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Vignette

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Revisiting energy efficiency

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Abstract

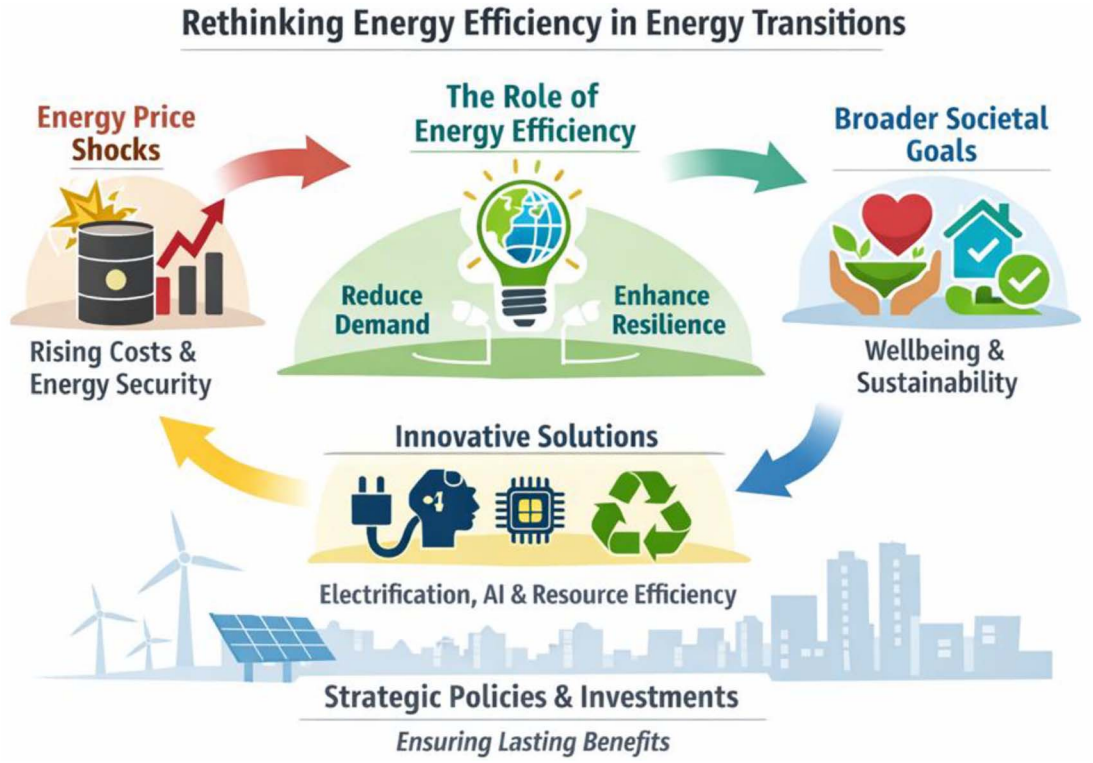
In this Vignette, leading experts advocate for a resurgence of interest in energy efficiency, placing a renewed emphasis on its strategic importance within energy transitions. In the current context of geopolitical instability, efficiency assumes heightened urgency as a rapid, cost-effective means to reduce exposure to energy price shocks and enhance energy security. By lowering demand, increasing system flexibility, and supporting more resilient and diversified energy systems, energy efficiency is a critical 'first fuel' in managing both short-term disruptions and long-term transitions. Energy efficiency has the potential to push transformative change through dynamic and systems-oriented strategies across research, policy, and practice. Such strategies must embed efficiency within broader societal goals—encompassing planetary boundaries and wellbeing—while ensuring that measures deliver synergies including energy security, public health, affordability, competitiveness, and responsible growth. New experiments and scenarios are needed to advance knowledge on potential efficiency pathways. Participatory methods in relation to energy poverty, justice, and sufficiency can help ensure its central role remains legitimate, accountable, and socially grounded. Alongside these societal dimensions, sections of the Vignette also emphasize new potentials enabled through greater electrification, artificial intelligence, and material resource management while recognizing associated rebound effects or efficiency-induced growth. Energy efficiency provides critical buffering against systemic disruptions in future societal

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transitions. Strategic policy interventions and financing mechanisms are required to align efficiency with both energy-system goals and wider societal objectives to foster enhanced resilience and wellbeing within ecological limits.

Graphical abstract



Lay summary

Energy efficiency plays a crucial role in making energy systems more resilient, especially during periods of geopolitical instability and rising energy prices. By reducing energy demand, it helps protect households and economies from price shocks while supporting a cleaner energy transition. To realize its full potential, efficiency must be integrated into broader societal goals such as wellbeing, affordability, and environmental limits. This includes addressing energy poverty and fairness, while leveraging opportunities from electrification, AI, and better use of materials. Effective policies and investments are essential to ensure energy efficiency delivers widespread and lasting benefits.

Keywords energy, efficiency, transitions, resources, wellbeing, policy

Introduction

(Lena Neij and Charlie Wilson)

Energy efficiency is crucial in energy transitions and a guiding principle for combatting climate change and environmental degradation. Lower energy demand enables a more resilient energy system that delivers multiple societal and economic benefits. Despite considerable progress and evidence of its contribution, interest in it has stalled, lost prominence, or become siloed across sectors and fields.

The current global energy crisis—driven by geopolitical tensions and disruptions to global energy markets—reinforces the urgency of efficiency as a core strategy for resilience and affordability. Energy prices shocks have exposed vulnerabilities in systems reliant on imported fossil fuels. Efficiency offers an immediate and cost-effective means to reduce demand, shield consumers from price volatility, and enhance energy security. These dynamics highlight efficiency not only as a climate mitigation solution but also as a systemic enabler of energy transitions.

In this Vignette, we revisit the discourse on efficiency with the ambition of revitalizing interest in the field. Moving beyond conventional sectoral silos (industry, buildings, transport) and purely technological perspectives, we explore cross-cutting themes. We emphasize the role of energy efficiency in driving transitions, particularly alongside electrification and the rise of artificial intelligence (AI), while also expanding the scope to include material resource efficiencies. Adopting a societal lens, we examine efficiency in relation to rebound effects, sufficiency, wellbeing, and just transitions, and highlight lessons from policy incentives, policy mixes, and financing initiatives.

This Vignette draws on contributions from leading scientists and professionals, each an expert in their respective field. Each contribution provides a concise synthesis of current knowledge on a specific topic (Fig. 1) and offers a perspective on what is required to strengthen and mainstream efficiency across research, policy, and practice for the energy transition.

In the concluding section, we synthesize insights across topics to identify key messages for rethinking energy efficiency. By integrating

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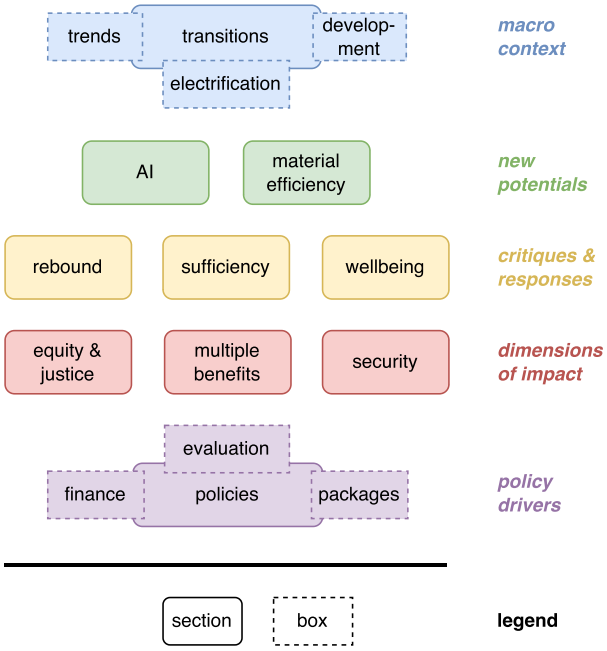


Figure 1 Structure of the vignette on Revisiting Energy Efficiency.

expert contributors' perspectives, the Vignette opens up a wide-reaching conversation on the role and importance of efficiency in energy transitions.

Energy efficiency in energy transitions

(Kathleen Araújo, Joana Portugal-Pereira, and Martin J. Pasqualetti)

Traditionally viewed as a conservation measure, energy efficiency has been increasingly redefined in the context of the global energy transition. No longer purely about demand reduction, energy efficiency is the 'first fuel'—a strategic lever for systemic change and a critical buffer against disruption in energy transitions.

The evolution of how energy efficiency is viewed occurred over five decades. During the 1970s, framed by resource scarcity and geopolitical oil shocks, energy efficiency was the cornerstone of Amory Lovins' 'soft energy path' for meeting rising demands [1]. In the 1980s, energy efficiency's scope broadened alongside emerging sustainability priorities, framing it as the 'hidden fuel' that could help mitigate environmental degradation (see Box 1 on trends) [2]. By the 1990s, the concept was closely linked to decarbonization in climate mitigation frameworks [3]. Then, into the modern era of the late 2010s–20s, energy efficiency became the 'first fuel' at the core of a dynamic, carbon-aware ecosystem where smart grids and AI increasingly manage energy in real time [4, 5].

While economies have become steadily more energy efficient despite rising populations and surging resource consumption (Fig. 2), the historical progress of energy efficiency has reached a plateau: the rate of improvement has recently slowed (see Box 1 on trends).

Ultimately, energy efficiency serves as a key driver in societal transitions and a crucial buffer against transition disruption. It insulates consumers from price volatility and nations from geopolitical supply threats, while simultaneously absorbing grid variability through demand-side flexibility. This reflects the power of the 'negajoule'—the energy that we don't use [6, 7]—which remains the fastest, cheapest, and most secure means for balancing energy supply and demand. As an example, if every air conditioner purchased globally since 2019 had met the highest efficiency standards, the resulting negajoules would have entirely offset the growth in data centre electricity demand for the same period [8].

