are typically around 6–7 Eurocent per kilowatt-hour (kWh) and, hence, are often higher than Hirth's "optimistic" assumption of 5 Eurocent/kWh, which is still at the lower bound of current estimates.

Solar power fares even worse in Northwestern Europe. For countries such as Germany, Belgium, Poland, the Netherlands, and France, Hirth finds the optimal solar share to be close to zero, even under the assumption of significant further cost reductions. This outcome reflects the relatively low solar radiation intensity in these countries, compared to Southern Europe. For instance, the average solar intensity amounts to about 1,825 kWh per square meter in Spain, compared to roughly 1,100 kWh/m² in Germany (Frondel, Ritter, Schmidt 2008). With over 3,000 solar hours per year in Spain—almost double Germany's 1,600 hours—the economic case for solar power is much stronger in southern than in northern Europe.

The consequences of heavy reliance on renewables in Germany are already visible today: While sufficient storage capacities as well as electricity demand are lacking, the massive expansion of photovoltaics regularly leads to surplus electricity on sunny days, as exemplified by Figure 1 for the time period from June 17 to June 22, 2025. Nevertheless, the production of solar and wind power is rewarded through feed-in tariffs, even when the electricity is not needed. Increasingly, this pushes prices on the electricity exchange into negative territory to attract additional demand from abroad, as supply and demand for electricity must always be in balance to avoid the extreme case of a blackout.

The scale of the problem is becoming ever clearer. In 2024, there were already 457 hours with negative electricity prices, about half again as many as in the previous record year 2023, when this number of hours amounted to 301 (BHKW info 2025). In addition, there were 62 hours with a price of exactly zero, more than twice as many as in the previous year. And in 2025 we are already heading for a new record: by the end of June, 389 hours of negative prices had been recorded—almost 75 percent more than in the same period in 2024. Negative prices mean that the producers have to pay for selling their product, rather than getting money for it — a clear indication for inefficiencies that cost German taxpayers and consumers billions of Euros.

For Germany, this is increasingly turning into a losing proposition. The difference between the guaranteed feed-in tariffs for feeding green electricity into the grid and the actual market prices is borne by taxpayers. The more often prices fall into negative territory, the more expensive it becomes for German taxpayers. In the end, it is no surprise that Germany's residential electricity prices are among the highest in the European Union (Eurostat 2025).

The broader lesson is that technology choice should be guided by regional conditions and cost-effectiveness. After two and a half decades of large-scale subsidization of photovoltaics through Germany's Renewable Energy Act— by far exceeding 200 billion euros (Andor et al. 2017, Frondel et al. 2010)—further subsidization should be abandoned, a conclusion that Frondel, Schmidt, and Vance (2014) already drew more than a decade ago. Instead of narrowing the electricity mix to renewables and natural gas backup plants, Germany could benefit from reassessing the role of other low-carbon technologies. This might include reintroducing climate-neutral nuclear power, which, despite its phase-out in Germany in 2023, could provide a reliable, zero-carbon complement to variable renewables in an optimal technology portfolio.

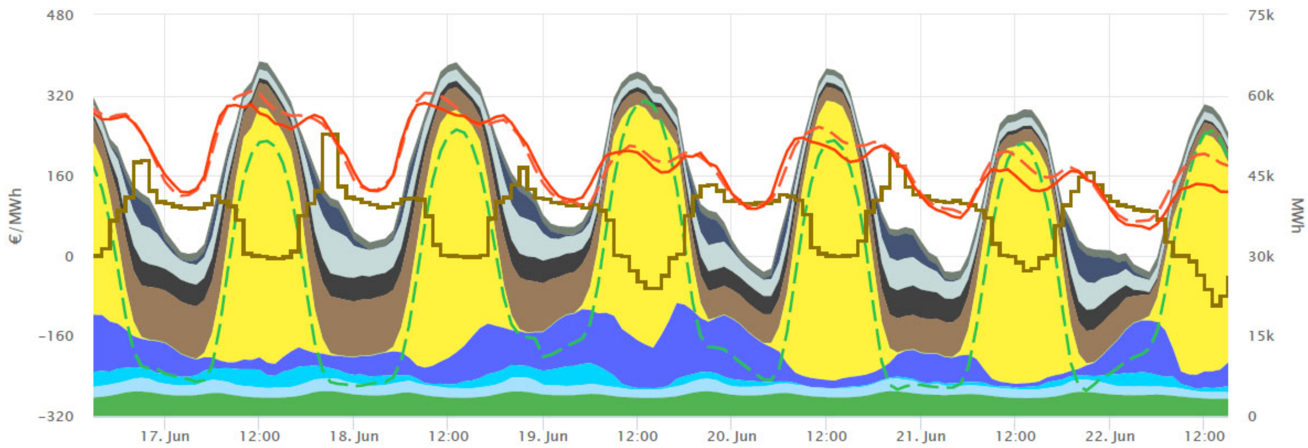

Figure 1: Electricity Demand (Red line) in Megawatthours (MWh), Spot Market Prices (Brown line) in Euros per Megawatthour, and Production in Megawatthours (MWh) from Photovoltaics (Yellow), Onshore Wind Power (Dark Blue), Off-shore Wind Power (Light Blue), Water Power (Very Light Blue), Other Renewables (Green), Lignite (Brown), Hard Coal (Black), Natural Gas (Light grey) in the Period from June 17 to June 22, 2025. Source: Smard, Federal Network Agency, Germany.

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When the duck turns turtle: Prosumage and the challenge of distribution grid management

BY **JOACHIM GESKE, BORIS ORTEGA, LAURA ANDOLFI, and RAWAN AKKOUCH**

Abstract

We simulate realistic cross-sector prosumage flexibility[1] for 2040 in Luxembourg at the distribution grid level. We find that the increase in electricity demand requires extensions of the electricity infrastructure, but it is the timing of this demand that causes the main infrastructure overload: the duck curve evolves into a turtle-like one. Thus, operators need to consider this evolution of demand to avoid grid overload or unsustainable investment.

