Low Energy Demand Scenarios for OECD Countries: Fairness, Feasibility and Potential Impacts on SDGs

Rachel Freeman, Pernille Merethe Sire Seljom, Pieter Valkering, and Anna Krook-Riekkola

Abstract While the sustainable development goals (SDGs) are most challenging for developing countries, they apply equally to OECD member countries and are important to consider during these countries' energy transition. Low energy demand (LED) scenarios, modelled with energy system optimisation models (ESOMs), show that there is potential for meeting national and global climate mitigation targets more economically and with less technological uncertainty, while buying time during the transition. Some LED scenario narratives envisage deeply transformative societal changes, while others are more focused on demand reduction with technology improvement measures such as energy efficiency. In a review of 11 LED modelling studies, demand reductions by 2050, compared to 2020, range from moderately (8%) to much higher (56%) than non-LED scenarios. SDG targets for OECD countries that are most likely to be negatively affected by a LED approach are poverty (1.2), overcoming inequality (10.1), and participatory decision making (16.7). Those SDGs more likely to see win-wins include access to energy (7.1), renewable energy (7.2), energy efficiency (7.3), and use of resources (12.2). When modelling LED scenarios in ESOMs, there should be more representation of the rebound effect and feedback between demand and economy, heterogeneity in societal responses to LED-type policies, and the idea of sufficiency to better reflect the novelty of pathways to achieving LED scenario narratives.

R. Freeman (✉)
University College London, London, UK
e-mail: Rachel.freeman@ucl.ac.uk; rachel.freeman@dnv.com

P. M. S. Seljom
Institute for Energy Technology, Kjeller, Norway
e-mail: pernille.seljom@ife.no

P. Valkering
VITO – Energyville, Boeretang, Belgium
e-mail: pieter.valkering@vito.be

A. Krook-Riekkola
Luleå University of Technology, Luleå, Sweden
e-mail: anna.krook-riekkola@ltu.se

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Key Messages

- LED scenarios can meet national and global net zero targets more economically and with less technological uncertainty compared to non-LED scenarios.
- LED scenarios require unprecedented transformative societal changes and therefore their feasibility is highly uncertain.
- In LED scenarios, SDG targets for societal inequality, fuel poverty, and participatory decision making indicators could be worsened, and win-wins could be seen in SDGs for energy access, renewable energy, energy efficiency, and resource use.
- ESOMs could be improved by expanding their scope to represent the societal transformation parts of LED scenario narratives and the feedback between demand and economy.

1 Introduction

While the sustainable development goals (SDGs) are most challenging for developing countries, they apply equally to countries of the Organisation for Economic Co-operation and Development (OECD) and are important to consider during these countries' transition to net zero emissions of greenhouse gases (GHG). Some SDG targets in OECD member countries are likely to be particularly affected, beneficially, or not, by net zero scenarios that are described as "low energy demand" (LED). LED scenarios explore the potential role of limiting energy demand in net zero pathways, with potential benefits including (but not limited to): faster achievement of net zero; reducing the need for more expensive and technologically challenging mitigation measures such as H_2 fuels and direct air capture; reduced overall cost due to less need for new supply capacity. While LED pathways are in general technologically easier and have lower total cost, they are likely to be more difficult socially and politically.

Scenarios for achieving net zero GHG emissions, towards 2050 and beyond, are commonly assessed using energy system optimisation models (ESOMs), which are mathematical representations of energy systems. ESOMs are comprehensive and scaled at the local, national, regional or global level. ESOMs can be stand-alone or part of a larger model such as a global integrated assessment model (IAM). ESOMs are used to turn scenario narratives into detailed quantified techno-economic pathways to a net zero energy system, based on cost optimisation. These pathways inform policymakers about the potential impacts of different approaches to meeting climate and energy targets, and what policy options exist (Krook-Riekkola 2015; Süsser et al. 2021). Variations in pathways are driven by differences in scenario narratives.

The word "demand" is used in different ways across the energy literature. An *overall* picture of demand could be derived from: (i) Primary energy demand for solid, liquid and gaseous energy sources that either are extracted or imported to the studied region, and used throughout the energy system, e.g. to generate electricity;

(ii) Final energy demand, which is the energy commodities delivered to the end users; users use the energy for creating energy services (i.e. not another energy commodity), e.g. electricity, district heating or some kind of fuel (e.g. natural gas, H2, ammonia and synthetic fuels); and (iii) Energy services demand (ESD), which is the societal needs either as a service or as goods (in variable units related to the service). In ESOMs, demand is usually represented with ESD as a model input where final energy demand is a model output. Whereas models that only cover the electricity sector typically use final demand as a model input. Consequently, ESD can identify the underlying mechanisms driving each specific type of final demand, such as transport using vehicles (bottom up), or by using ESD projections from sources such as government studies. In many TIMES models (Loulou et al. 2016), for example, ESD in buildings, transport and industry are introduced via exogenous demand projections for the analysed model horizon. Adjustments to ESD can be made by changing the underlying model mechanisms and assessing how these impacts demand, or by increasing or decreasing exogenous projections by a certain percentage. Measures to reduce demand through behavioural change or structural change are rarely included in the model's objective function.

ESOMs primarily focus on techno-economic factors and do not explicitly represent social aspects of energy transition in much detail or depth; those ESOMs that do consider social aspects primarily do so through exogenous assumptions (Krumm et al. 2022). Inclusion of energy justice and fairness dimensions is rarely done, although it is being increasing added (Vågerö and Zeyringer 2023). ESOMs are sometimes soft-linked to smaller simulation models of a single sector such as transport or buildings, with modelling methods such as agent-based modelling (Bale et al. 2015) and system dynamics (Papachristos 2019). These smaller models provide better representation of heterogeneity and complex system responses within particular sectors, without having to add more complexity to a national or global model. ESOMs can also be linked with CGE models, allowing alignment of demand with the economy (Labriet et al. 2015; Krook-Riekkola et al. 2017).