Typologies of structural change

To realize the potential of energy efficiency, future energy transitions can be characterized through distinct 'typologies of change':

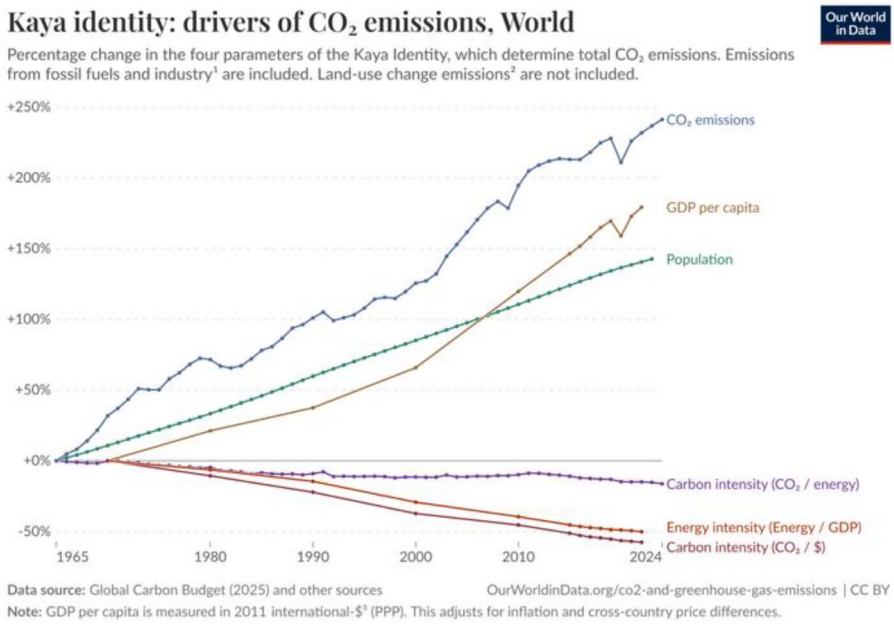


Figure 2 Kaya decomposition of global trends in CO2 emissions (1965–2024). Historical improvements in the relative energy efficiency of economies have offset absolute growth in GDP per capita and population. Source: Our World in Data.

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Box 1 Energy efficiency long-term trends.

(Nicholas Howarth)

Over the last 50 years, global energy intensity has followed a relatively steady progression, accelerating from an average improvement of 1% per year in the 1980s and 1990s to 1.5% in the 2000s to peak at just under 2% from 2010 to 2019. This came about as the result of gradual decoupling of energy demand from economic growth. Following this progress, nearly 200 countries agreed on the First Global Stocktake of the Paris Agreement at COP28 in Dubai [16] including quantitative targets of double efficiency progress, from 2% to 4%, by 2030. Still, progress between 2019 and 2025 of just 1.3% on average means the world is not yet on track to reach this 2030 ambition. Figure 3 shows the global trends from 1980 to 2025; Fig. 4 compares three time periods for select countries and regions.

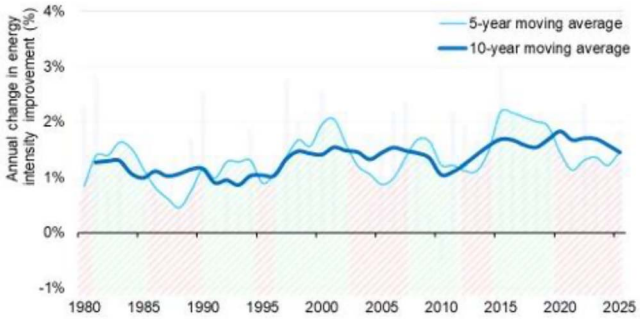


Figure 3 Long-term trends in global energy intensity rates. Sources: IEA World Energy Indicators, 2026; IEA Energy Efficiency Progress Tracker, 2026. Accessed January 2026. Primary energy intensity = Total Energy Supply divided by Gross Domestic Product (GDP 2020 Purchasing Power Parities). An improvement is defined as a reduction in energy intensity. 2025 values are preliminary estimates. Green and red shading represents increasing and declining momentum, respectively.

The International Energy Agency's 2025 Energy Efficiency Market Report outlined four key trends behind the recent general slowdown and the policies needed to accelerate progress [17]. First, around two-thirds of the growth in final energy demand between 2019 and 2024 has been concentrated in industry. Unlike other sectors, global industrial energy demand did not decline during the COVID-19 pandemic but increased, even though industrial economic output slowed down. Second, energy-efficiency policies, such as performance standards, have been lagging behind advances in technology. Many appliances sold today are only half as efficient as the best available options commonly found on the market. Third, warmer temperatures and increased access to air conditioners have led to an increase in cooling related electricity demand. While higher incomes and living standards enable more people than ever to access cooling solutions, most air conditioners sold are not energy efficient. A final key factor slowing recent energy efficiency progress, has been growth in global electricity demand outpacing renewable supply, leading to an overall increase in less efficient fossil fuel generation. As renewables avoid heat losses involved with the direct combustion of fossil fuels, this trend should reverse as renewables replace more fossil capacity. The COP28 doubling target has come at a vital time to strengthen efficiency's role in energy transitions—to bring down costs, provide jobs, strengthen energy security, and lower emissions [18].

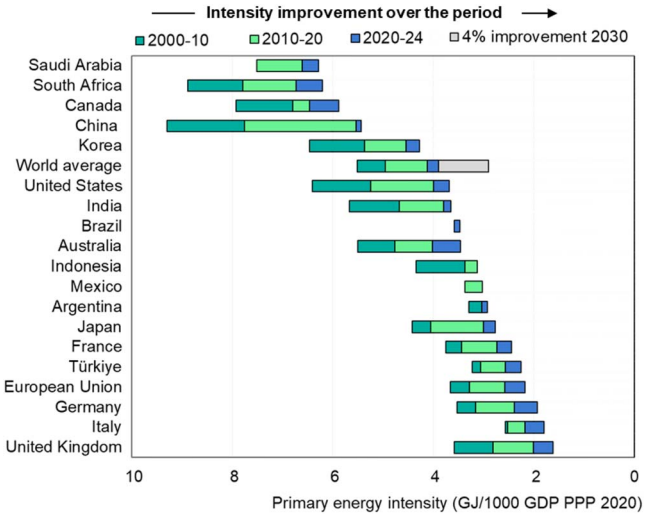


Figure 4 Energy intensity improvements for selected countries and regions. Source: IEA, World Energy Indicators, 2026. Note: 4% improvement 2030 = actuals to 2024 and 4% per year on average to 2030 consistent with the IEA Net Zero Emissions by 2050 Scenario.

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Box 2 Electrification.

(Nick Eyre)

The zero-carbon transition is a systemic change from heat-producing to electricity-producing energy sources. Electrification will play a dominant role in the decarbonization of global energy use, displacing the direct use of fossil fuels. Electrification is a central contributor to all plausible net zero emissions scenarios [19, 20]. It hugely increases the potential for energy efficiency, primarily because of the shift from using combustion to electricity at the point of end use [21]. The potential for end-use electrification to improve energy efficiency is largest in transportation [22], as light electric vehicles are typically four times more efficient than the internal combustion engines they replace, due to high efficiency of electric motors over the whole duty cycle of the vehicle. In buildings, electrification will reduce losses of heat in combustion products. However, there is an even larger potential from using ambient heat, as heat pump use increases [23]. In industry, there is more complexity, due to the diversity of industrial processes. Ambient energy via heat pumps has a role but only at temperatures below 200°C. The elimination of waste heat in combustion products is more significant, especially for high-temperature processes [24].

Electrification also improves systemic efficiency by reducing waste heat in electricity production as generation moves away from the energy sources that require fossil fuel combustion to lower cost renewable electricity sources, mainly photovoltaics and wind. There will also be reduced losses in activities such as drilling for oil, coal mining, and refineries, as fossil fuel production declines. When efficiency benefits are combined across end-use sectors, final energy use can be reduced by 40% for the same levels of service demand [21]. When reduced energy sector losses are included, the scope for primary energy efficiency improvement is even larger—to approximately a factor of two.

The key role of electrification in the current transition has major implications for energy efficiency policy. Policy packages will still be important, but need to be re-directed away from the efficient use of fossil fuel and towards the efficient use of electricity [25]; see the Energy Efficiency and Effective Policy Mixes section and Box 5 on policy packages for further discussion.

technological, integrated digital–physical systems, and socio-technical as well as planning.

First, with 'technological' change, energy efficiency may take shape generally as an addition, subtraction, or substitution. It is best illustrated by replacing legacy equipment with higher-performance alternatives. For instance, internal combustion engine vehicles lose ∼70%–80% of their energy as waste heat, whereas electric vehicle (EV) motors convert over 85%–90% of electrical energy into motion [9]. Assessed through a life-cycle lens, widespread electrification offers similar step-change improvements by eliminating the inherent inefficiencies of fossil fuel combustion (see Box 2 on electrification).

Second, energy efficiency may be driven by an integrated, 'digital–physical' approach that leverages system-wide capabilities. By integrating physical infrastructure with digital intelligence, this approach can transform the built environment into a responsive and more efficient ecosystem [4]. However, a key paradox remains—the energy to optimize may offset the very energy efficiency gains they achieve (see the Energy Efficiency and Rebound Effects section).

Third, energy efficiency change may be realized through a 'socio-technical and planning' approach that integrates human behaviour with macro-spatial design of the built environment. Strategic land-use and transit-oriented development, for instance, embed energy efficiency into a community's physical layout and character, reducing the need for energy-intensive transit.

This planning approach can manifest in two distinct spatial-energy efficiency archetypes. 'Urban efficiency' specifically leverages density through economies of scale. In such environments, buildings may act as 'prosumers' (simultaneously consuming and producing energy), and district networks may transform industrial waste heat into residential fuel. By contrast, 'rural efficiency' utilizes decentralized optimization. By deploying microgrids and smart irrigation—and using AI to manage renewables—rural areas can minimize transmission losses and function as highly efficient self-contained nodes in the energy landscape (see the Energy Efficiency and AI section).

Cross-sectoral strategies and the cascading economy

To realize the potential of energy efficiency in energy transitions, pioneering nations are already shifting from basic energy conservation towards systemic decarbonization strategies (see the Energy Efficiency and Effective Policy Mixes section). For example, France's 'Strategic Rail Pivot' leverages high-speed rail as an efficiency engine, by actively discouraging short-haul flights where rail is a viable alternative [10]. Meanwhile, Japan's 'Top Runner Program' has long mandated future commercial targets that exceed current best-in-class performance, consistently driving appliance efficiency to attain new benchmarks [11].

Energy efficiency is also bridging traditionally siloed sectors. In vehicle-to-grid (V2G) initiatives such as those in Norway and the Netherlands, electric vehicle batteries serve as mobile infrastructure. By standardizing bi-directional charging, transport fleets become flexible storage assets that stabilize the electricity grid and support buildings during peak demand [12]. Similarly, with an industrial waste heat initiative in Germany, the Energy Efficiency Act mandates that large facilities and data centres capture waste heat for local networks, transforming surplus thermal energy into a new resource [13].