Introduction

Globally, the energy transition is being shaped by, among others, a rapid expansion of renewable energy generation and the electrification of the heating and mobility sectors (IRENA, 2024). The electrification of these two sectors is re-shaping and increasing electricity demand and generation. However, as intermittent renewable generation cannot shift to meet demand, demand must adjust accordingly. This call for demand-side flexibility, enabled by behavioural changes and storage, arises as a key alternative to support the ongoing electrification of different sectors. Additionally, demand-side flexibility or more generally, cross-sector prosumage flexibility, has the potential to make use of the existing grid infrastructure in a more efficient way to avoid expensive reinforcement to distribute electricity (IEA, 2023).

Currently, an increasing share of households are equipped with electrical and thermal storage solutions, highly insulated buildings (that will also serve as heat storage), electric vehicles (EVs), heat pumps, and photovoltaic (PV) systems. Additionally, automation, paired with the above technologies, will enable households to respond to market prices and signals. This response can take the form of shifting or reducing net demand, and using PV systems and storage solutions to profit from price differentials. Thus, a share of households will start supplying cross-sector prosumage flexibility, including reducing and shifting net demand.

But, how does this cross-sector prosumage flexibility look like in practice? To answer this question, in this paper, we model household load profiles in 2040 with different levels of flexibility and technologies for Luxembourg. Luxembourg serves as an interesting case study as there is close collaboration among energy stakeholders,[2] allowing for rich data availability. Additionally, Luxembourg has ambitious energy goals and, with over 95% of households already equipped with smart meters (ACER, 2022), aims to cut greenhouse gas emissions by 55%, limit final energy consumption to 35.6 TWh, and reach 37% renewables in gross final consumption by 2030 (Government of the Grand Duchy of Luxembourg, 2020).

While cross-sector prosumage flexibility plays a central role in the Luxembourgish strategy, helping to balance intermittent renewables and ensure supply security, does it really solve infrastructure overload? Or might it cause new issues? The answers to these questions concern grid operators beyond Luxembourg, and this paper provides insights based on an active building model of cross-sector prosumage flexibility.

Joachim Geske is a research scientist, **Boris Ortega** and **Laura Andolfi** are research associates, and **Rawan Akkouch** is a PhD candidate, all at the Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg. Corresponding author **Joachim Geske** can be reached at joachim.geske@uni.lu.

Active building model and scenarios

The analysis uses an active building model to simulate hourly household electricity demand and supply for a full year. Households are grouped into non-technological, technological non-flexible, and technological flexible. Non-technological households do not possess advanced energy technologies; rather, they may own an EV, operated without consideration of price signals or grid conditions. Technological non-flexible households own the full bundle of technologies (heat pumps, EVs, PV systems, heat storage and batteries) but do not optimise their energy usage according to electricity costs based on wholesale market prices. Technological flexible households are equipped with the same bundle of technologies as the previous group, but they use their technologies to minimise energy costs. We assume perfect foresight of prices based on 2040 Entso-e Ten Year Network Development Plan (TYNDP) scenarios, solar capacity factors, and outdoor temperature.

The model applies linear optimisation, considering technical limits (e.g., 11 kW EV charging and cycle lifetimes), thermal dynamics, and grid constraints. It evaluates low-voltage transformer loading for 166 representative households (scaled to Luxembourg's rural/semi-urban grid), comparing different flexibility shares, to identify its impact on the transformer load. We assume, in line with the national energy and climate plan and demographic statistics, that in 2040, around 60% of the households are technologically equipped. Therefore, we simulate flexibility shares of 0%, 30%, and 60% of all households.

Results

In the baseline scenario without flexible households (Figure 1, dotted red line), the average weekday load of the 166 households follows the well-known duck

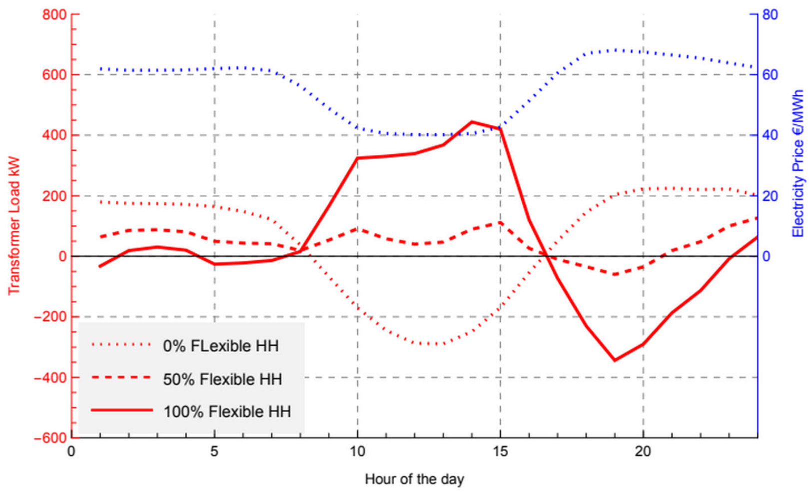

Figure 1: **Household Net Electricity Imports.** *It displays households' net electricity imports on the transformer level for an average weekday in 2040 with varying shares of flexible households. The x-axis represents the hour of the day, while the y-axis denotes power imports (kW). The blue line depicts scaled TYNDP electricity prices of 2040. The red lines represent scenarios of household consumption patterns - dotted curves 0% dashed 30% and solid curves 60% of flexible households.*