This chapter reviews published LED studies from a novel angle, namely the way they treat social issues like fairness, feasibility and the potential impacts on the SDGs. This chapter reviews published LED studies to assess which SDGs could be impacted by LED narratives and in which ways. The study was initiated through a series of IEA-ETSAP funded workshops that benefited from attendance and written contributions from over 30 participants (see Acknowledgments). The following steps were taken.

1. A set of 11 LED scenarios are reviewed and the following core characteristics are compared: (i) LED scenario narrative, (ii) scenario modelling approach, (iii) LED mitigation measures in the pathway, (iv) modelled demand reductions, (v) overall benefits from LED. The characteristics vary depending on the purpose and scope of the scenario, the optimisation approach, and the ambition of the LED narrative.
2. LED scenarios narratives are described, along with methodologies used to translate them into modelled pathways. Differences in the boundaries adopted for creating narratives and for modelling are observed, illustrating a lack of clarity.

These differences could be resolved through including more explicitly in ESOMs the drivers needed to achieve LED, and/or providing more detail in LED narratives about which types of measures would be the least disruptive to society and people's access to various energy services.

3. LED scenarios are reviewed for their potential societal impacts in OECD countries. In theory, achieving LED has the potential to decrease energy fairness, relative to current conditions—although impacts from demand reductions will vary for different types of societal actors and under different economic conditions. Additionally, there is high uncertainty about the feasibility of implementing LED pathways since there is little historical evidence of the types of demand changes envisioned in LED scenarios being enacted.
4. The potential impacts of feasibility and fairness concerns related to LED scenarios are applied to a set of selected SDGs that are relevant for OECD member countries currently transitioning towards net zero. The impacts on SDGs can include both benefits and disbenefits, depending on how the LED scenarios are achieved through policies and choice of mitigation measures.

2 Review of Published LED Scenarios

2.1 Scenarios Overview

Table 1 presents highlights from a set of 11 published LED scenarios. Of key interest to this study are the LED narratives, the types of modelling, how energy service demand (ESD) is included in models, and the documented benefits of the LED scenario approach. The choice of which LED studies to include in this study was made by doing a scan of the literature from within and outside the ETSAP community, then selecting a set of LED scenarios that represents the leading approaches at three levels of scale: global, continental/EU and national. LED modelling studies for five OECD countries were included to represent a diversity of conditions for decarbonisation and content focus (sector, energy system, integrated covering all GHG) but staying within the focus on OECD countries. Some of the LED studies include multiple pathways with varying degrees of avoid, shift and improve type interventions (Creutzig et al. 2018). The most ambitious and transformative scenarios from each of the 11 LED scenario publications were selected for analysis.

The LED scenario characteristics presented in Table 1 illustrate how much variety there is in scenarios considered to be LED. This is largely due to the varying geographical areas covered, modelling teams, models used, and purpose of each study. Most studies use established models and introduce exogenous changes to achieve modelling of a LED scenario. The UK CREDS study goes further, introducing methodological novelty by soft linking a TIMES model with several sectoral-level models that are more suitable for modelling demand in detail. Regarding the guiding narrative for modelling, some scenarios focus predominantly on changes to energy demand through efficiency and/or economic changes (e.g. Norway LOW,

Table 1 Summary of reviewed LED scenarios

Scenario name, model name, sources	Type of modelling	LED scenario narrative	Overall benefits from LED
Global IIASA (LED): (Grubler et al. 2018; McCollum et al. 2017, 2020; IIASA 2018)	MESSAGEix-GLOBIOM—global integrated assessment modelling of climate change drivers and impacts. ESD is Exogenous	The Low Energy Demand scenario includes rapid social and institutional changes in how energy services are provided and consumed. Less reliance on stringent climate policy than comparable low-emission scenarios. Strongly focused on energy end-use and energy services.	Downsizing the global energy system dramatically improves the feasibility of a low-carbon supply-side transformation; the scenario meets the 1.5 °C climate target as well as many SDGs without relying on negative emissions technologies (NETs).
Global IEA (NZE): (International Energy Agency 2021)	Hybrid approach, combining WEM (simulation model that replicates competitive energy markets) and ETP (large-scale, partial-optimisation, technology model). ESD is endogenous	The Net-Zero Emissions by 2050 Scenario (NZE) is designed to show what is needed across the main sectors for the world to achieve net zero CO_2 emissions by 2050.	In the NZE pathway, by 2030 the world economy is 40% larger but uses 7% less energy. There is a major worldwide push to increase energy efficiency. Energy intensity improvements are three times higher than in the last two decades.
Global IMAGE (SSP1): (Bauer et al. 2017; van Vuuren et al. 2017; Riahi et al. 2017)	IMAGE. Global integrated assessment modelling of climate change drivers and impacts. ESD is Exogenous	SSP1 includes sustainable consumption patterns; fast energy efficiency improvements; rapid deployment of renewable energy; economic activity decouples from energy demand; lifestyle changes; social acceptability is low for all technologies except non-biomass renewables.	Challenges to mitigation in SSP1 are low, including consumption patterns, technological change, fossil fuel availability and efficiency improvements. SSP1 assumes decoupling of economic growth and energy demand, achieved by increasing energy efficiency and renewables.
EU CLEVER: (Bourgeois et al. 2023)	Set of modelling tools covering different sectors; ESD is Exogenous	The CLEVER (Collaborative Low Energy Vision for the European Region) narrative combines sufficiency, efficiency, and renewables. It adds representation of the	The CLEVER scenario reaches climate neutrality in 2045, with rather conservative assumptions on GHG sinks, and a 93% decrease in net GHG emissions.