A key force multiplier for these efficiency efforts is a cascading economy in which there is strategic and sequential material reuse [4]. Yet managing operational energy is only half the challenge (see the Material Resource Efficiency and Energy Efficiency section). Policy must also account for 'embedded or embodied energy', the total energy consumed during a product's raw material extraction, refining, and manufacture. Doubling the operational lifespan of high-impact goods effectively reduces the primary energy required to sustain modern services over time. Governments are increasingly stimulating 'demand pull' incentives for such shifts through procurement standards and mandates, such as the EU's 2024 'Right to Repair' directive and France's mandatory repairability index [14, 15].

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Box 3 Energy efficiency in Global South development.

(Joyashree Roy)

Strong energy efficiency programmes in many countries of the Global South have not only reduced energy use per unit of economic output (Figs 4 and 5) but also spurred on job creation, improved social welfare, and reduced emissions by almost one-third [27]. Figure 4 gives examples of energy intensity improvements for South Africa, Indonesia, and other emerging economies. Figure 5 shows time trends for the major regions of the Global South including Africa and Asia-Pacific. Efficient growth strategies enable developing countries to support decent living standards for all with a tenth of the energy consumed by the United States in 2020 [28]. Measures often referred to include LED lights, energy-efficient refrigerators and washing machines, two wheelers, and air conditioners (Acs). At a household level, such measures can help save money. At a country level, they can largely decouple economic development from its energy use and emissions [29–32].

However, there are also barriers for less developed countries in pursuing energy-efficient economic growth. In many countries the regulations for energy efficiency standards, project implementation, financing, pricing, and energy audits are weak and energy efficiency progress is limited [33, 34]. Lack of research and development (R&D) and pilot projects create technological uncertainty. Keeping energy or electricity prices low in many political decisions disincentivizes energy-saving practices. Energy service users, financiers, and industrialists are either unaware of the benefits of energy-efficient technologies and policies, or they lack agency. In many developing countries, limited access to information hampers reliable, efficient affordable power. There is a lack of data in the public domain on inefficiencies and resource potential, demand-side data, cultural characteristics, diffusion potential, and consumer satisfaction which create impediment to energy efficiency. Lack of 'efficiency' awareness and gaps can be resolved through targeted policy actions and capacity-building programmes. One example is the implementation through Perform Achieve and Trade (PAT) in India—a combination of regulatory and market-based instruments focusing on energy efficiency in energy-intensive industries. This programme created a skilled workforce, energy auditors, and institutions like the Bureau of Energy Efficiency [35].

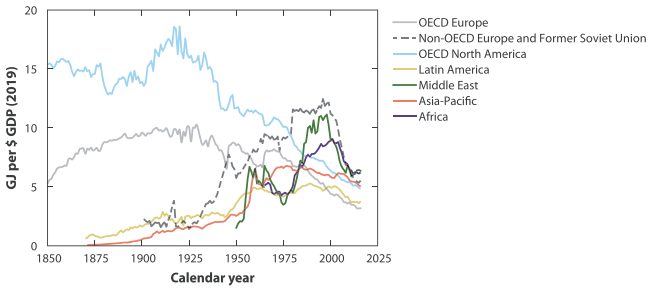


Figure 5 Historical trends in energy intensity by world region. Source: [26].

Future directions for research, policy, and practice

- Systemic resilience: Energy efficiency should be prioritized as a rapid, least-cost, and environmentally friendly buffer against geopolitical and environmental disruption.
- Interface optimization: Policy can concurrently optimize the digital–physical infrastructure and socio-technical planning to insulate economies from energy price volatility and power system fragility.
- Structural integration: By embedding efficiency into our national and regional hard wiring, alongside our products' lifecycles, we move towards a system that is not only cleaner but inherently less prone to the shocks of a changing world.

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Energy efficiency and AI

(Lynn H. Kaack and Chiara Fusar Bassini)

AI is and will be an important driver of efficiencies in energy transitions. However, digitally enabled efficiencies can induce additional demand and drive further energy and resource consumption.

AI encompasses a range of analytical tools that can unlock new approaches to energy and resource efficiency throughout the economy. In the transportation sector, for example, AI can aid in various ways to make the sector more energy efficient, including improving logistics, vehicle efficiency, and operations of electric vehicles [36]. At the same time, it's important to recognize that AI is a multi-purpose technology and other uses, e.g. for cost efficiency, may run counter to decarbonization objectives [37]. Deep learning models for generative AI approaches, such as large language models (LLMs), also have a sizable energy footprint [38].

AI applications considered in this section are predominantly based on machine learning (ML), which encompasses statistical and computational approaches that improve by 'learning' from data. There are many examples of AI for energy efficiency across sectors including buildings, transport, power, and industry. We organize these examples under four themes, following Kaack *et al.* [37]: forecasting, system optimization and control, data mining and assessment, and accelerated experimentation.

First, AI applications improve forecasting capabilities for weather-dependent resources, which is crucial for a safe and efficient transition of the electricity sector to renewables [39]. AI-based forecasting in electricity systems can also enable network operators to develop more precise network schedules [40]. At the buildings level, ML-driven forecasts of electricity consumption can be leveraged by consumers

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with battery storage and rooftop solar to optimally schedule their demand to match renewable generation using reinforcement learning [41].

Second, a wide variety of AI and ML applications help manage, control, and optimize the energy efficiency of processes and systems. AI also enables optimal scheduling of flexible loads including electric vehicle charging and heat pumps. In supply chain management, ML is used for planning transportation networks and routing vehicles [42]. Transportation in urban areas can be made more efficient with ML that assists the planning and operations of public transportation systems [43]. Manufacturing processes such as battery production can be more systematically optimized for energy efficiency [44]. AI can also help to reduce material waste by analysing raw materials of various qualities, including recycled materials, to achieve efficiency improvements, for example, in the steel industry. Building energy management makes use of AI in various ways to improve efficiency including predicting occupancy rates to efficiently allocate resources and automated fault detection that help avoid unnecessary energy losses.

Third, AI is a tool for mining unstructured data to extract decision-relevant information, which, for example, can help in assessing efficiency costs, potentials, and opportunities. In electricity markets, the growing share of renewables and distributed demand require innovative approaches to market design. AI can help assess market efficiency, for example, by evaluating the flexibility of conventional generation units [45]. In buildings and other sectors, AI can improve the estimation of energy savings and the cost-effectiveness of efficiency measures implemented [46].

Fourth, AI assists and helps accelerate experimentation and innovation processes. AI provides new means for innovation in manufacturing by helping to identify promising approaches to optimize processes, for example, by identifying new catalysts [47] and helping to scale up perovskite solar cell manufacturing [48]. Also, research and development of electric and more efficient vehicles benefits from accelerated experimentation and improved modelling with ML.

While there are substantial benefits of AI for enabling energy and resource efficiency, AI is not a panacea. AI may also be used in ways that increase energy consumption, for example, when it is primarily used to find a cost-optimal solution that may be at odds with energy efficiency or sustainability objectives. In addition, AI-driven energy efficiency is subject to rebound effects and other system-level effects that may change the way the overall impact on greenhouse gas emissions should be evaluated [37]. For example, autonomous vehicles, which are fully based on AI, have potential for energy efficiency gains but may also result in increased overall energy usage [49]. The system-level impacts of AI in practice are, however, still poorly understood and a scientifically rigorous evaluation of AI is hindered by the appeal of novelty and optimistic views of its potential.

In addition, some AI models have a sizable computational energy footprint. As the computing demand for AI is growing fast, significant investments are currently underway to expand data centre capacity globally [50]. The computing-related, or direct, energy footprint of AI differs significantly between model types, and the current growth is driven by generative AI and LLMs. However, the types of models that are predominantly used in energy efficiency applications are not generative but are based on much smaller, specialized AI models.

Future directions for research, policy, and practice

- AI applications for improving the energy and resource efficiency of activities, processes, and systems throughout the economy are many and varied, yet their deployment in practice is slower than consumer-oriented AI applications. Their development and deployment are steered by the incentive structures facing firms and AI providers. Public policy has an important role to play in orienting incentives towards delivering AI for efficiency.
- The direct operational energy footprint of AI infrastructure including data centres needs careful management although most AI applications for improving efficiency are not dependent on energy-intensive LLMs.
- The impacts and deployment rates of AI applications in different energy-using sectors need more systematic assessment and reporting, as these data are needed for downstream research, energy modelling, and policy analysis.

Material resource efficiency and energy efficiency

(Edgar Hertwich)

While energy efficiency traditionally focuses on operational energy use, the energy embedded in materials is becoming increasingly significant. In this vignette section, we emphasize the importance of including the material dimension in energy efficiency strategy and analysis.

Material production constitutes the largest industrial energy demand [51–54]. Energy carriers are used in industry as feedstock and process chemicals to produce plastics and reduce metal oxides, as heat source for decomposes limestone, and steam-cracking hydrocarbons, and as electricity to refine aluminium and copper [54]. Using less materials therefore reduces industrial energy use [52]. Because primary production of many materials is energy intensive, recovering materials from used products can also reduce energy demand. Reviews point to a significant potential for material efficiency [55–57].

The most important material uses in terms of energy required to produce the materials are construction, the manufacturing of machinery, equipment, and vehicles, and the production of consumer goods [58]. Most material services are provided by stocks of materials in buildings, factories, and cars, while most energy services are driven by flows of energy through buildings, factories, cars, and appliances. Material use is hence connected to stock expansion and replacement more than to throughput [58].

The International Resource Panel summarizes seven approaches for reducing energy use through material resource efficiency along the product lifecycle from design to end-of-life [53]. Here, we illustrate each of these as applied to buildings and vehicles.

First, ‘using less material by design’ reduces embodied energy [52, 53, 55, 59, 60]. Structural elements in buildings are often overdesigned in terms of potential load bearing capacity by a factor of two. More compact building typologies reduce material intensity per unit of floor area. In most regions, two to eight-storey multifamily buildings require less material per unit of living space than single-family homes and reduce infrastructure requirements for transport and utilities. An exception occurs where single-family homes are light wood structures and multifamily buildings rely on reinforced concrete. In vehicles, lightweight design and the choice of smaller models reduce material input and operational energy use.

Second, ‘material substitution’ can lower life-cycle energy demand when less energy-intensive or functionally superior materials are used [52, 53, 55, 60]. Substitution in vehicle manufacturing towards

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lightweight materials such as aluminium and composites reduces in-use energy demand but increases embodied energy. The overall benefit depends on vehicle lifetime, electricity mix, and recycling performance. In buildings, substituting bricks and reinforced concrete with timber, plywood, bamboo, or rammed earth can reduce embodied emissions. Wood structures are lighter and can store carbon, while rammed earth provides thermal mass that reduces cooling demand in hot climates.