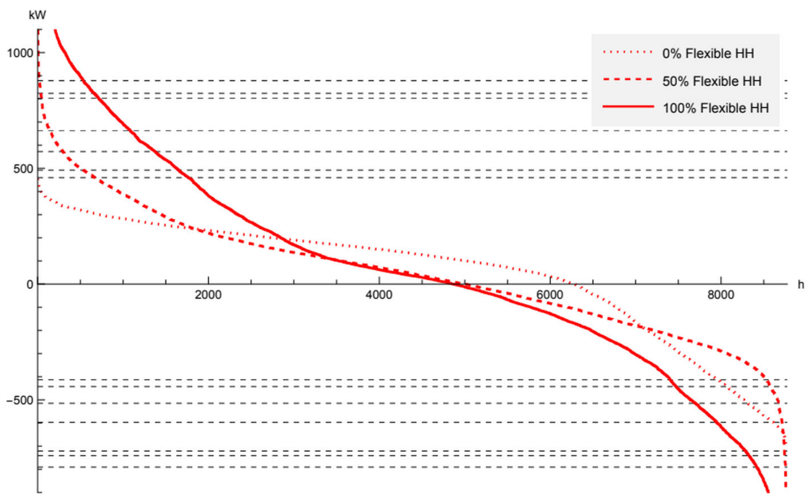

Figure 2: **Load Duration at the Transformer Level.** *It shows the load duration at the transformer level for all the hours of the year. The positive values represent the electricity imported from the grid to the households, while the negative values show the exports from the household to the grid. The horizontal dashed lines represent the upper and lower bounds of the representative transformer capacities.*

curve driven by midday PV systems exports and evening EV charging peaks (CAISO, 2013). In the second scenario, with 30% flexible households (dashed red line), households start to arbitrage wholesale prices: charging in low-price midday hours (blue dotted curve) and discharging/avoiding imports in high-price evenings. This behaviour flattens the aggregate load curve, arguably a desirable state. However, as flexibility provision increases to 60%, arbitrage increases until the duck curve inverts: substantial midday imports and evening exports from the household perspective, leading to the new turtle-like curve (solid red curve).

However, as aggregate loads do not exceed 500 kW, we are still within current transformer capacities ranging from 500 to 900 kW (according to data from the distribution grid operator). However, recall that Figure 1 represents average loads, meaning that intermittent supply (intermittent renewable generation) and demand (via temperature) cause high price peaks that motivate extreme trading activities of the flexible households (load duration in Figure 2). Therefore, in 2040 even without flexibility exporting households exceed capacities of four out of seven representative transformers (right-hand side) while the import capacities are sufficient (left-hand side). At 30% flexibility, all transformers overload at least once for both, import and exporting activities

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(dashed red curve). Finally, at 60% flexibility, overloads occur thousands of hours, with up to three additional transformers required per site (solid red curve).[3]

Discussion

While the turtle-shaped curve may support PV integration (i.e., by increasing midday consumption during high PV generation), it also introduces new stress points for grid infrastructure, particularly at the distribution transformer level. This potential grid overload calls for an urgent evolution of the market towards a design that harnesses the potential system-wide benefits of flexibility while ensuring a reliable and sustainable grid.

Unregulated or unaccounted cross-sector prosumage flexibility can overwhelm local infrastructure, offsetting its potential benefits, which highlights the need for careful policy design. Policymakers must ensure that flexibility is enabled responsibly, through supportive market mechanisms that (1) avoid allocating the system costs of flexibility to non-flexible households, (2) apply dynamic pricing to provide the right local signals to households, and (3) encourage investment in digital grid management that allows real-time management of the system. More than a challenge, the evolution from duck to turtle should be seen as an opportunity to, for example, integrate renewable generation and optimise the use of the grid infrastructure; however, to fully capture the potential system-wide benefits of this new paradigm, we must start now understanding the nuances of this new reality and properly prepare our energy system.

The results shed light on the importance of considering the effects of cross-sector prosumage flexibility at the transformer level. However, it must be noted that there are other infrastructure aspects (i.e., voltage levels, line congestion, etc.) that policymakers and system operators must take into consideration for the system-wide adaptation. Our analysis is a step to integrate grid and other system aspects in addition to wholesale markets and transmission capacity.

Conclusions and Future Research

Driven by increasing household flexibility and prosumer engagement, the shape of electricity demand is evolving. In this paper, we estimate cross-sector prosumage behaviour and flexibility configurations for 2040 and its grid implications at the low-voltage transformer level.

We show that a high share of prosumage flexibility in 2040 leads to the evolution of the duck curve towards a turtle-like one. While this transformation may support renewable integration, the price-responsiveness of households may also introduce new grid challenges if markets do not adapt and provide the right signals. These effects suggest that flexibility is not inherently beneficial or harmful, but its value depends on how, when, and where it is activated. To fully harness its potential, we must develop strategies that coordinate and localise flexibility activation, avoid grid congestion, and support consumer empowerment without unfairly shifting risks onto households.

Our results assume that electricity prices do not respond to the cross-sector prosumage flexibility. This limitation most likely leads to overestimation of the hours exceeding the transformer capacities, as flexible prices would adapt to the flexibility supply. While the TYDNP scenario prices already incorporate some degree of flexibility, as evidenced by the high night average prices (recall the blue curves of Figure 1), fully dynamic prices have the potential to mitigate some of the challenges of flexibility supply described in Figure 2. Nevertheless, our results provide valuable insights into the potential problems of unregulated cross-sector prosumage flexibility.

While the insights presented here are informative, they also highlight the need for further research to fully understand the evolving shape of electricity demand. This modelling framework offers opportunities to explore several interesting venues, such as the role of individual technologies in shaping the profitability of arbitrage, as well as the potential unintended consequences of flexibility, like increased electricity use for heating to leverage buildings as storage units. It also draws attention to the significance of out-of-home EV charging, particularly at workplaces, and the varying effects of market and non-market mitigation mechanisms like grid tariffs, curtailment, or local capacity markets. Altogether, the future shape of electricity demand is far from settled, and holds fascinating questions that are only beginning to be explored.