(continued)

Table 1 (continued)

Scenario name, model name, sources	Type of modelling	LED scenario narrative	Overall benefits from LED
		potential for sufficiency and innovation in energy practices.	
Germany LED: (Eerma et al. 2022)	AnyMOD.jl: based linear cost minimising, bottom-up planning model; ESD is Exogenous	The scenario "societal commitment" aims for a strong change of behaviour towards a sustainable lifestyle. The potential for demand reductions based on behavioural changes in the heat, mobility and electricity sectors are estimated based on an extensive literature review.	Behavioural changes achieve total system cost savings of up to 26% and reduce required generation and storage capacity by 31% and 45%, respectively, in the High Ambition scenario.
Ireland LED: (Gaur et al. 2022)	TIMES Ireland. ESD is Exogenous	The Low Energy Demand scenario includes ESD being decoupled from economic growth by shifting travel modes, increasing end-use efficiency, densifying urban settlement, focusing on low-energy intensive economic activities, and changing social infrastructure.	Compared to a business-as-usual growth scenario, steep decarbonisation targets are achieved with a less rapid energy system transformation, lower capital and marginal abatement costs, and with lower reliance on the deployment of novel technologies.
Netherlands LED: (Scheepers et al. 2020)	OPERA energy system planning model; ESD is Exogenous	The Transform scenario describes transformative systemic change, including high awareness and behaviour change, individual and collective action, ambitious government, and company policies.	Total system costs in the TRANSFORM scenario are substantially lowered, compared to the other scenario ADAPT, due to lower energy demand, decreasing technology costs and no CCS.
Nordic CNB: (Wråke et al. 2021)	Nordic TIMES; ESD is Exogenous	The Climate Neutral Behaviour (CNB) scenario reflects Nordic societies adopting additional energy and material efficiency measures in all sectors,	Behavioural change buys time for the transition, reduces pressure on biomass resources, reduces costs of infrastructure expansion. Total system costs are 10%

(continued)

Table 1 (continued)

Scenario name, model name, sources	Type of modelling	LED scenario narrative	Overall benefits from LED
		ultimately leading to lower demand for both.	lower in CNB compared to a scenario considering current national plans, strategies, and targets.
Norway LOW: (Rosenberg et al. 2015)	Norway TIMES; ESD is Exogenous	The LOW activity scenario assumes higher electricity process, with decreased energy demand of industry, the possibility to invest in energy efficiency measures, and decreased transport demand.	In the LOW scenario, net power trade is highest due to decreased domestic energy demand and increased power production. Domestic electricity use is increased rather than exported. Higher economic activity is achieved without a net import of electricity.
UK CREDS LED: (Barrett et al. 2021, 2022)	UK TIMES plus 5 sectoral models (mobility, nutrition, shelter, non-res buildings, materials, and products); ESD is soft linked with sector models	There are two LED scenarios. The "transform demand" scenario has transformative changes in technologies, social practices, infrastructure, and institutions to deliver reductions in energy.	Energy demand reductions lead to less reliance on high-risk carbon dioxide removal technologies, only moderate investment requirements and more space for ratcheting up climate ambition.
UK Transport (LSEV): (Brand and Anable 2019; Anable et al. 2012)	MARKAL MED; UKTCM; STEAM; ESD is soft linked to sector model with energy demand elasticity	In the Combined lifestyle and EV scenario (LSEV), radical changes in travel patterns and travel mode choices lead to relatively fast transformations and new demand trajectories, along with high EV adoption and petrol/diesel phase-out.	Meeting legislated carbon budgets can be achieved by combining radical changes in travel patterns, mode and vehicle choice, vehicle occupancy and on-road driving behaviours, and fast electrification of vehicles.

Ireland LED, Global IEA), while others envisage transformative societal changes that reduce demand (e.g. UK CREDS, Global IMAGE SSP1, Netherlands LED). EU CLEVER presents a novel theoretical approach, using a holistic narrative that combines sufficiency, efficiency and renewables; it achieves the quickest net zero transition of the five national studies. Germany LED models demand reductions from behavioural changes derived from a literature review, giving the narrative a grounding in evidence.

In all the 11 studies, high demand reductions enable meeting net zero targets in time. Indeed, the UK CREDS study finds that ambitious climate targets can *only* be achieved when demand is reduced, compared to a reference scenario. All of the LED scenarios show additional benefits to meeting emissions reduction targets, such as reducing total system costs (UK CREDS, Norway LOW, Nordic CNB, Ireland LED, Netherlands LED), avoiding the need for negative emissions technologies (Global IIASA, EU CLEVER, UK CREDS), buying more time for the transition (Nordic CNB), and achieving high rates of decoupling between economy and emissions (Global IEA, Global IMAGE SSP1). The reviewed scenarios indicate, overall, that the LED approach holds potential for OECD countries to significantly improve the likelihood of achieving their targets, reduce the need for novel and complex technologies, and reduce the total cost of the net zero transition.

2.2 Demand Mitigation Measures

The potential for demand reductions by measure varies considerably by many factors, including: the existing make up of demand side technologies and infrastructure, the types of measures to be applied in each sector, the availability of replacement technologies for mass deployment over time, and the local geography and climate which affects the suitability of measures. It was not possible to determine the relative importance of each measure to achieving annual demand reductions from the review of scenario publications. The precise definitions of the LED scenario pathways—if available at all—differ between studies and therefore do not allow consistent comparison.

The 11 LED scenarios include a wide variety of demand mitigation measures. These can be classified, broadly, as "avoid" (avoiding the demand for energy services), shift (shifting to more efficiently provided energy services), or "improve" (improving the efficiency of end-use technologies and buildings)—as defined in (Creutzig et al. 2018). All the measures reduce total demand, although it should be noted that in Global IIASA LED and Global IEA NZE there are increases in demand in some sectors and end uses. The measures included in the 11 LED scenarios were identified, from the publication sources, and analysed according to types defined by Creutzig et al. (2018). The type allocations were done by the authors, based on knowledge of how the measures are achieved.