Third, 'fabrication yield improvements' reduce waste and the need for primary material production [52, 53, 55, 60]. In construction, prefabrication and standardization lowers off-cuts and on-site losses. In vehicle manufacturing and component production, improved forming, cutting, and casting processes can reduce scrap rates.

Fourth, 'more intensive use' of existing stocks reduces the need for new material production and lowers operational energy demand [52, 53, 55, 60]. For buildings, reducing vacancy and under-use offers the largest mitigation potential. More intensive use of existing floor space decreases demand for new construction and reduces heating, cooling, and lighting needs. Tax incentives, demographic patterns, and transaction costs often discourage downsizing or shared use, leading to overprovision of residential space particularly among high income groups. Car sharing, ride sharing, and better matching vehicle size to trip requirements reduce the total vehicle stock needed to deliver mobility services. This lowers material demand for vehicle production and associated energy use.

Fifth, 'product lifetime extensions' reduce material throughput but may interact with operational energy efficiency [52, 53, 55, 60]. Building lifetimes vary widely, from around 23 years in China to more than 100 years in parts of Europe. Extending lifetimes reduces material demand for replacement but without renovation may lock in inefficient energy performance. Lifetime extension of vehicles has been less prominent because newer models are often more energy efficient. Early retirement of inefficient internal combustion vehicles and replacement with electric vehicles powered by renewable electricity reduces life-cycle emissions.

Sixth, 'recovery, remanufacturing, and reuse' of components and products preserves embodied energy and reduces demand for primary materials [52, 53, 55, 60]. In buildings, reuse of components is common in informal contexts but less so in large-scale formal markets. While architectural reuse of iconic elements is increasing, cost-effective reuse of large volumes of structural components remains limited. Reuse of entire structures often has greater potential than dismantling for component recovery. In vehicles, remanufacturing can extend component lifetimes and reduce the need for new metal production.

Seventh, 'end-of-life recovery and recycling' reduce the need for primary production [52, 53, 55, 60]. Metals in buildings and cars are widely recycled. Because metal production is energy intensive, recycling provides substantial energy savings. However, in vehicles, steel recycling often results in downcycling to construction steel due to alloy contamination. Improved separation into alloy groups can enable closed-loop recycling and retain functional properties, saving an additional share of embodied energy [55].

Modelling studies quantify the potential savings of these seven approaches [53, 56]. They are commonly informed by engineering considerations and utilize dynamic product cohort models, life-cycle descriptions of product production, use, and end-of-life of products, and information on markets [59].

Material resource efficiency is complementary to other energy and climate strategies. While evidence for buildings and vehicles is increasingly robust, important gaps remain.

Future directions for research, policy and practice

- Expand modelling and empirical analysis of machinery, equipment, and appliances including the trade-offs between lifetime extension and technological upgrading, and system-wide rebound and interaction effects.
- Reform taxes, planning, and building regulations to encourage compact settlements, space sharing, high-yield construction, high-quality reuse and recycling, and renovation over demolition.
- Promote integrated design approaches that combine structural optimization, material substitution, prefabrication, shared use models, and high-value recycling to align material and energy efficiency objectives.

Energy efficiency and rebound effects

(Daniel Guzzo & Daniela Pigosso)

Energy efficiency is at the heart of rebound effect research. The basic insight that efficiency improvements do not translate proportionally into reductions in energy use has shaped decades of scholarship, from early work on fuel efficiency and industrial productivity to contemporary debates on green growth and climate mitigation pathways.

Research increasingly conceptualizes rebound effects as emergent outcomes of complex socio-technical systems influenced by the interplay of economic, behavioural, social, and institutional dynamics [61–63]. They are the outcome of induced changes in system behaviour that offset the potential sustainability performance of interventions. While the range of rebound magnitude ranges from 2% to 7000% across 300+ cases [64], the median rebound magnitude of 50% positions rebound effects as a critical issue in the energy and sustainability transitions agenda.

The empirical literature of rebound effects is strongly concentrated on energy efficiency interventions across a wide range of areas [64, 65]: (i) in housing, efficiency improvements often lead to comfort take-back, extended appliance use, or increases in dwelling size; (ii) in mobility, lower per-kilometre costs stimulate additional travel, while efficiency gains in freight and logistics support expanding transport volumes; and (iii) in production, efficiency reduces unit costs and stimulates output expansion, triggering economy-wide effects through reinvestment and structural change [66]. While the rebound magnitude—i.e. the gap between potential savings and actual savings—varies across studies, their interpretation remains contested due to methodological heterogeneity and differences in system boundaries.

A defining development in rebound scholarship is the shift from simply measuring rebound magnitudes to understanding the underlying mechanisms that produce these effects (i.e. specific causal chains triggered by sustainability-oriented interventions [61, 67]. While economic mechanisms (income, substitution) remain central at the firm and macroeconomic levels [66], behavioural mechanisms (including moral licensing, cognitive biases, and diffusion of responsibility) are pivotal from the user perspective [68]. In addition, rebound effects

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unfold as part of the performance of everyday life, shaped by their socio-temporal and spatial contexts [69]. Understanding these dynamics requires combining distinct theoretical perspectives to systematically identify how interventions stimulate specific triggers, such as money, time, and convenience, and how these subsequently feed back into production and consumption.

As rebound effects are not static phenomena, grasping their emergence over time requires a dynamic and systemic perspective [70]. System dynamics research demonstrates that rebound effects emerge from feedback-rich structures in which efficiency improvements alter system behaviour in counterintuitive ways [61, 71]. For example, efficiency-driven cost reductions may reinforce growth-oriented feedback loops in production systems, while behavioural adaptations stabilize at higher-than-expected demand levels through systemic reactions. A dynamic perspective toward rebound effects can help prevent the systematic overestimation of efficiency-led innovation strategies.

In terms of energy transitions, rebound effects expose a structural tension between efficiency-led innovation strategies and the dynamics of demand, individual behaviour, growth, and social practices that characterize contemporary energy systems. They arise from interactions across micro-level behaviour, meso-level organizational strategies, and macro-level economic and infrastructural dynamics [63]. Nevertheless, rebound effects remain weakly integrated into transition models and pathway analyses. This lack of integration may be the cause of a comparability crisis, where high variability in magnitude estimations and conflicting data stall action [64]. To resolve this, the field must establish transparent protocols for rebound estimation that clarify definitions, boundaries, and counterfactual procedures [72].

Alternative sustainable consumption models to efficiency are also potentially associated with rebound effects [64, 73]. Access-based and service-oriented models might lead to behavioural rebound via careless use, higher turnover, or increased consumption. Social norms, identity factors, or compensatory behaviour may undermine sufficiency-oriented interventions (see the Energy Efficiency and Sufficiency section). These insights challenge the idea that effectiveness and sufficiency are naturally rebound-free and highlight the importance of systematic rebound analysis across all sustainability strategies.

Rebound effects should be assessed not only in relation to environmental impacts but also in terms of their broader social implications. In particular, it is necessary to ask whether interventions that increase environmental pressures, while simultaneously allowing unmet needs to be fulfilled, ought to be classified as rebound effects. In that sense, further defining the concept of rebound effects in relation to human wellbeing and fair allocation of environmental sustainability thresholds becomes critical to ensure just transitions.

A further shift in the literature is the move from mitigating rebound effects *ex post* towards preventing them *ex ante*. Design-oriented research argues that rebound effects should be anticipated early in the design of products, services, and socio-technical systems [67]. Behavioural design strategies, including nudging, feedback, defaults, and practice-oriented interventions, have been proposed as means to prevent rebound effects by targeting specific behavioural mechanisms [74, 75]. While empirical validation remains limited, these approaches align closely with transitions thinking by focusing on shaping practices and system dynamics rather than correcting outcomes after implementation (see the Energy Efficiency and Just Transitions section).

Future directions for research, policy, and practice

- Rebound effects should be defined in relation to absolute environmental sustainability limits and human wellbeing.
- Rebound mechanisms improve the systemic understanding of rebound effects by capturing the interdependence of economic, behavioural, and systemic drivers.
- A dynamic and system-oriented perspective enables the *ex ante* identification, quantification, and mitigation of rebound effects.
- Standardized protocols for estimating rebound effects improve comparability across studies, strengthen the evaluation of interventions, and facilitate integration into policy and business decision-making.

Energy efficiency and sufficiency

(Bryony Parrish and Tina Fawcett)

In response to rebound effects and growing pressures on resources, sufficiency offers an alternative perspective to efficiency that is oriented towards defining and meeting needs within ecological limits.

Energy sufficiency is attracting increasing research and policy attention. Princen's seminal work characterized sufficiency as an organizing principle for sustainable living and offered an initial definition of this principle as 'a sense of "enoughness" and "too muchness"' [76]. As sufficiency becomes more widely researched, many other definitions have been proposed, including those narrowly focused on individual, voluntary behaviour change [77].

Here, we adopt a wide-reaching definition of energy sufficiency as 'a state in which people's basic needs for energy services are met equitably and ecological limits are respected' [78] and an organizing principle for achieving that state. As a state, sufficiency meets the ethical need to provide a social floor (equitable access to needed energy services) within the absolute biophysical limits of an environmental ceiling. As an organizing principle, it rests on the idea that needs can be differentiated from wants. It also distinguishes fundamental needs, like health and education, from energy services as means to meet these needs. It identifies both wants and needs as socio-technically constructed: emerging from interactions between technologies, infrastructures, and wider society. This means achieving sufficiency requires negotiating with what is socially and individually considered to be 'enough' energy services, interlinked with how we construct and use technologies, infrastructures, and systems of provision to provide for needs [79].

Energy efficiency is also both a state and an organizing principle or strategy. As a technical state, efficiency is the ratio of desired outputs to energy inputs. This be calculated at different temporal and spatial boundaries. For example, operating a heat pump flexibly will reduce the efficiency of the heat pump itself but might increase the efficiency of the electricity system. However, the basic nature of efficiency as a ratio remains the same. The deployment of energy efficiency can also be used as a strategy (see section on Energy efficiency long-term trends). Technical efficiency improvements tend to feed into broader trajectories of growth [80]. Efficiency as a strategy does not explicitly question absolute levels of service demand—high energy consumption can co-exist with high energy efficiency. Efficiency as a strategy also does not say anything about the distribution of harms or benefits.