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Notes

[1] We define cross-sector prosumage flexibility as the electricity production and consumption behavior of the households across different sectors like transportation (EV), heating (heat pumps), electricity storage, etc.

[2] The analysis was conducted within the FlexBeAn (Flexibility Potentials and User Behaviour Analysis) project together with CREOS (grid operator) and Luxembourg Institute of Science and Technology (LIST). FlexBeAn examines how households, SMEs and industry can provide flexibility to support the energy transition. The project combines behavioural, technical, economic, and market perspectives to inform policy and grid operations (Luxembourg Institute of Science and Technology et al., 2025).

[3] Estimations of additional transformer needs available upon request.

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Integrated Spatial Strategies for Electricity Demand and Supply

BY HIROAKI ONODERA

Hiroaki Onodera
Researcher and Energy system modeler of National Institute for Environmental Studies, Japan (NIES)

Abstract

Rising electricity demand calls for new adaptation strategies. Beyond expanding supply capacity, integrated siting of demand and generation emerges as an overlooked solution. Some case studies have demonstrated renewable-energy-driven demand relocation can be mutually beneficial for end users and power systems.

Introduction

The pursuit of further socioeconomic growth drives substantial increases in electricity demand. According to scenarios in IPCC AR6, global electricity demand may rise from approximately 25 PWh today to more than 80 PWh by 2100, and up to roughly 170 PWh under stringent climate-mitigation and adaptation pathways (Fig. 1) [1]. In the short term, additional demand raises CO_2 emissions as fossil-fired plants are ramped up; in the long term, it increases pressure on clean-energy investment, threatening the feasibility of ambitious climate goals such as the 1.5 °C target. Rising demand also implies higher prices, exacerbating energy poverty and energy-access challenges. Yet strategies to address these risks from surging demand remain underexplored. By reconsidering where new demand emerges, power systems may unlock overlooked, transformative solutions.

Rising Demand and Adaptation Strategies

While the trajectory of future economic activity remains uncertain, electricity demand is very likely to increase substantially. Low energy demand pathways that ensure human well-being while mitigating planetary pressures have been widely explored. Yet even as these pathways reduce overall final energy use, they substantially increase final electricity consumption. For instance, in the LED scenario developed by Grubler et al. [2], total final energy demand falls by about 40%, but electricity demand increases by a factor of 1.8 in 2050.

If demand continues to grow, can the challenge be solved simply by adding generation and transmission? Historically, yes: utilities expanded supply and networks. Hundreds of megawatt-class fossil-fuel plants and gigawatt-class nuclear units were built to meet growth. Once power infrastructure matured, new MW-scale loads were often welcomed because they raised utilization of existing assets. However, new GW-scale consumers—such as semiconductor fabs or data centers—now risk straining the residual capacity of existing infrastructure, necessitating additional investment. In most countries under climate targets, new fossil plants

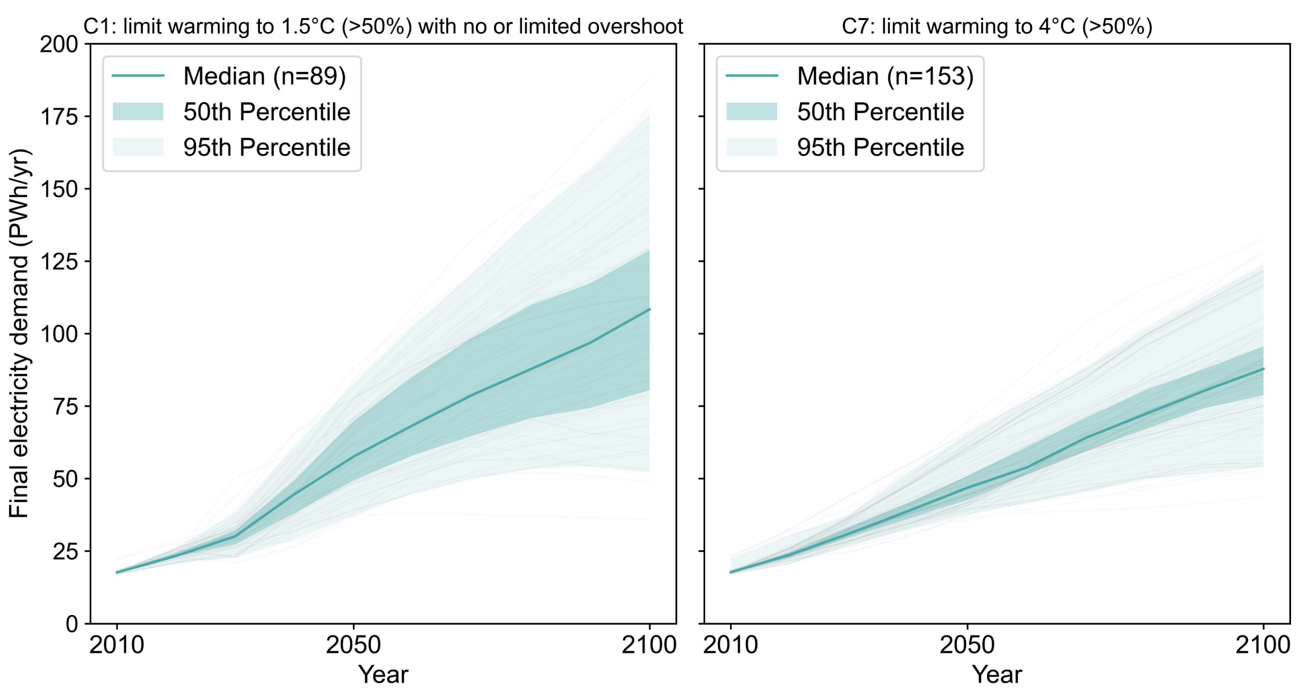

Figure 1: Global final electricity demand trajectories under the 1.5 °C target (left) and 4 °C pathways (right). n *represents the number of scenarios. Source: IPCC AR6 scenarios database* [1].