Avoid measures are generally very low cost, perhaps saving money for consumers, but the potential for demand savings from avoid type measures is limited since some energy services will always be needed. Thermostats can be lowered in winter but there is a minimum amount of heat needed. The following measures from the LED scenarios were categorised as avoid: car/trip sharing, telework/shorter working week, less freight (as international shipping and aviation, road freight), generic reduction of transport passenger-km, lower speed limit for transport, lower indoor room temperature, reduced living space area, reduced hot water consumption, and reduced office space area.

Shift measures are a crucial part of demand reduction for particular end uses that require sectoral structural changes and can enable deeply transformational changes in demand patterns. They can depend on there being supporting changes in infrastructure such as the building of new public transport networks or the availability of goods with lower environmental impact. The following measures from the LED scenarios were categorised as shift: modal shift passenger transport, modal shift freight transport, lower demand for energy-intensive commodities, alternative production processes in manufacturing (inc. fuel switch), longer-lasting products, and a shift to less energy-intensive sectors in an economy.

Improve measures are the most common type and are the standard type in both transformative scenarios such as EU CLEVER and SSP1, and in the less transformative, more technology focused scenarios. Improve measures have more potential for demand reduction than avoid or shift measures as they can rely on technological changes in end use equipment that are like-for-like replacements (or at least similar-use equipment such as electric vehicles replacing combustion vehicles) and thus are more likely to be widely adopted or even mandated through regulation. In Global IEA NZE, for example, transport electrification contributes to a large share of energy demand reduction in transport compared to shift type interventions like modal shift. The following measures from the LED scenarios were categorised as improve: transport electrification or other fuel switch, efficiency improvement freight transport, smaller cars, buildings renovations, reduced electricity consumption for appliances, demand reduction for heating and cooling, urban planning and densification, heating electrification, smart heating, recycling, alternative materials in construction, efficient technologies, material efficiency, dematerialisation.

Figure 1 illustrates the number of different types of demand mitigation measures in the selected scenarios according to their avoid-shift-improve classification. The overall share of measures is 40% as improve, 35% as avoid, 25% as shift. A broad comparison of total demand reductions in each scenario with the number of measures finds no correlation. It is notable, however, that the two studies with the most methodological innovation and intention to improve modelling of transformative scenario narratives, UK CREDS LED and EU CLEVER, include the most variety of measures.

2.3 *Impacts of LED Scenarios*

Figure 2 presents a summary of impacts on final energy demand from the reviewed scenarios as changes in final energy consumption in 2050 compared to the baseline year (where data is available). The baseline year is 2020 for all the studies reviewed, except for Netherlands LED for which it is 2030. This approach allowed a consistent comparison between the different LED scenarios. Data for IMAGE SSP1 is an analysis of data downloaded from USS data download facility for IMAGE 3.0 (Stehfest et al. 2014), for Western Europe, scenario SSP1 SPA1 RCP 1.9. Four scenarios (Global IIASA LED, Global IMAGE SSP1, EU CLEVER and UK

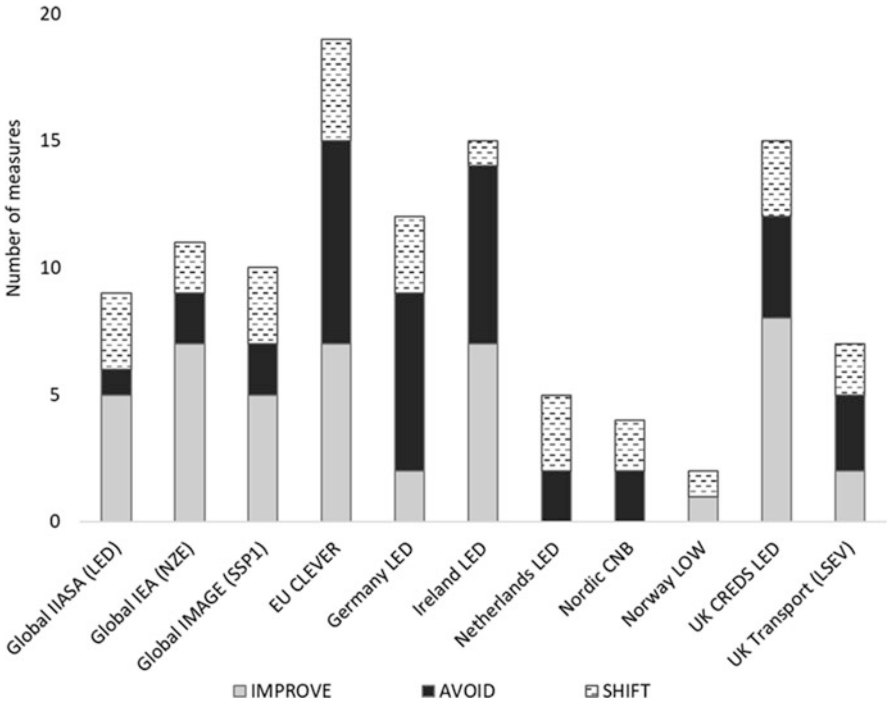
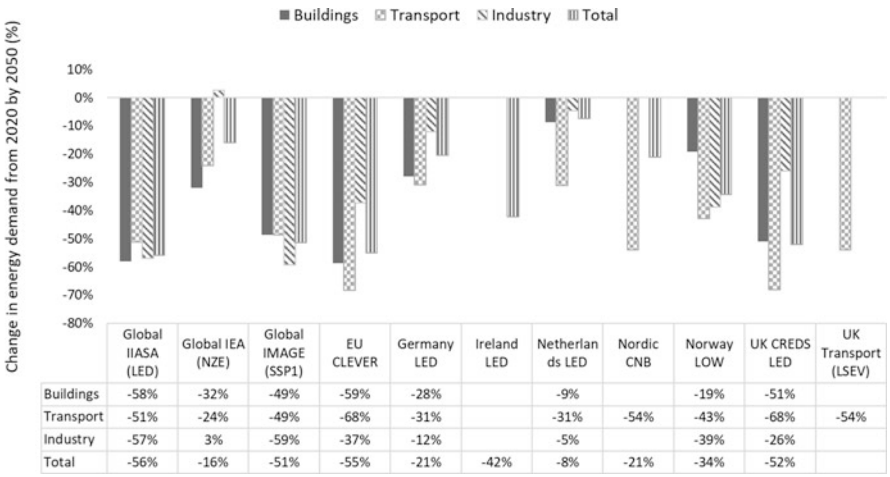