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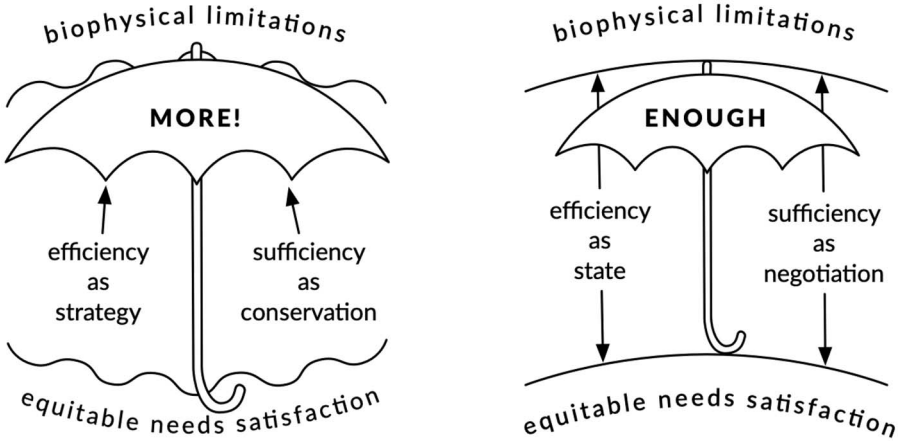


Figure 6 Different roles for efficiency and sufficiency and how that impacts on meeting human needs and staying within biophysical limits. Credit: Yekatherina Bobrova.

These distributional issues, as well as absolute constraints on resource consumption from planetary boundaries, mean the need to pursue sufficiency has been increasingly recognized, alongside reliance on improving technical efficiency. Conference papers to the European Council for an Energy Efficient Economy (ECEEE) illustrate this shift. Early contributions highlighted that policy makers are mistaken to act as though increasing technical efficiency automatically translates to reduced energy use, since historical energy use within the OECD use has continued to grow alongside increases in efficiency [81]. This is problematic given that developing countries need to increase access to energy and energy services, and that all forms of energy supply have environmental impacts (ibid.). This led to calls for European policy makers to look beyond technical efficiency to address consumer demand for energy services [82]. While not yet mainstream in policy by 2019 [83], more recently, sufficiency has increasingly entered French public debate [84]. It informs the most recent IPCC assessment on mitigating emissions from buildings [85] and UK energy demand reduction scenarios [86].

Efficiency improvements need to be implemented within an organizing principle of sufficiency to achieve their full benefits. This idea is similar to the SER (Sufficiency, Efficiency, Renewables) framework referenced in the IPCC Sixth Assessment Report ([85] p. 95). Increasing technical efficiency is positioned as an important tool within a 'sufficiency strategy' as it allows more people to meet their needs using less energy. However, if sufficiency is narrowly understood as a set of 'sufficiency actions' focused on voluntary behaviour change, then these may be used to serve 'efficiency strategies', through which resulting energy savings in one place can enable continued energy growth elsewhere [87].

Figure 6 visualizes these contrasting relationships between efficiency and sufficiency. On the left-hand side, energy savings from both efficiency and sufficiency feed into supporting the current paradigm of continued growth. Biophysical limitations and the need for equitable needs satisfaction remain fuzzy because they are not directly addressed by the forms of action represented here, and they are being transgressed. The right-hand side represents a paradigm shift to the organizing principle of sufficiency. Here, both technical efficiency and sufficiency actions are implemented with the specific aim of providing equitable needs satisfaction within biophysical limitations. Sufficiency actions can include voluntary behaviour change, but go beyond this to include society-level negotiations with what we really need, and how this can be provided.

Future directions for research, policy, and practice

- Energy sufficiency as a strategy is not currently central to the energy transition. One route to mainstreaming sufficiency is strengthening the evidence base by trialling and evaluating different experiments with sufficiency in buildings, transport, and land-use planning (e.g. [88]).
- Developing sufficiency scenarios for global and national net zero or just transition modelling exercises will give sufficiency more prominence.
- The transformative principle of sufficiency needs to be much more widely understood, discussed, and debated, with diverse lay and expert audiences engaged in participatory and deliberative processes.

Acknowledgements

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Energy efficiency and wellbeing

(Sascha Nick)

Energy transitions, energy efficiency, and sufficiency need to be understood through their contribution to human wellbeing. Yet, energy analysis still tends to treat energy use and efficiency as goals in themselves, rather than as means towards meeting fundamental human needs.

The conditions under which energy efficiency developed differ fundamentally from those facing societies today. Climate change, biodiversity destruction, and material constraints dominate today, not scarcity of productive capacity. In rich countries, basic energy services are already saturated, while additional consumption delivers diminishing or even negative wellbeing returns [89]. Under these conditions, the efficiency-first approach becomes problematic. More efficient buildings, vehicles, or appliances reduce energy use per unit,

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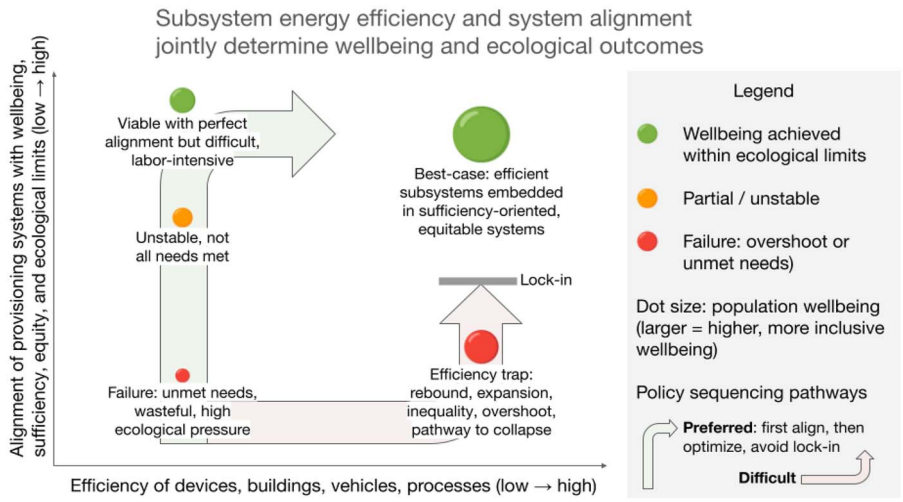


Figure 7 Energy efficiency (*x*-axis) and system alignment (*y*-axis) jointly determine wellbeing.

while enabling larger dwellings, more travel, or energy-intensive lifestyles. This increases environmental pressures, exceeding local and global limits.

A deeper issue relates to the definition of 'useful output' itself. Efficiency metrics traditionally compare energy inputs to energy services (heated space, passenger-kilometres, data processed), not wellbeing outcomes. If energy-intensive satisfiers become normalized, such as large private living spaces or car-based mobility, efficiency helps stabilize provisioning patterns that are misaligned with collective wellbeing, equity, and ecological limits. The problem is systemic. Efficiency is not just an imperfect metric but can actively reinforce unsustainable lock-ins when applied without a sufficiency and wellbeing perspective [90–92].

Extensive scholarship on human needs distinguishes between universal, unchanging human needs, and the culturally specific, historically evolving 'satisfiers', means through which these needs are met [93, 94]. Energy and energy services are only indirectly relevant, as inputs shaping how satisfiers are produced, accessed, and experienced. Crucially, wellbeing goes well beyond aggregating individual utilities. Most fundamental needs, like participation, identity, protection, or affection, are inherently relational and collectively produced, depending on social institutions, spatial organization, and shared meanings [89]. From this perspective, performance of energy systems must be evaluated beyond technical metrics by how they contribute to collective wellbeing within ecological limits.

Energy efficiency misconceptions arise from how system boundaries are defined. Efficiency is often calculated for small subsystems, such as an efficient heater, a better-insulated room, or a high-performance building. At these levels, improvements appear unambiguously positive. However, as the boundary expands, the picture changes. Improved heating efficiency at the appliance or room level reduces energy use per square metre, but at the building or neighbourhood level, the resulting savings typically lead to increased floor area, higher indoor temperatures, or unsuitable occupancy patterns. Zoning efficiency locks in urban sprawl. At the societal level, these changes interact with housing markets, land-use planning, and social norms, increasing total energy and material demand while delivering mixed wellbeing [95]. Resolving this boundary problem requires a societal provisioning perspective [96]. System-level energy efficiency cannot be meaningfully assessed in isolation from social systems (housing, mobility, food, care), nor from the institutions that shape them (Fig. 7). What matters is not individual component efficiency but how the overall configuration of provisioning systems delivers wellbeing with minimal energy, materials, and ecosystem pressure [97].

From a wellbeing perspective, energy efficiency remains important, but its role changes: efficiency becomes secondary to fundamental societal decisions about which satisfiers are desirable and compatible with ecological limits. Efficiency then supports these satisfiers by reducing energy intensity, without driving their expansion. This shift requires moving from energy ratios to wellbeing outcomes as the primary evaluative frame. Conceptually, satisfiers can be understood as vectors in multidimensional needs spaces, defined by: 'norm' (magnitude—how well they satisfy needs), 'dimensionality' (the range of needs they help meet), and 'direction' (avoid negative impact on any need). Importantly, some satisfiers are 'synergistic', satisfying multiple needs simultaneously with the same resources; for example, walkable neighbourhoods that support social participation, protection, health, and identity. Such satisfiers easily outperform energy-intensive alternatives in wellbeing terms, even if they appear 'less efficient' when assessed narrowly. Reframing energy efficiency in this way requires us to collectively rethink what constitutes a good life, what is desirable, and how wellbeing is collectively produced. Without this grounding, efficiency is unlikely to lead to wellbeing, overcoming inequality and unsustainable consumption.

Future directions for research, policy, and practice

- A perspective on 'energy and wellbeing' requires transdisciplinary approaches and metrics that go beyond energy to include wellbeing outcomes, distributional effects, and absolute ecological pressures.
- Transition pathways and policy sequencing are central to policy development, defining desirable provisioning patterns and sufficiency goals before optimizing their efficiency.
- Closer engagement between energy professionals, spatial planners, and residents is important for advancing wellbeing outcomes in practice.

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Energy efficiency and just transitions

(Caroline Zimm, Benigna Boza-Kiss, Jihoon Min)

Linking wellbeing to fairness and equity, energy efficiency must also be considered within the context of just transitions. This section explores how efficiency can support inclusive and equitable outcomes across diverse social and economic settings.