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are politically, financially, and socially difficult to implement, while nuclear power continues to face unresolved issues of social acceptance, waste management, and proliferation concerns. In short, society can no longer rely on large, centralized supply-side expansions, even as GW-scale demand additions are emerging.

Reactivating dormant nuclear plants offers a partial, location-specific solution. Microsoft, for example, has announced plans to colocate a data center with a reactivated Three Mile Island nuclear facility. Such opportunities are not universally replicable, but they demonstrate how power-hungry end users are. Renewable energy remains the other major clean option. Although its expansion has provoked conflicts with biodiversity, landscapes, and other local values, significant potential remains. Yet cost-competitive, GW-scale renewable resources are often far from demand centers. This raises a fundamental choice: should we transmit renewable electricity over long distances to consumers, or should new consumers relocate near renewable supply? Conventional power-system planning has overwhelmingly prioritized the first option. Emerging studies, however, suggest that the second—demand relocation—can be mutually beneficial for consumers and the power system [3,4]. A few case studies of electricity-intensive industries (e.g., chemicals, data centers) indicate that renewables can attract new demand; this mechanism is often termed the "renewables pull effect" or "green relocation."

Potential of Strategic Siting: A Case Study of Data Centers in Japan

Japan provides a timely case to explore these dynamics. Electricity-intensive new demands—including data centers, semiconductor plants, electric arc furnaces, and hydrogen electrolysis—are expected to grow rapidly. In February 2025, citing these emerging loads, the Japanese government shifted its stance on nuclear power: after years of aiming for reductions, it announced a policy to promote nuclear restarts. Simultaneously, it introduced the Green Transformation (GX) growth strategy, emphasizing spatial integration of supply and demand ("GX industrial siting") to better utilize distributed clean-power sources. This policy shift reflects a structural imbalance. As in many countries, Japanese data centers are highly concentrated in metropolitan hubs, particularly Tokyo and Osaka—a siting pattern that historically minimized communication latency by clustering data centers, internet exchanges, and landing stations near end users. Is such spatial concentration still sustainable in a decarbonized future? What siting strategies should guide future industries and power systems?

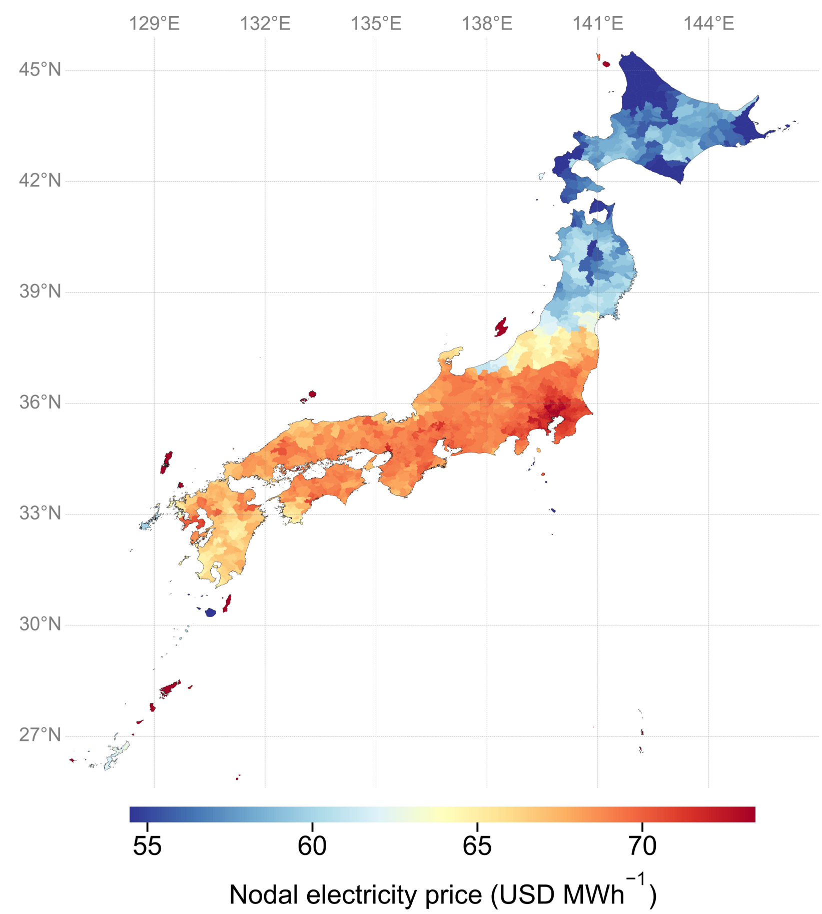

Figure 2: Nodal electricity prices for Japan in 2050 under the 1.5 °C target.

To address these questions, I conducted a case study of data-center siting in Japan. A high-resolution power system model covering all 1,741 municipalities was used to examine various siting strategies of data centers under the commitment to the 1.5 °C target. As a result, if data centers continue to increase (by about 8% of national electricity demand in 2050) and concentrate in metropolitan areas, system costs rise by 5.1% compared to the case without data center expansion. In contrast, if data centers pursue locations aligned with inexpensive and clean electricity, the additional system costs can be reduced by up to 19%. The optimal siting patterns are well explained by nodal electricity prices (i.e., average local marginal prices (LMP)). Under a 1.5 °C scenario for 2050, these nodal prices vary widely: they are highest on isolated islands and in the congested Tokyo metropolitan area, and lowest in Hokkaido, where offshore wind resources are abundant (Fig. 2). Such spatial variation of LMP is also observed in the United States [5]. In optimized siting scenarios, these low-cost nodes emerge as prime candidates for new data centers. For example, if retail electricity prices reflect nodal prices, relocating a data center from the Tokyo metropolitan area (e.g., Inzai City) to Hokkaido (e.g., Ishikari City) could reduce per-kWh electricity costs by ~19.5%, even if region-specific climate conditions increase electricity demand by 3%. This implies that strategic siting can reduce both end-user electricity expenditure and the investment required for power-system decarbonization.