Fig. 1 Count of demand mitigation measures included in LED scenarios, as AVOID, SHIFT, or IMPROVE



	Global IIASA (LED)	Global IEA (NZE)	Global IMAGE (SSP1)	EU CLEVER	Germany LED	Ireland LED	Netherlands LED	Nordic CNB	Norway LOW	UK CREDS LED	UK Transport (LSEV)
Buildings	-58%	-32%	-49%	-59%	-28%		-9%		-19%	-51%	
Transport	-51%	-24%	-49%	-68%	-31%		-31%	-54%	-43%	-68%	-54%
Industry	-57%	3%	-59%	-37%	-12%		-5%		-39%	-26%	
Total	-56%	-16%	-51%	-55%	-21%	-42%	-8%	-21%	-34%	-52%	

Fig. 2 Demand impacts in selected LED scenarios; percentage change in demand between 2020 and 2050, by sector and overall (where data available)

CREDS LED) achieve a more than 50% reduction in total demand, while UK Transport (LSEV) achieves a 54% reduction in the transport sector (in which has historically been difficult to reduce demand). Without calling into doubt the methodology of the reviewed studies, considering past and current patterns of demand in most countries, a more than 50% reduction in demand within 30 years seems unlikely to be achievable.

The demand impacts shown in Fig. 2 rely on many modelling assumptions. Baseline assumptions are indicators for socio-demographics and economic development and estimates of potential demand savings by measure. Socio-economic assumptions used in global scale LEDs are generally in line with business-as-usual projections, with minor differences. For example, a projection for global population of 9 billion by 2050 in Global IIASA LED compared to 9.8 billion in Global IEA NZE. The five national studies also take business as usual projections for population and economic growth, which are typically medium growth estimates from national statistics offices. The much higher demand reductions in the modelled LED pathways are achieved principally through including a wider range of the demand reducing measures described in Sect. 2.2, and/or a higher uptake of those measures. In other words, none of the reviewed LED scenarios assume that lower demand can be achieved through population decline or economic recession.

3 The Feasibility and Fairness of LED Scenarios

There are many, many factors that are already influencing, and will continue to influence, the feasibility of modelled pathways, at the scale of nations, global regions, and globally. For LED scenarios in particular there are four key issues: (i) the economic ability of countries to fund the transition especially in transforming mass consumer technologies, (ii) the ability of those governing the transition to guide it effectively, (iii) whether the expected rate of progress in commercialising and deploying new technologies will be realised, and (iv) societal ability and willingness to implement measures to reduce demand—in particular, shift and avoid measures. LED studies are generally quite limited in addressing the feasibility and fairness aspects of scenarios; however, these issues are particularly important for implementing LED scenarios. Additionally, feasibility and fairness are related, since if policies are, or are felt to be, unfair then there will be less willingness of the public to make them happen, reducing feasibility. We examine here three issue of particular importance for modelling LED scenarios.

3.1 The Economy and the Rebound Effect (Feasibility)

3.1.1 Demand and the Economy

It could be argued that LED and economic growth are generally counteractive to each other, since historically the two have been very tightly coupled. A look at historical demand patterns will illustrate that when there are serious economic downturns there are simultaneously decreases in energy demand. However, looking forward, this is not the case in several of the LED narratives. In the EU CLEVER narrative, '*sufficiency proposes a restructuring of society that, when combined with efficiency measures and renewables deployment, has*. . .*been shown to increase employment in the long term'* (Bourgeois et al. 2023)—however, this is more of a qualitative statement than an outcome of analysis. The SSP1 narrative envisions *'the emphasis on economic growth shifts toward a broader emphasis on human well-being'* (Riahi et al. 2017). Results of modelling the Shared Socioeconomic Pathways (SSPs) show income levels in the USA (as sample OECD country) growing faster in SSP1 compared to "middle of the road" SSP2 (Dellink et al. 2017); however, this is dependent on exogenous inputs to the scenarios and not a modelled outcome of the future economic implications of a LED scenario. The relationship between LED and economic growth being considered in a positive way in the LED narratives, with expectations that the two are compatible, is a strong departure from the past. In the context that the need to decarbonise is well established across the world, and the LED approach is economically less risky than a high-tech approach, this makes sense. There are also innovations associated with LED that could benefit the economy as a whole, including urban densification, digitization, sharing and circular economies, energy efficiency, environmental awareness, energy independence, and local manufacturing.

A way to improve modelling would be to put in feedback between demand and the economy. In theory, part of the outcomes from LED scenarios should be that significant decoupling between economy and demand is achieved, and so this dynamic is an important part of modelling LED scenarios. Linking ESOMs with macro-economic models by modelling feedback between them is one approach, as proposed in (Krook-Riekkola et al. 2017; Andersen et al. 2019; Crespo del Granado et al. 2018). One example of this method is in (Glynn et al. 2015); however this models economic impacts from climate policies rather than LED policies. Since the precise impacts on the economy from reducing demand are currently not well understood, they are difficult to capture in a macro-economic model. In addition, macro-economic models do not, in general, capture changes in cost structure such as for cost intensive measures that reduce demand; models tend to "overconsume" these services requiring manual model adjustments (Krook-Riekkola et al. 2017).