Energy efficiency improvement is a cornerstone of climate mitigation and sustainable energy systems. However, it may inadvertently reinforce inequalities if benefits are disproportionately captured by wealthier households or regions, or if policies fail to consider vulnerable populations [98]. 'Just transitions' ensure that climate action does not exacerbate social inequities while creating new opportunities in a decarbonized economy [99]. The majority of just transition discourse focuses on job creation, reskilling, and resource use within energy transitions and clean energy access for poor households. Aligning energy efficiency with just transitions offers a framework that integrates diverse justice considerations (e.g. distributional, procedural, temporal) into energy policy by delivering societal co-benefits while reinforcing climate objectives [100, 101]. The following aspects of just transitions are closely connected to energy efficiency interventions.

First, 'affordability, equity, and development': improvements in energy efficiency can contribute to distributive justice by reducing utility bills and mobility costs, lowering energy burdens while improving wellbeing through positive rebound effects enabling suppressed demand [102]. Similarly, in developing country contexts, efficiency programmes can support development goals by freeing up resources for other individual or societal priorities and decrease the financial burden of energy access, highlighting the importance of intentionally linking energy efficiency to just transition principles. Climate resilience and adaptability of systems (e.g. shading, passive cooling) and reduced lock-ins, gained through energy efficiency interventions, will alleviate the mitigation and adaptation burdens of future generations, leading to higher intergenerational justice.

Second, 'reskilling & employment': energy efficiency projects are usually labour-intensive and require new skills and expertise from workers, and offer more local, green, and nonoffshorable opportunities, serving the prime goal of just transitions.

Third, 'participation & multi-level collaboration': participatory approaches ensure that energy efficiency strategies reflect local needs, values, and capabilities. Co-designing interventions with communities avoids top–down impositions and strengthens social acceptability, which is essential for sustainable implementation [103]. Energy efficiency solutions are typically granular and more local. Community-led retrofit programmes, social housing upgrades by municipalities, and public partnership programmes increase ownership and decision-making roles for a wider population. Nick and Sharma [104] showcase how neighbourhood-level housing and mobility governance lead to better living outcomes, while people exercise agency and contribute to planning their own community (see the Energy Efficiency and Wellbeing section). These energy efficiency actions enable the participation of diverse groups in the energy transition and contribute to climate mitigation and procedural justice.

Fourth, 'health & productivity': energy efficiency improvements can also improve health outcomes by reducing exposure to cold, damp, or polluted indoor environments [105]. Employment in high-efficiency buildings can lead to one to five active days gained per person and better work outputs in a European setting [106].

Fifth, 'challenging the high consumption paradigm': energy efficiency framing increases awareness about 'less is more' and service-orientation, in line with sufficiency (see the Energy Efficiency and Sufficiency section) and low-carbon or 1.5-degree lifestyle—i.e. the decoupling of wellbeing from high consumption and material-intensive lifestyles.

Energy efficiency without explicit attention to equity can perpetuate or worsen inequalities, for example, delays and temporal uncertainty imposed on communities constitute a distinct and underexamined form of injustice [100]. Marginalized populations (e.g. ethnic minorities, immigrants, indigenous groups) face higher hurdles in accessing energy efficiency–related benefits [107, 108], such as in structural barriers to more energy-efficient housing driven through racism [109].

Wealthier households may disproportionately capture energy efficiency benefits, such as increased energy service use, cost reductions, or access to subsidies, which are not equally accessible for lower-income households due to preventive high upfront costs. Similarly, in the residential sector, many energy efficiency measures are tied to property ownership where lower-income renters do not benefit in the short term. Also, energy-efficient housing tends to experience price premiums that benefit property owners [110].

Synergies between energy efficiency and just transition are not a given [111]. Single-sector interventions can fall short if justice is not considered. Energy efficiency policies must be paired with social protection, inclusive workforce development (i.e. current workforce shortages disproportionally affect rural and indigenous communities [112]), and participatory governance mechanisms [113]. Targeted subsidies for energy efficiency improvements, product purchase, or energy vouchers can protect and benefit less advantaged consumers.

Energy audit programmes, information campaigns, and specific consultations with a focus on vulnerable groups help overcome barriers, such as poorer access to information and renovation planning, financing, or monitoring and limited time. Multi-level governance has proven effective in aligning energy efficiency with broader social goals. For example, EU and US policies that integrate building efficiency standards with low-income retrofit programmes demonstrate the potential of coordinated approaches [114] (see section on Energy Efficiency and Effective Policy Mixes). Table 1 summarizes examples of energy efficiency interventions and their implications for a just transition.

Future directions for research, policy, and practice

- Key challenges to integrating energy efficiency within just transitions include financing constraints, measuring social impacts, and managing rebound effects that disproportionately benefit wealthier groups [107, 115].
- Opportunities include linking energy efficiency to broader social policies, leveraging climate finance to support equitable deployment across marginalized groups, and integrating energy efficiency with co-benefits such as health, education, and local economic development.
- Context-sensitive approaches are essential: what works in the Global North may require adaptation in low-income, high-growth regions to ensure both environmental and social objectives are met.

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- Future research should explicitly integrate equity metrics, monitor social outcomes, and explore participatory governance mechanisms and temporal justice in energy efficiency programmes.

Table 1 Examples of energy efficiency interventions for just transitions.

Sector	Example interventions	Social & equity implications
Residential buildings	Low-income retrofits, appliance subsidies, pay-as-you-go schemes, energy audits	Reduces energy bills, avoids energy poverty, green premium (increased building value)
Industrial	Energy-efficient machinery, process optimization	Job creation in green sector, potential workforce displacement
Transport	Efficient public transport	Improved mobility access at lower costs, reduced emissions
Governance	Participatory planning, participatory business models, inclusive regulation, innovative financing/metering, energy cooperatives	Empowers marginalized communities, builds trust and buy-in

Energy efficiency and multiple benefits

(Frederic Berger and Tim Mandel)

Energy efficiency is more than just a way to reduce energy consumption. It typically delivers a wide range of benefits from health and security to pollution reduction and cost savings—referred to as 'multiple benefits'.

Environmentally, energy efficiency can lower greenhouse gas emissions and decrease reliance on finite resources. Economically, it can reduce energy bills for households and businesses, boost productivity, and enhance competitiveness by lowering operational costs. For governments, it can strengthen energy security and reduce the need for costly new infrastructure. Socially, the multiple benefits of energy efficiency can alleviate energy poverty, improve public health through reduced air pollution, increase comfort in homes and workplaces, and create employment [116, 117]. By addressing these interconnected challenges, energy efficiency is a powerful tool for sustainable development, offering benefits for individuals, communities, and the planet alike.

Although the concept has been around for decades in the scientific community, multiple benefits took the spotlight following the International Energy Agency's (IEA's) landmark publication "Capturing the Multiple Benefits of Energy Efficiency" [118–120]. Initially conceived as a means to allow more holistic considerations of energy efficiency, both qualitatively and quantitatively [i.e. in the framework of cost–benefit analyses (CBA)], the concept allows for more tangible narratives to push for energy efficiency, as shown notably with the focus on energy security in the aftermath of Russia's invasion in Ukraine [121, 122].

In addition, the enshrinement of the 'Energy Efficiency First' principle in the Energy Efficiency Directive, which also requires the consideration of wider benefits, has further abetted the application of multiple benefits in CBAs. It stipulates that in case of substantial investments into supply-side infrastructure, the potential of demand-side solutions to deliver the same objective in a more cost-effective manner needs be assessed. Yet, this has also shifted the reference baseline: in contrast to previous multiple benefits assessments, mainly comparing energy efficiency to the status quo, 'Energy Efficiency First' requires the comparison to other decarbonised alternatives, such as renewables.

However, this inevitably leads to the question, for whom energy efficiency needs to be holistically economically viable, as results strongly differ between private and societal cost perspective. Societal CBA provides the normative benchmark for public decision-making by capturing benefits that are not fully reflected in market transactions, including public health improvements, resilience, and avoided infrastructure expansion [123]. In contrast, private actors make investment decisions based on subjective perceptions of costs and benefits, shaped by prices, tariffs, and actor-specific discount rates. While some multiple benefits may be partially internalized (such as network costs passed on through regulated tariffs or emissions reflected in energy taxation), many remain external, or weakly perceived, such as improved indoor environmental quality or increased asset value. Consequently, private investment decisions will tend to underweight multiple benefits relative to their societal value, reinforcing the need for public appraisal frameworks that explicitly recognize them [124].

Moreover, the assessment of most multiple benefits is based on a smorgasbord of assumptions, ranging from substituted energy carriers and future prices to discount rates and monetization factors, engendering significant margins of error. While these mostly statistical deviations are still better than the alternative systematic deviation resulting from ignoring multiple benefits altogether, they put the frequent deterministic interpretations of assessment results into question. Although rarely used, probabilistic approaches would better reflect the (often fine) margins separating different assessed solutions and better show the sensitivity to parameter variations. This issue is further exacerbated by a misunderstanding of health monetization factors (such as the value of a life), generally contributing substantial benefits to CBAs. In contrast to frequent belief, these factors do not reflect a citizen's value in terms of forfeited productivity or economic revenue. Instead, they are based on willingness-to-pay studies and represent the value a society should be willing to spend to avoid any death. While their inclusion in CBAs is meant to internalize this implicit valuation, this should not be a technical consideration, given associated ethical implications.

Future directions for research, policy, and practice

- Mainstreaming the multiple benefits of energy efficiency requires their systematic integration into public planning and appraisal exercises that shape long-term system outcomes. Societal CBA is particularly relevant in contexts such as *ex ante* policy impact assessments, network development planning, local energy plans, and transport and mobility strategies, where decisions determine infrastructure scale, technology choices, and long-lived investments.
- From a methodological perspective, mainstreaming multiple benefits requires the use of extended CBA frameworks, complemented by multi-criteria analysis. Extended CBAs allow system benefits to be quantified using energy system and network models, health benefits through exposure-response functions, and broader

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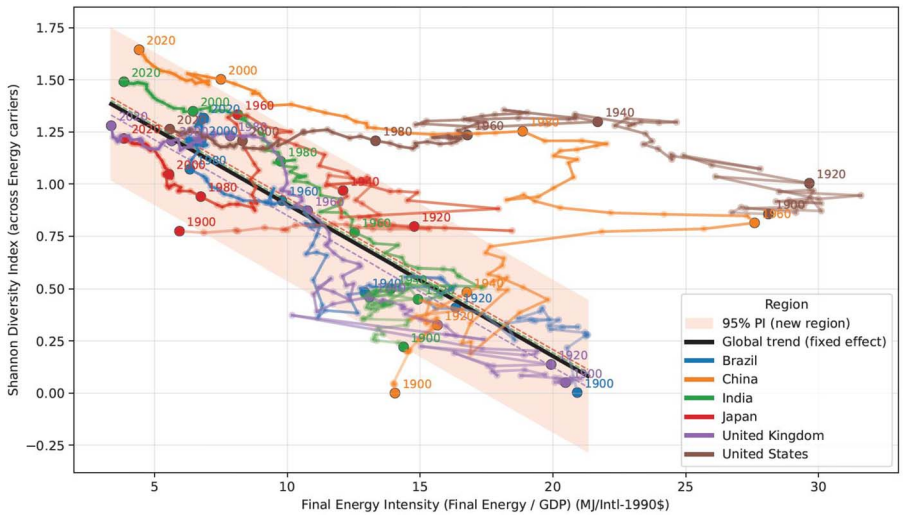


Figure 8 The efficiency–diversification relationship across a century of energy-system change. Trajectories for six developed and developing economies (1900–2020), representing over half of global final energy consumption over time, mapping energy intensity (final energy/GDP; MJ per 1990 international Geary-Khamis $) against the diversity of final energy supply (Shannon index). Across countries and over time, movement towards lower intensity tends to coincide with higher diversity, suggesting synergistic feedback. Markers indicate decadal observations; lines trace the direction of time. Global trend line and the 95% prediction interval are based on a linear-mixed effects model accounting for the residual and group variance of the regions, excluding the outliers China and the United States. Sources: [125, 126].

economic impacts via input–output or computable general equilibrium models.