Conclusions

Strategic demand relocation is an overlooked but beneficial option for adapting to rising electricity demand. Spatially aligning large-scale demand with clean power sources can generate win–win outcomes for both system operators and consumers.

While case studies demonstrate this potential, practical barriers remain. For data centers specifically, the emergence of ultra-low-latency technologies such as electro-optics is promising, yet further validation is needed to ensure that both communication quality and power system security can be secured under dispersed siting. For other electricity-intensive industries, such as electric arc furnaces or semiconductor fabrication, similar system-cost benefits may be achievable. However, these potential gains must be weighed against possible increases in supply-chain costs for materials and products, which could offset savings from reduced energy expenditure. Ultimately, these findings motivate further research on the coupling between the electricity system and other societal infrastructures—such as communication networks and industrial supply chains. Addressing these interdependencies will be essential to reconcile growth, decarbonization, and resilience in the decades ahead.

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Electricity in the Context of the Energy Transition

BY LUIS RENATO AMÓRTEGUI RODRÍGUEZ

Abstract

This article analyzes how electricity is the secondary energy source that will support the global energy transition projected for the mid-21st century, especially that produced renewable energy on the path toward decarbonization, considering that the essence of these sources is electricity generation. This gained relevance with the 1973 oil embargo, as efforts were made to make solar and wind energy competitive with conventional sources of generation, ensuring energy security and national interests.

Energy Transition

The transition is the transformation of the global energy sector from fossil fuels to zero-carbon sources by 2050, in order to reduce energy-related CO2 emissions to mitigate climate change and limit global temperature to 1.5°C above pre-industrial levels, positioning electrification and energy efficiency as key drivers, supported by renewable energy, hydrogen and sustainable biomass, aimed at achieving a climate-safe future, in line with the objectives of the Paris Agreement (International Renewable Energy Agency - IRENA).

Based on the above, the objective of this transition is to reduce the share of fossil fuels: oil, natural gas and coal in the energy mix, due to their 85% share, leading to the energy system being polluted, and contributing two-thirds (2/3) of greenhouse gas emissions. Regarding oil, given the concentration of reserves in a few regions of the world, the supply is vulnerable to geopolitical crises, leading to political instability, militarization of producing areas, economic volatility due to price fluctuations, market cartelization, and risks to energy security and national interests (The Economist, 2020a).

With the emergence of the new energy system, renewable electricity -solar and wind- is expected to increase their share from 5% (2020) to 25% (2035), and then to nearly 50% (2050). This decarbonization will bring benefits, avoiding runaway climate change in terms of droughts, famines, floods, and population displacement. It is also expected to be a more stable system politically due to the geographical and technological diversification of supply, and economically, because electricity prices will be determined by the market and gradual improvements in efficiency.

Renewable energies

Renewable energies are those sources that are neither consumed nor depleted in their energy transformation and utilization processes, generating lower environmental impacts than those produced by conventional sources (Deloitte, 2016), which are used to produce electricity, heat, and fuels (Dumbar, 2014).

It is worth mentioning that energy sources in their original, unaltered form, available in nature before transformation, are called primary energies; in contrast, secondary energies result from the conversion of primary energies into energy carriers such as electricity, hydrogen, gasoline, diesel, and fuels in general, facilitating their transportation and use (Repsol, 2025).

Primary sources include coal, hydrocarbons (oil and natural gas), and nuclear energy, as well as renewable energies, including those generated by wind and the sun, rivers, tides and waves, the Earth's internal heat, and biomass and biofuels created from plant matter. All of these are transformed to release their contained energy and primarily generate electricity.

Due to the physical and chemical characteristics of hydrocarbons, oil is focused on the production of liquid fuels for the transportation sector, and natural gas on electricity generation. Additionally, as natural gas is the least polluting source of fossil fuels, it is viewed as the energy source for the transition process, capable of replacing coal in electricity production and gasoline and diesel as fuel for automotive vehicles, reducing carbon dioxide (CO2) emissions and improving air quality (Royal Dutch Shell plc, 2023).

Regarding renewable energy, the decisive push for renewable energy is related to the challenges to energy security due to the 1973 oil embargo imposed by the Organization of the Petroleum Exporting Countries (OPEC) cartel on Western countries. Energy diversification strategies were defined, as the disruption in supply led to volatility in oil prices, affecting global economic stability in terms of inflation, economic growth, and well-being (Smil, 2017).

Although scientists maintained an interest in generating electricity from renewable sources, it was not until 2015 that this objective was achieved commercially, with annual investments doubling those in fossil fuel production, leading to wind and solar energy becoming cost-competitive with conventional forms of electricity generation (Usher, 2019).

Luis Renato Amórtegui Rodríguez is a PhD candidate in Political Science and Administration and International Relations from the Complutense University of Madrid, Spain. Master's degree in Strategy and Geopolitics from the General Rafael Reyes Prieto Higher School of War, Colombia. Master's degree in business administration - MBA from the University of the Andes, Colombia. Master's degree in Regional Development Planning and Administration from the University of the Andes, Colombia. Economist from the Pontifical Javeriana University, Colombia. Experience in the oil industry in financial planning, financial evaluation of projects, and structuring of oil businesses, Ecopetrol S.A. Contact: lamorteg@ucm.es - ORCID: https://orcid.org/0000-0003-4093-2913

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Electricity generation with renewable energies

As mentioned, electricity is a secondary source or energy vector capable of storing and transporting energy for subsequent conversion and use in the form of heat, light, or movement. It is characterized by its controllability, versatility, and cleanliness. It can be generated in large, concentrated quantities for transportation to consumption sites, or produced and consumed locally in a decentralized manner.