3.1.2 The Rebound Effect

A significant complication in understanding and modelling demand reductions is the rebound effect. The rebound effect reduces expected savings from efficiency improvements (Stapleton et al. 2016; Freeman et al. 2015); as energy services become more affordable through improved efficiency, supply-demand economics means that there is increased demand for energy services and so savings are reduced. At a macroeconomic level, the rebound effect can act as a "fuel" for economic growth, with its associated growth in use of resources (Ayres and Warr 2009). An analysis of the impact of social trends on energy demand found that in the worst case, the rebound effect from new societal trends could lead to an increase in energy consumption of 40% (Brugger et al. 2021). The rebound effect could act against the demand changes envisaged in LED scenarios.

Most ESOMs acknowledge the rebound effect but its representation in models, including its potential solutions, is generally weak. This is partly due to a lack of relevant research: '*understanding the macro-level rebounds of demand-led transitions, and their negation, is an important avenue for further work and policy development'* (Barrett et al. 2022). Of the 11 reviewed LED scenarios, several do not mention the rebound effect at all. EU CLEVER makes rebound an important topic: '*rebound effects and upward consumption trends attest to the fact that efficiency alone cannot realise all of Europe's resource savings potential'* (Bourgeois et al. 2023). UK CREDS LED mentions its importance: *'avoiding increased energy demand due to rebound effects requires policies that ensure optimised and shared use of energy services and technologies'* (Barrett et al. 2021). Global IIASA LED calls the rebound effect the "elephant in the room". A possible starting point for introducing the rebound effect is by adding simple adjustment factors that reduce expected savings from energy efficiency, from published studies of the rebound effect for particular technologies and sectors. A more dynamically responsive way would be to introduce a feedback mechanism that represents the causes of the rebound effect and how it changes over time, as proposed in (Guzzo et al. 2023).

3.2 Price Elasticity (Fairness)

In general, ESD tends to increase along with energy affordability and GDP. Decoupling demand from these factors by more than a few percent is in theory achievable but in practice has rarely been observed except due to economic restructuring in countries that deindustrialise and move to service economies. Measures with the least uncertainty, partly due to there being the most historical evidence, are improve type measures such as energy efficiency, electrification of vehicles, and building renovations, which also impact the lifestyles of people the least. There is a lack of historical evidence that shift and avoid type measures included in LED pathways are achievable at the mass implementation level expected in LED scenarios.

There are growing concerns that energy transition could reduce the affordability and access to energy services in developed regions. *'Carbon mitigation strategies that neglect any social, geopolitical, and macro-economic considerations, are likely to exacerbate labour market inequalities. . .national and region-specific disparities will result in deeper social divisions'* (Patrizio et al. 2020). The lifestyle changes envisaged in LED scenarios may be, or may be perceived to be, unfair depending on how they are achieved. If LED pathways are in fact particularly unfair in their practical implementation, there is likely to be a public backlash against policies (Patterson 2023) and insufficient willingness and/or ability of societal actors to implement the required changes in the LED pathway (Freeman and Pye 2022; Stern et al. 2022).

One mechanism for provoking society to adopt shift and avoid measures is though energy pricing. In many ESOMs the price elasticity of demand is used to dynamically model changes in demand, including in TIMES (Loulou and Labriet 2008). In practice, price elasticities vary considerably, depending on variables such as fuel type, the maturity of technologies, types of actors by demographics or income level, and the timeline (short or long term). Thus, when modelling the effects of price elasticity it is important to have accurate elasticity values, and to represent enough heterogeneity in the model to reflect the different effects of real-world price elasticities. Example price elasticity studies include (Patankar et al. 2022; Salvucci et al. 2018; Daly et al. 2014; Labandeira et al. 2017). Price elasticities tend to be used in more detailed sector models, and are used in the UK Transport LSEV model but not in others in our set of 11. A lack of representation of the variability in price elasticity across society could mean that modelled LED pathways are insufficiently realistic. Price elasticity is also related to fairness, since policies that use it to reduce demand, such as carbon pricing, are regressive (Nemet and Greene 2022), negatively affecting lower income groups disproportionately.

3.3 Model Boundaries (Methodology)

Many IAM scenarios are *'conservative with respect to their assumptions on demand-side transformations. . .suggesting that the power of demand-side changes might be underexplored'* (Brutschin et al. 2021). Partly this is because of the difficulty of modelling innovation to support a LED future, which can include *'many heterogeneous adopters; small granular scale, many iterations; local system integration; and rebound effects'* (Nemet and Greene 2022)—changes which do not fit easily within linear techno-economic models. The energy service cascade (ESD) (Kalt et al. 2019) is a conceptual framework that describes the whole energy chain, and it is useful for examining the role of model boundaries in modelling LED scenarios. Table 2 shows the five elements of the ESC and how they are typically included in LED scenario narratives and ESOMs.