- The assessment of multiple benefits inevitably raises normative and philosophical questions, *inter alia* regarding societal discount rates, the value of statistical life or life years, or the valuation of alleviating energy poverty or improving housing quality. These parameters shape the relative weight assigned to different benefits and reflect ethical judgements rooted in welfare economics. Making these value choices explicit is essential to ensure that multiple benefit assessments support legitimate, accountable, and socially grounded energy transition decisions.

Energy efficiency and security

(Nuno Bento, Arnulf Grübler, Simon De Stercke)

More efficient energy systems tend to become more diverse and more secure. The relationship between energy efficiency, diversification, and security is an important societal and geopolitical dimension in energy transitions.

Energy efficiency is usually framed as a lever for reducing costs or mitigating climate change. The recent geopolitical crises have re-demonstrated the importance of energy efficiency for energy security. Since 1900, higher energy efficiency and greater diversification have moved together (Fig. 8). This is consistent with a reinforcing relationship in which efficiency expands the feasible set of secure supply options, while diversification accelerates efficiency. Representative countries tend to drift from high-intensity, relatively concentrated energy systems towards lower-intensity, more diversified ones. The relationship is not perfect, and the trends shown in Fig. 8 do not prove causality, but their persistence across different political economies hints at something stronger than coincidence: efficiency and energy security may be mutually reinforcing.

Energy security is often discussed as supply acquisition with a focus on primary energy and reduced to security of supply [12, 127, 128]. But security is equally about 'reducing required supply per unit of service', with a focus on final energy. As energy services are delivered with less final energy per unit of output, economies (firms and households) become less exposed to shocks in any single fuel, supplier, or conversion chain—and they also find it easier to accommodate a broader portfolio of energy sources. It has also been shown that countries with higher efficiency tend to face lower energy cost burdens (on GDP) [127].

One way to read Fig. 8 is through the mechanisms that turn 'less energy per service' into 'more options under stress'. Historically, three mechanisms are: electrification (see Box 2), decarbonization (transition towards domestically scalable low carbon supply often enabled by electrification), and innovation in service provision that increases substitutability and system modularity.

First, 'electrification of energy systems': the share of electricity in final energy consumption has increased in the world at a compound average rate of 3.9% per year since 1900, even if the pace has slowed to 1%–1.3%/year since 2020 [126]. Moving from many (small) combustion conversions to higher-efficiency electric end use coupled with centralized generation (and later, more distributed production with, e.g. solar PV) enhanced overall efficiency (see Box 2 on electrification). Electrification also broadened the portfolio behind electricity (from fossil fuels to renewable energy sources) and made demand-side flexibility possible, improving security. The two effects are synergistic. Once electricity is the platform, security investments (grids, interconnection, reserve margins) reinforce efficient devices and system optimization.

Second, 'decarbonization and transition to domestic renewable energy sources': the global carbon intensity of energy ($MtCO_2/EJ$) declined by 0.23% annually from 1900, but the rate has slowed to 0.06%/year since 2000 [126]. The main drivers of this decarbonization shifted from fuel switching (coal/biomass to oil/gas) to electrification and expansion of domestic low carbon renewables, more recently. Domestic renewables reduce reliance on imported fuels and concentrated suppliers, diversifying portfolios geographically and technologically [129]. On the other hand, efficient end use reduces supply needs,

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import exposure, and emissions per unit of service. Strategies focusing on reducing the energy demand in end uses such as improving the energy efficiency of buildings have been shown to provide more benefits for enhancing energy security than supply side measures like investing in infrastructures for energy imports diversification [127].

Third, 'innovation in service provision—diversification and complexity': the carbon intensity of global GDP (CO_2 emissions per unit of economic output) has declined since 1900 at the rate of 0.8%, accelerating to 1.6% since 1980 [126]. Innovation in appliances, mobility options, logistics, and industrial processes, enabled by digitalization (including digital convergence of services previously provided by hardware onto digital interfaces with software or apps), has decoupled energy and material consumption per service [130]. More end-use technologies, more energy vectors, and control layers means less single-point dependence (e.g. transport options, distributed assets, more granular balancing). Granular technologies not only diffuse faster through economies of scale and learning [131] but also create redundancies across the different levels of the energy system improving the overall security.

Future directions for research, policy, and practice

- Efficiency reduces exposure (less energy required per unit welfare), diversification reduces vulnerability (more options when one source fails). Together they create a virtuous cycle: efficiency makes diversification cheaper and faster to achieve, while diversification makes further efficiency investments less risky and more reliable to operate. Both improve wellbeing by easing burdens to service access and improving societal and individual security alike.
- A century of country trajectories suggests the efficiency–security relationship is not accidental. The question is no longer whether efficiency belongs in security strategy, but how explicitly we design the next wave of electrification and diversification to reinforce it.

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Energy efficiency and effective policy mixes

(Benigna Boza-Kiss, Diana Ürge-Vorsatz)

Realising the diverse benefits of energy efficiency requires coordinated and well-designed interventions to transform market conditions, behaviours, and infrastructures. Energy efficiency policy packages incorporate heterogeneous mechanisms and sequence instruments to achieve complex policy goals that value benefits of energy efficiency beyond economic or physical savings over the long term.

Recently, the rationale of energy efficiency policies has shifted from supply security, via cost efficiency, to co-benefit valuation [132]. Historically, 'silver bullets', i.e. highly effective or cost-efficient single policies, such as Minimum Energy Performance Standards, tailored subsidies, labelling, and technology bans were favoured [133]. In the 1970s–80s reactionist era, policy focused on fuel efficiency, relying mostly on single instruments to promote technological innovation, accelerated the adoption of efficient technologies [134], while service levels declined or staggered. During the 1990s, emphasis moved to the wider economic benefits of efficiency improvement and to managing rebound effects to deliver energy savings [135] (see the Energy Efficiency and Rebound Effects section). Mixes of policies were introduced to support the central single instruments with, for example, behavioural nudging, financial incentives, and taxes [136], but the integrity of policy mixes was low and needed regular adjustments. In the 2000s, policy density grew rapidly worldwide, with increased specificity and stringency, and with incremental sequencing, which enabled progressive reduction of economic, societal, and political barriers [137]. Multilateral, socio-technical mixes emerged, putting citizens in the centre of the solution and the benefits [138], including innovative financing solutions (see Box 4 on financing), technical assistance for industry and one-stop shops for households, energy citizenship, low-carbon or 1.5-degree lifestyle solutions, reskilling, and training programmes, as well as varied informational measures.

More recently, the ambition of packages has become complex, combining carbon emissions reductions, energy security, affordable energy services, and increasing wellbeing [139, 140]. This is augmented with policy mixes in the Global South to deliver development and improve health impacts and access to energy services (see Box 3 on development). Future mixes are expected to scale up or multiply efficiency impacts.

Box 4 Energy efficiency and financing.

(Paolo Bertoldi)

Energy efficiency projects usually entail large up-front investments. In most cases, energy efficiency investments are profitable, in the sense that the financial savings due to the reduced energy consumption are bigger than the initial financial investments [142], often with additional nonenergy benefits [143]. However, a number of barriers prevents several profitable investments in energy efficiency, such as long payback periods, uncertain returns due to fluctuation in energy price and productions levels, split incentives between owners and tenants [144], limited access to external funding, lack of specialized expertise, complex project, and high perceived risks [145]. Many organizations face internal budget limitations or difficulties securing external, affordable financing [146]. Moreover, energy efficiency projects are often small-scale, leading to high transaction and due diligence costs relative to project size, which complicates financing [147].

There are a number of well-established financial mechanisms that support energy efficiency projects [148]. Grants and subsidies directly reduce the upfront capital burden faced by end users; however, their effectiveness is constrained by limited public budgets, administrative complexity, transaction costs, and, in some cases, insufficient targeting [149]. Moreover, grant-based financing schemes may lack long-term financial sustainability and can generate stop–start investment patterns depending on public funding cycles. Tax deductions and property tax reductions aim to reduce the net cost of renovation for property owners and can incentivize investment without requiring direct upfront public expenditure ([150]. Nonetheless, their design and uptake vary significantly across jurisdictions. In addition, tax-based incentives may disproportionately benefit higher-income households

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with sufficient tax liability and capital for the initial investment, thereby raising concerns regarding equity and distributional impacts. National energy efficiency obligations and white certificate schemes have supported energy efficiency projects with private capital, very often raised through energy tariffs and energy prices. This mechanism tends to favour the most cost-effective efficiency opportunities [151]. Loans and credit enable end-users to spread renovation or energy efficiency costs over time. Loans address liquidity constraints, whereas access to credit depends on borrowers' creditworthiness, and risk assessments may exclude low-income or high-risk companies.

In addition to conventional financial mechanisms, innovative financing models have been introduced. On-bill financing or Pay-As-You-Save is one such model, allowing repayment of residential renovation investments through utility bills rather than through conventional loan instalments. Nevertheless, implementation depends on regulatory frameworks that permit utilities to act as financial intermediaries and manage associated risks [152]. Property tax-based financing, including models such as Property Assessed Clean Energy, represents another innovation for renovation of buildings. Under this mechanism, renovation costs are repaid via an additional property tax assessment attached to the building rather than the individual owner. This feature addresses the 'split incentive' problem, particularly relevant in rental markets [153]. Recently energy efficiency mortgages, which incorporate energy performance criteria into mortgage lending practices, have been offered by an increasing number of financial institutions [154]. Another innovative concept discussed in literature is the application of feed-in tariff logic to energy savings [155]. For the nonresidential sector, Energy Service Companies (ESCOs) are a major enabler of private financing for the renovation of existing buildings, in particular in the public sectors [156]. Beyond discrete financial mechanisms, there is a need to stress the importance of supportive institutional models, such as one-stop shops, [157, 158].