Electricity is obtained through the conversion of conventional and renewable primary energy sources, using the heat released by the combustion of fossil fuels, the fission of nuclear minerals, the potential of water, and, in general, the rotational mechanical energy obtained from any energy source to be transformed into electricity by electromagnetic devices called generators (Barrero González, 2004).

Regarding electricity generation using renewable energies, such as the sun (solar), wind (wind), water (hydro), the Earth's heat (thermal), tides (tidal), waves (wave), and biomass (bioenergy), whose characteristics and essence lead them to focus primarily on electricity production, the following is a brief description of their technical principles according to (Dumbar, 2014):

- Solar energy: derived from solar radiation converted into heat and electricity. While photovoltaic solar systems convert solar energy into electricity, concentrated solar power plants use mirrors or lenses to concentrate on sunlight and create temperatures that drive turbines or motors to produce electricity.
- Wind energy: come from air flow. In this case, the kinetic energy of the wind moves the rotating blades of the turbines, generating electricity. Offshore wind turbines located in coastal regions typically have better wind resources than onshore ones. • Hydroelectric energy: This energy comes from the energy of moving water. The scientific principle is that turbines installed along rivers or in dams convert the kinetic energy of water into mechanical energy, which in turn converts it into electrical energy.
- Geothermal energy: this energy is obtained from the Earth's heat and can be used directly as heat or to generate electricity. These sources include deposits of hot water or steam deep within the Earth, which are accessed by drilling (geothermal reservoirs) and through surface terrain.
- Ocean energy: this energy is derived from the potential and kinetic energy of the ocean. Tidal energy uses the rise and falls of tides, and wave energy depends on the movement of waves generated by the wind. Electricity is generated by converting the kinetic energy of water through hydraulic turbines.
- Bioenergy: obtained from biological sources (biomass) to generate heat, electricity, or transportation fuel. Traditional biomass (wood) is used for heating and can also be transformed into biogas to produce electricity. The heat produced by burning other forms of biomass in a boiler can be used to generate electricity using a steam turbine.

It could be said that the origins of renewable energy date back to the scientific development of solar energy with the identification of the photovoltaic effect by French physicist Edmond Becquerel (1839), which was used in the 1880s to produce the first photovoltaic or solar cells. This was followed by the development of commercial water heaters in the United States (1930) (Burton, 2016).

In the case of wind energy, in 1888, the American Charles Brush used a windmill to drive a 12 kilowatt (kW) electric generator, from which developments related to battery charging and the supply of electricity to farms and remote locations were derived, reaching powers of one (1) MW by the end of the 1930s (Walker & Swift, 2015).

The Emergence of Electricity and the Evolution of Sources

The origins of electricity date back to the early 19th century with the design of the first prototypes of motors and generators to convert electrical energy into mechanical energy, as well as batteries for storage. In this process, an electric generator was connected to a coal-fired steam engine, producing large flows of electricity (Bradford, 2006).

In the second half of the 19th century, the American inventor Thomas Alba Edison began to apply these technologies, driving the creation of the electrical industry. He succeeded in making the incandescent light bulb work (1879) and widespread its use with the construction of the Pearl Street Power Station in New York (1892), using coal as fuel. In this way, electricity was used to light offices and began to replace kerosene (petroleum) and natural gas in lamps, as it was characterized by being a cleaner, safer, and lower-cost energy source. This has increased productivity in businesses and industries, as well as improved safety conditions at work, in homes, and in communities.

Given the expansion of electricity, technological advancements have shifted toward generators, transformers, power transmission networks over longer distances and voltages, and steam turbines (Smil, 2017). Thus, the hydraulic turbine was developed to harness river flow through hydroelectric plants, with the first plant being built in Northumberland, England (1880) (Sanz Osorio, 2016). his was followed by the harnessing of the potential of natural lakes with the Niagara Hydroelectric Power Station (1896), which became one of the most important sources of primary energy with the highest yields. This was followed by the construction of dams for the generation of large volumes of electricity, the first of its kind being the Hoover Dam on the Colorado River in Nevada (1936) (Usher, 2019).

n this sequence, the first natural gas-powered power plants (thermal) were built in the United States in the 1920s; however, after World War II (WWII), a significant market share was reached (Boston University Institute for Global Sustainability, 2025). Finally, nuclear power

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generation began with the construction of the first reactor to produce commercial energy in Calder Hall, England (1956), allowing the replacement of energy sources such as coal (Tester, Drake, Driscoll, Golay, & Peters, 2017).

The Electrification of the Transportation Sector

Technological advances enabled the use of electricity in railroads and trams, and in 1884, the development of the first electric car. It was quiet, smooth, and easy to operate, placing it in the competition for supremacy in the automotive industry, alongside the internal combustion engine running on gasoline and diesel, and steam cars (McNally, 2007). Compared to these alternatives, the gasoline-powered car prevailed due to its greater energy storage capacity, greater power and range, and faster travel. Additionally, technological advances in the oil industry and new discoveries in Texas and Oklahoma ensured the future supply of the vehicle fleet, consolidating oil as an important energy source (Roberts, 2004).

With the rise of the automotive industry at the beginning of the 20th century, economic development, the spatial integration of cities and markets, and improved population well-being were promoted. However, emissions generated by oil combustion have fueled climate change. For this reason, the transportation sector is key to the energy transition to achieve net-zero carbon emissions. In this regard, (BloombergNEF, 2023) argues that electrification is spreading to all segments of the road vehicle fleet, projecting that electric vehicles will equal and surpass sales of combustion-engine vehicles by the 2040s. Furthermore, in terms of fleet composition, sales of electric passenger vehicles are expected to reach a 75% market share and close to 50% of the vehicle fleet in this segment.