Table 2 The energy service cascade (ESD) and scenario narratives, models, and demand mitigation measures

ESD elements (this column adapted from (Kalt et al. 2019))	Typical inclusion in LED scenario narratives	Typical inclusion in ESOMs
Biophysical and societal **structures related to energy conversion chains**: natural resources, socio-technical structures, governance structures.	Transformative narratives may envisage socio-technical and governance structures significantly different to those of today.	Structures are represented as economic structure, data on biophysical resources, and governance structure through energy policies. LED measures (e.g. SHIFT measures that enable modal shifts in transport) usually included in model objective function.
Functions: physical actions performed by the energy chain. The relationships between inputs and outputs. E.g. accelerating a vehicle, transmitting thermal energy to a living space. Measurable in physical units but not necessarily energy units.	Usually not described in detail although implied through narratives about different types of fuel switching, electrification, etc.	Represented by data on end-use technologies that perform functions. E.g. types of vehicles that convert final energy into acceleration and motion. Efficiency limits for functions may need to be included (Cullen and Allwood 2010). LED measures (e.g. technology shift, efficiency improvements) sometimes included in model objective function.
Services: what is actually demanded. Services enhance wellbeing but are not identical to wellbeing contributions. A service is only a service if a human beneficiary can be identified.	Narratives often include descriptions of societal demand for services within a larger response to climate change, defined as increases/ decreases on a baseline level of service demand.	Model optimisation calculations meet services demand and climate targets at least-cost. Some models include energy price elasticity of services demand. Services examples: travel (pkm/year), floor space (m^2/cap), production of steel (tons/year). LED measures (e.g. reduce services demand, shifting to different energy services) rarely included in model objective function.
Benefits: contribution to aspects of wellbeing. Benefits are the outcome of services, for example, thermal comfort in indoor spaces which contributes to wellbeing, or artificial light which enables activity after sunset such as reading.	Sufficiency is related to benefits, used to define ‘sufficient service demands’ (Bourgeois et al. 2023), and to represent a reasonable minimum consumption level, (Cordroch et al. 2022; Zell-Ziegler et al. 2021; Best et al. 2022; Arnz and Krumm 2023).	Not usually included in ESOMs, but could be included as interventions to reduce energy wastage, so that benefits and services are in line and demand projections are therefore reduced. LED measures (e.g. reducing energy waste, price

(continued)

Table 2 (continued)

ESD elements (this column adapted from (Kalt et al. 2019))	Typical inclusion in LED scenario narratives	Typical inclusion in ESOMs
		responsive demand, active travel) not included in objective function.
Values: individual attitudes, preferences and habits about how benefits are valued, that influence the demand for an energy service. Social groups' perceptions and actions are shaped by shared meanings, heuristics, rules of thumb, routines and social norms (Geels et al. 2018).	Values can be included as a description of general societal attitudes to sustainability and consumption. For example, the relative value given to tackling climate change, ecosystems, material wealth, employment, economic growth, etc.	Not usually included explicitly. In economic terms, values translate into '*willingness to pay for energy services*' (Patankar et al. 2022) and climate change mitigation. LED measures (e.g. adjusting societal expectations about what is a "normal" level of ESD in daily practices) not included in objective function.

LED narratives tend to cover more of the ESC than the ESOMs which are used to model the narratives. In particular, the values and benefits part of the ESC are a key part of the more transformative LED narratives, yet these are not directly included in ESOMs as drivers. Differences in the boundaries adopted for narratives and for modelling show a lack of consistency in the process of describing and the modelling LED scenarios. Some essential parts of the narratives are missing in the modelling, which reduces how well the models represent the real-world future described in the LED narratives. Suggestions for improving LED scenario modelling include adding the more subjective aspects (e.g. benefits and values) as model inputs in the form of bespoke indicators influencing society's willingness to change behaviours, or evaluating the fairness of LED pathways off-model. The need for methodological development in modelling is highlighted in (Grubler et al. 2018): '*low energy demand outcomes depend on social and institutional changes that reverse the historical trajectory of ever-rising demand. How these can be endogenously represented in modelling studies remains a critical, multidisciplinary research agenda*'. Of the 11 reviewed LED scenarios, only UK CREDS and EU CLEVER include some methodological developments in line with the call from Grubler et al. for endogenously including social and institutional changes.

4 Impacts of LED Scenarios on SDGs

In this section, the discussion of LED scenarios from the previous sections is applied to a set of selected SDGs that are relevant for OECD member countries transitioning towards net zero. The selected SDG's targets and indicators are presented along with potential benefits and disbenefits from the LED approach, in a high-level and largely theoretical discussion. The following three assumptions are made as a basis for the discussion: (i) The starting point for OECD countries in 2020 is that they are industrialised and have mature and (generally) reliable and affordable energy supply and distribution. (ii) All OECD countries have established some kind of climate change emissions reduction target (usually net zero by 2050) and will stay committed to achieve it up to 2050 and beyond. (iii) Should the LED approach be adopted by countries, the process of emissions reductions will have a noticeable effect on some of the SDG targets; however, the size and direction of these effects will be affected by a wide range of physical and economic constraints, and the strategies used to pursue the LED approach.

4.1 SDG 1.2: Poverty

Target Reduce at least by half the proportion of people living in poverty (UN World Data Forum 2023).

Indicator 1.2.1 Proportion of population living below the national poverty line (UN World Data Forum 2023).

LED Alignments with SDG If LED policies are done well, such as through mass installation of energy efficiency measure and providing energy services in more efficient ways, household and business expenditure on energy would be reduced and fewer people would be in poverty due to high expenditure on energy.

LED Misalignments with SDG If regressive taxes that rely on energy price elasticity are used to reduce demand or encourage electrification, energy affordability will decline—although perhaps temporarily. Prices of goods and services could increase as a secondary effect of the cost of net zero to the country, forcing more people into fuel poverty. Feedback between economy and demand could force the economy into recession should demand decline quickly, leading to loss of jobs.

4.2 SDG 7.1: Access to Energy

Target Ensure universal access to affordable, reliable and modern energy services (UN World Data Forum 2023).

Indicators 7.1.1 Proportion of population with access to electricity, 7.1.2 Proportion of population with primary reliance on clean fuels and technology (UN World Data Forum 2023).

LED Alignments with SDG In the longer term, a LED approach would reduce the total cost of reaching net zero compared to non-LED scenarios, meaning lower retail energy prices. Decarbonisation could improve energy security for countries and regions if domestic generation with renewables replaces fuel imports. Digitalisation such as smart meters and smart grid could improve reliability of supply and provide more options for consumers to participate in flexibility markets.