Box 5 Illustrative examples of successful policy packages.

(Benigna Boza-Kiss, Diana Ürge-Vorsatz)

Heating and cooling package. Upper Austria, a region of Austria introduced a coordinated energy efficiency policy package with three pillars, combining 'sticks' or pull-measures (minimum heating and cooling requirements, certification, renewable heating obligations), 'carrots' or demand-push measures (financial instruments of grants, loans, and R&D programmes), and 'tambourines' (energy advice and audit programmes, training, campaigns, local strategies) that had delivered over half of public space heating by renewables, several 10 000 nearly-zero buildings and all of those owned by the region leading to healthier and cheaper homes and buildings [159].

Nearly-zero energy buildings package. Successful sequencing of energy efficiency policies in Brussels, Belgium, led to a system of stringent building regulations (PEB Regulation), upskilling, public information measures, one-stop shop, public exemplary building catalogue, and financial support programmes (BatEx programme). Consequently, new buildings and renovations reach almost passive house levels since 2017, and heating energy use per capita dropped by 25% and greenhouse gas emissions by 16% between 2004 and 2014 [160]. This policy portfolio effectively combines multilevel governance, replanting the EU's Energy Performance of Buildings Directive and the national building codes into regional level regulation. This integrated approach stimulated market transformation, scaled passive construction, generated employment, and achieved significant CO_2 emission reductions.

Road transport decarbonization and wellbeing package. Although single emission-standard policies—such as the Corporate Average Fuel Economy (CAFE) standard in the United States—have achieved an efficiency duplication in the United States between 1975 and 2010s, these could only modestly constrain total emission [161]. Other countries adapted CAFE, such as India, Brazil, China, South Korea, Canada, and the EU, and combined with incentives, industry development policies, and social policies to further enhance fuel shift, e.g. towards electric cars or public transport. However, policies reducing overall travel demand remain rare and largely ineffective [162], although these could deliver multiple benefits. Modal shift to active travel (cycling and walking) leads to positive health impacts, avoided infrastructure development, and thus economic savings. A comprehensive 'avoid, shift, improve' package is needed, integrating active travel promotion, infrastructure and safety investments, congestion pricing, and parking restrictions, public transport improvement. These packages are highly context-dependent, and differences of 12% in vehicle use between households were found to be linked to the urban environment [161] or socio-economic status.

Box 6 Energy efficiency and policy evaluation.

(Jean Sébastien Broc, Stefan Thomas, Christine Wörlen)

Evaluating impact. The primary objective of energy efficiency policies is to achieve energy savings, so their evaluation is often focused on assessing their energy-saving impacts. The main methodological challenge is that energy savings and other impacts of energy efficiency can often not be measured directly but need to be estimated in relation to a baseline (counterfactual) that would have persisted without an energy efficiency intervention or policy—but this counterfactual cannot be observed. This raises various issues that can be summarized going from assessment at micro (action) to macro (economy-wide) level [163]. Methods for evaluating net impacts and considering additionality to the baseline have been extensively discussed, with a growing focus on experimental methods, as in other policy fields [164]. Disentangling effects from overlapping policies, or at the opposite, evaluating the effects of policy mixes or packages, has been subject to more research, as policy interventions became more complex and interrelated [165].

Evaluating system change. An 'integration' aspect specific to the field of energy efficiency policies is related to the evolution of the energy system as a whole (e.g. increased share of noncontrollable renewables, electrification). Impact evaluations therefore need increasingly to assess the contribution to flexibility (i.e. when and where energy is saved). Moreover, evaluations should consider a broad scope of impacts, in line with the scope of objectives the policies may contribute to or interact with (see the Energy Efficiency and Multiple Benefits section). This requires multidisciplinary approaches and often raises methodological challenges. Considering multiple impacts, this goes beyond discussing evaluation methods. It relates to analysing the policy theory or intervention logic with a broader perspective [57], as

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well as the hierarchy in the objectives and different viewpoints (e.g. investor, State, society, consumer, supply chain, policy-maker).

Going beyond traditional evaluations. Research about evaluation use has investigated the integration of evaluation in the policy cycle or decision-making process. The development of mid-term or continuous evaluations (e.g. through observatories) can support this integration. Likewise, internal reviews can overcome the drawback of independent evaluations, where the evaluand might be more unwilling to share about failures or difficulties encountered, and then to accept and implement evaluation recommendations. Evaluation research has also discussed how evaluation approaches, notably theory-based approaches, can support transformative changes [166]. This acknowledges that achieving sustainability requires to go beyond incremental changes. Evaluations should therefore support learning and radical transformations. This evolution can be seen in international aid frameworks, where institutions such as the World Bank, UN agencies, and national agencies (e.g. GiZ) have developed or promoted MEL (Monitoring, Evaluation and Learning) initiatives and guidelines [167]. Evaluations of energy efficiency policies could benefit from this evolution, which could also favour complementing techno-centric approaches of energy efficiency, with more systemic approaches of sufficiency. Coherence and relevance of policy bundles should be considered more systematically, so that evaluations can highlight to policy makers the complexity of policy impact pathways, and empower them to understand their interventions in a deeper sense. With that, evaluations can help decision makers to keep their 'eye on the ball' of higher-level objectives (e.g. climate change mitigation, climate, and energy justice), and the longer-term sustainability of transformational change.

Box 5 illustrates examples of policy packages. Although in general policy packages outperform single instruments, there are circumstances where simpler, dedicated solutions are preferred [141]. Policy packages require higher governance quality and depend on cross-discipline, multi-layered decision-making, as well as associate with more complex implementation and enforcement. Complex packages may face high administrative and transaction costs, and higher demand on human capacity and coordination. Political economy constraints, including conflicting interests and policy capture, can further undermine implementation. Poorly designed mixes may exacerbate social inequalities or other hazards, unless the portfolio is specifically designed to care for these issues (see the Energy Efficiency and Just Transitions section). Moreover, evaluation of policy mixes is difficult (see Box 6 on evaluation). Still, contexts with multiple actors and their respective incentive structures that may foster or impede energy efficiency improvements will continue to need carefully designed policy packages, until highest energy efficiency solutions have become the market default.

Future directions for research, policy, and practice

- The next frontier is not more policies but smarter combinations. Policy packages make it possible to capture both energy system and nonenergy objectives, and ensure low-cost service provisioning, as well as to increase wellbeing with low environmental impact that incorporates health, social services, appropriate shelter, food, mobility, and safe industry.
- Mature policy portfolios secure cross-institutional, multi-level, multi-objective, and politically receptive implementation. Currently, evaluation frameworks lag behind policy complexity.

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Conclusions

(Lena Neij and Charlie Wilson)

The experts who contributed to this Vignette agree that energy efficiency will continue to serve as a vital lever of transformation, reducing costs, mitigating climate change and environmental degradation, and buffering against systemic disruption in future societal transformation. To date, energy efficiency has been central to development across both the world regions and will remain a cornerstone of responsible growth. Efficiency can enhance and accelerate welfare outcomes in the Global South. Electrification remains a core element in advancing energy efficiency globally, primarily through end-use electrification but also through systemic efficiency. AI applications offer new avenues for energy efficiency across the economy; however, systems-level impacts of AI remain poorly understood. Material resource efficiency is also a potential force multiplier for energy efficiency, complementary to, or synergistic with, other ways to reduce energy use. To fully understand this potential and its limitations, systems approaches are needed with improved modelling, alternative design approaches, and reforms in policy and planning. A recurring theme across the expert-led sections is the necessity of systemic strategies that bridge multiple sectors to capture the full potential of energy efficiency in future transitions.

The Vignette underlines that energy efficiency needs to be envisioned not narrowly in terms of specific sectoral applications but thematically in terms of rebound effects, sufficiency, and wellbeing. Rebound effects, in particular, must be integrated more explicitly into energy efficiency analysis through dynamic and system-oriented perspectives. The focus should shift from assessing the magnitude of rebound to understanding the mechanisms that underlie it so they can be prevented by design. Sufficiency experiments and scenarios can help advance our understanding of how energy efficiency and activity growth effect interact within future transformation pathways. The intersection of energy efficiency and wellbeing further require transdisciplinary approaches and metrics that extend beyond energy use to include wellbeing outcomes, distributional effects, and planetary boundaries. Future scenarios should also embrace just transitions that engage diverse societal actors, and future research explicitly incorporate equity metrics, monitor social outcomes, and explore participatory governance.

Key opportunities lie in linking energy efficiency to broader societal co-benefits, such as public health, affordability, and competitiveness. Of particular importance is the valuation of energy poverty alleviation, reflecting ethical judgments rooted in welfare economics to support just, accountable, and socially grounded transitions. The relationship between energy efficiency, diversification, and security is an

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important additional societal and geopolitical dimension in energy transitions. While efficiency makes diversification more affordable, diversification makes further efficiency investments less risky. Both improve wellbeing and improve security alike.

Overall, the expert contributions to this Vignette emphasize dynamic and systemic strategies aligned with broad policy interventions. These interventions aim to capture both energy-system and nonenergy objectives, ensuring low-cost service provisioning while enhancing wellbeing with minimal environmental impact and broader societal benefits. Advancing energy efficiency in policy and practice requires moving beyond isolated measures towards integrated and well-coordinated policy mixes (in practice and evaluation). These should align efficiency with broader societal goals, including equity, wellbeing, and environmental limits, while addressing barriers such as financing constraints, information gaps, and institutional fragmentation. Embedding efficiency within long-term planning, infrastructure development, and regulatory frameworks will be critical to ensure sustained impact and to avoid lock-in of inefficient systems.

Finally, mainstreaming energy efficiency requires stronger alignment with societal priorities and active participation across stakeholders. Policies and interventions should be designed to be inclusive, context-sensitive, and responsive to diverse needs, particularly in addressing energy poverty and enabling just transitions. By linking efficiency to broader development goals and fostering collaboration across sectors and governance levels, it can become a foundational strategy for resilient, equitable, and sustainable energy transitions.

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Conflicts of interest

None declared.

Data availability

Not applicable.

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