As transport is responsible for 13.7% of global greenhouse gas emissions, in its decarbonization process, personal electric vehicles participated with more than 20% of vehicle sales in 2024, and in 2025 it is expected to reach 25% (20 million), likewise public charging stations have doubled in the last two (2) years in response to this growth; therefore, together with advances in renewable energies, these actions will help reduce emissions from the transport sector (United Nations Development Programme, 2025).

The Challenges of an Electrified World

Within this research process, several concerns related to the implementation of the energy transition will be presented. One of these is the role of critical minerals in the evolution toward an energy system based on renewable energy (solar farms, wind farms, and electric vehicles), as they require greater quantities of materials than a system powered by fossil fuels. Thus, an electric vehicle requires six times (6x) more minerals than a combustion vehicle, and a wind power plant, nine times (9x) more than a natural gas thermal plant (International Energy Agency, 2022). For this reason, this transition is characterized by the intensive use of minerals and metals, driving the demand for fifty-one (51) critical materials (International Renewable Energy Agency, 2023).

Regarding the manufacturing and supply of infrastructure to the market to structure a renewable energy-based system using critical minerals, Chinese companies by 2020 produced 72% of the world's solar modules, 69% of its lithium-ion batteries, and 45% of its wind turbines, suggesting that China could temporarily gain influence in the global energy system due to its dominance in the manufacturing of key components and the development of new technologies. It also controls much of the refining of essential minerals for clean energy, such as cobalt and lithium. In this way, the petrostates that concentrate hydrocarbon reserves and production could be replaced by electrostates (The Economist, 2020b).

From a geopolitical perspective, the evolution from an energy model based on fossil and nuclear energy to one based on renewable sources must entail significant changes, as long as countries have a sufficient portfolio of renewable sources such as water, air, and sunlight, which are freely and non-exclusively available. In general terms, this process should lead to the end of international relations based on a state's power or influence over energy resources. Therefore, it is not justifiable for a country to control a country's energy resources abroad. However, these relationships of dependence can be maintained through the support and financing of renewable energy projects controlled or managed by large energy companies, allowing them to play a greater role than international oil companies (Mañé, 2020).

On the path toward a clean energy-based system, political leaders fear that ambitious measures will exacerbate geopolitical problems and affect energy security. Therefore, they are promoting strategies that include fossil fuels and clean alternatives, avoiding a shift from dependence on imported oil to imported lithium. Thus, the energy transition requires policies that recognize the growing demand for oil and natural gas in the medium term, while renewable energy is becoming more widespread. The process should be approached as a means to solve global problems, not as an end in itself: achieving net-zero emissions by 2050 (O'Sullivan & Bordoff, 2024).

Because a major challenge of the transition is ensuring energy security in terms of supply, failure to meet these expectations could trigger a public backlash against energy and climate policies, and because it is also important to recognize that oil and natural gas will play an important role in the energy mix for longer than expected, requiring investments in supply and infrastructure. Additionally, developing countries that need reliable and affordable energy must balance climate priorities with the need for economic development, so the energy transition competes with the priorities of economic growth, poverty reduction, improved health, and in some cases, survival needs (Yergin, Orszag, & Arya, 2025).

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Table A.1b: World energy supply

	2010	2022	2023	Announced Pledges (EJ) 2030	2035	2040	2050	Shares (%) 2023	2030	2050	CAAGR (%) 2023 to: 2030	2050
Electricity and heat sectors	**200**	**249**	**255**	**271**	**285**	**314**	**378**	**100**	**100**	**100**	**0.9**	**1.5**
Renewables	20	41	43	88	134	180	255	17	33	68	11	6.8
Solar PV	0	5	6	27	49	71	104	2	10	28	25	11
Wind	1	8	8	21	34	46	66	3	8	17	14	7.9
Hydro	12	16	15	18	20	22	25	6	7	7	2.4	1.9
Bioenergy	4	9	10	15	20	25	32	4	6	9	6.6	4.5
Hydrogen	-	-	-	0	1	2	2	-	0	1	n.a.	n.a.
Ammonia	-	-	-	0	0	0	2	-	0	0	n.a.	n.a.
Nuclear	30	29	30	39	49	59	69	12	14	18	3.6	3.1
Unabated natural gas	47	56	57	53	43	36	26	22	19	7	-1.1	-2.9
Natural gas with CCUS	-	-	-	0	0	1	1	-	0	0	n.a.	n.a.
Oil	11	9	8	4	2	2	1	3	1	0	-12	-8.1
Unabated coal	91	112	115	86	50	29	13	45	32	4	-4.0	-7.6
Coal with CCUS	-	0	0	0	3	4	7	0	0	2	60	30

Source: (International Energy Agency, 2025, pág. 302)

Finally, about the projected share of primary energies in electricity generation by 2050, Table A.1b: World energy supply from the (International Energy Agency, 2025, pág. 302), was taken as a reference, corresponding to the *Announced Pledges Scenario (APS)*[1], visualizing that renewable energies will have a share of 68% (solar: 28%, wind: 17%, hydraulic: 7% and modern bioenergy: 9%), fossil energies (natural gas: 7% and coal: 6%) 13%, nuclear energy 18% and hydrogen 1%. With respect to a 17% share of renewable energies in the electricity matrix in 2023, fossil energies with 70% (oil: 3%, natural gas: 22% and coal: 45%) and nuclear energy with 12%.

Thus, hydrocarbons and other sources will remain in place until 2050, with their share varying due to the evolving energy transition toward renewable sources. The assumptions are that carbon capture, utilization, and storage (CCUS) technologies will be used in the production and consumption of natural gas and coal, oil will be used marginally as fuel, and nuclear energy will decline in share.

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Note

[1] The Announced Pledges Scenario (APS) examines what would happen if all national energy and climate targets made by governments, including net zero goals, are met in full and on time.

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