LED Misalignments with SDG Transformative changes happening simultaneously across the energy system have potential to introduce new system risks and vulnerabilities that are difficult to predict or remedy. Distributed control of energy flows and distributed generation could affect the ability of system operators to maintain reliability of supply.

4.3 SDG 7.2: Renewable Energy

Target Increase substantially the share of renewable energy in the global energy mix (UN World Data Forum 2023).

Indicator 7.2.1 Renewable energy share in the total final energy consumption (UN World Data Forum 2023).

LED Alignments with SDG LED scenarios align well with this SDG as they tend to also include high levels of renewables.

LED Misalignments with SDG None.

4.4 SDG 7.3: Energy Efficiency

Target Double the global rate of improvement in energy efficiency (UN World Data Forum 2023).

Indicator 7.3.1 Energy intensity measured in terms of primary energy and GDP (UN World Data Forum 2023).

LED Alignments with SDG LED scenarios align well with this SDG target as they include high levels of ambition for energy efficiency. Energy efficiency improvements can especially benefit lower income groups, although subsidies might be needed to cover upfront costs.

LED Misalignments with SDG Programmes for energy efficiency should ensure that any efficiency improvements do to not unintentionally lead to worsened energy services, as has happened in a few cases (e.g. cavity wall insulation creating damp problems in housing in the UK (Eco Experts 2022)).

4.5 SDG 10.1: Overcoming Income Inequality

Target Achieve and sustain income growth of the bottom 40% of the population at a rate higher than the national average (UN World Data Forum 2023).

Indicator 10.1.1 Growth rates of household expenditure or income per capita among the bottom 40% of the population (UN World Data Forum 2023).

LED Alignments with SDG If LED scenarios are achieved successfully, the net zero changes could significantly improve a country's economy and international competitiveness, leading to more employment opportunities for lower income groups.

LED Misalignments with SDG Lower income groups may have to take avoid measures to reduce demand because of tight budgets, while higher income groups can afford to implement improve and shift measures. If governance is not done well the burden of demand reduction would be placed on those who can least afford it. Lower demand could lead to negative macro-economic impacts. Declining economies would mean lower wages and/or higher prices that disproportionately impact lower income groups. The closure of fossil fuel industries will lead to job losses and negative impacts on local economies.

4.6 SDG 12.2: Use of Resources

Target By 2030, achieve the sustainable management and efficient use of natural resources (UN World Data Forum 2023).

Indicator 12.2.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP (UN World Data Forum 2023).

LED Alignments with SDG Most LED scenarios align well with this SDG in that lower energy demand through shift and avoid type measures would reduce the demand for the resources used in providing energy services, both material and by energy vectors.

LED Misalignments with SDG Most LED pathways include very high rates of build of new renewables capacity. If not done with effective planning, this new capacity could cause damage to ecosystems both onshore and offshore. Of particular concern are expectations of increasing supplies of biomass and the accompanying need for land, fertilisers, and water. For scenarios that include mass adoption of electric vehicles and fuel cell technologies, environmental damage is possible from mining due to the need to source increasingly large amounts of metals, and critical and rare minerals, compared to the past.

4.7 SDG 16.7: Participatory Decision Making

Target Ensure responsive, inclusive, participatory and representative decision-making at all levels (UN World Data Forum 2023).

Indicator 16.7.2 Proportion of population who believe decision-making is inclusive and responsive, by sex, age, disability and population group (UN World Data Forum 2023).

LED Alignments with SDG This can be achieved within LED scenarios if sufficient consultations with publics is done.

LED Misalignments with SDG There is a danger that the drive towards net zero will lead to governments mandating disruptive changes to energy services to meet ambitious net zero pathway targets, without giving those affected a voice in decision making through open and democratic processes. There are concerns about how much government could and should influence energy consumption. Ideally, some of the LED changes could be achieved through the intrinsic motivation of people, or through beneficial societal innovation in energy services (Geels et al. 2018; Bai et al. 2016).

5 Conclusions

LED scenarios are of particular importance to those planning pathways to net zero in OECD countries. LED modelled pathways typically reach net zero targets in time and at a lower total cost than more technology focused scenarios. LED scenarios can reduce the need for the more risky and expensive technological solutions such as negative emissions technologies and the use of hydrogen as an energy vector, which are included in most non-LED scenarios. However, they also require far deeper and more disruptive changes to the lifestyles of energy consumers.

Eleven LED scenarios were reviewed. High demand reductions in each scenario enable meeting net zero targets in time, and additional benefits such as reducing total system costs, avoiding the need for negative emissions technologies, buying more time for the transition, and achieving high rates of decoupling between economy and emissions. Overall, that the LED approach holds potential for OECD countries to significantly improve the likelihood of achieving their targets, reduce the need for novel and complex technologies, and reduce the total cost of the net zero transition.

LED narratives tend to cover more of the energy services cascade (Kalt et al. 2019) than the ESOMs which are used to model the narratives. In particular, the values and benefits aspects are a key part of the more transformative LED narratives, yet these are not directly included in ESOMs as drivers. Since some essential parts of the narratives are missing in the modelling, this reduces how well the models represent the real-world future described in the LED narratives. Two key issues for LED scenarios are the rebound effect, which could reduce the achievability of deep demand reductions, and the unfairness of policies that work based on price elasticity, including carbon taxes, if not designed with this in mind. There is a need for methodological development in ESOMs (Grubler et al. 2018), which two of the 11 reviewed LED scenario studies do achieve, endogenously including social and institutional changes to support a LED pathway.

Five types of SDGs are evaluated for the potential alignments and misalignments with LED scenarios: poverty, access to energy, renewable energy, energy efficiency, overcoming inequality, use of resources, and participatory decision making. The SDGs most at risk of declining in an LED scenario are poverty, overcoming inequality, and participatory decision making. The remaining SDGs are likely to be well aligned with LED scenarios.

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