Net-Zero by 2050: Evaluating Energy Efficiency and Sufficiency Contributions in Europe Using PyPSA-EUR

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Abstract:

The current approaches to achieving a successful energy transition predominantly focus on two key pillars: expanding renewable energy deployment and enhancing energy efficiency in technologies and processes. While these strategies are essential, they alone are insufficient to achieve climate targets due to the complex nature of energy systems. To truly transform our energy landscape, a more holistic approach is necessary, one that integrates renewable energy technologies and efficiency measures across all sectors, including industry, transportation, and buildings, while also recognizing and addressing energy sufficiency, an area that remains largely underexplored. Energy sufficiency, although often conflated with energy efficiency, has the potential to play a game-changing role in the energy transition. Rather than focusing solely on optimizing the energy performance of existing systems, energy sufficiency seeks to reduce overall energy consumption by encouraging less energy-intensive behaviors and practices at both the individual and societal levels. This shift in perspective is essential in the context of sustainability and achieving the ambitious energy goals set by governments and organizations worldwide.

This study employs PyPSA-Eur, a sector-coupled model designed to optimize multi-energy systems, to analyze the energy frameworks of 28 interconnected European countries. By incorporating energy efficiency and sufficiency measures across a range of sectors, the study investigates how energy efficiency and reducing unnecessary energy demands can contribute to a more sustainable and resilient energy future. The results indicate that efficiency (mainly through the electrification of the energy system) reduce total system losses to 33% of primary energy, down from over 50% in 2020. Incorporating sufficiency measures further decreases losses by an additional 6%, while lowering CO2 emissions by 30%. The study emphasizes that energy transition requires a comprehensive approach that includes not only energy efficiency and renewable energy integration but also a focus on energy sufficiency.

Keywords:

Energy Modeling, Energy transition, Energy sufficiency, Energy efficiency, Renewable energy, PyPSA-Eur

1. Introduction

The Fit-for-55 EU package [1] aims to cut greenhouse gas emissions by 55% by 2030 through energy efficiency and renewable expansion, aligning with the Paris Agreement. The REPowerEU [2] initiative further accelerates the shift to green energy, enhancing energy security. While the EU targets climate neutrality by 2050, many member states struggle to meet these goals [3]. The IPCC's latest report warns that the world is off track for the 1.5°C and 2°C targets, urging immediate action to curb carbon emissions. Kaya's identity [4] breaks down global emissions F into four key factors: population P, GDP per capita G/P, energy intensity of GDP E/G, and the carbon intensity of energy F/E as shown in Equation 1. This decomposition underscores three critical levers for emissions reduction: (1) transitioning to low-carbon energy to reduce carbon intensity, (2) enhancing energy efficiency to lower energy intensity, and (3) adopting energy sufficiency to reduce per capita consumption. While the first two areas are well-researched, credible pathways for integrating energy sufficiency remain underexplored.

$$F = P \cdot (G/P) \cdot (E/G) \cdot (F/E) \tag{1}$$

Energy sufficiency[1] involves actions like lowering heating settings, reducing living space per capita, and favoring public transport [6]. It can be driven by societal norms, behavior shifts, or policy measures at various levels. While the EU Commission has yet to adopt sufficiency as a policy, the Ukraine crisis highlighted its importance, prompting a 15% gas reduction target in winter 2022 under REPowerEU. The core idea is that overconsumption can be reduced without compromising a decent standard of living, as most countries currently exceed the necessary energy threshold [7].

Recent studies have explored low-demand scenarios using equilibrium and integrated assessment models (IAMs) to project future energy pathways and sectoral demand reductions. The applications of equilibrium models include [8, 9], while IAMs are explored in [10, 11, 12]. Equilibrium models and IAMs provide valuable insights for high-level policy analysis and evaluating the effects of economic and policy trends. However, they have limitations, such as restricted pathway optimization, limited temporal and technological granularity, and insufficient consideration of energy infrastructure and operational constraints. Energy system models are also employed in sufficiency studies, with notable examples including [13, 14, 15, 16], but these studies are limited to a single country. A detailed study on energy sufficiency at the country and European levels, using dashboards, is presented in [17]. It shows that achieving the 1.5°C target is possible through sufficiency measures across all energy sectors, focusing on energy efficiency and renewable energy integration, without relying on nuclear or CCS technologies. The study highlights significant potential for reducing final energy and service demands at the country level and increasing energy independence in Europe. However, it is limited by low temporal resolution and does not account for investment costs, grid expansion, flexibility, adequacy, or VRE intermittency.

This study utilizes a sector-coupled energy system optimization model to assess the impact of sufficiency and efficiency measures across 28 interconnected European countries. Using one-hour timesteps over a year, it provides detailed temporal resolution. A comparative analysis between a sufficiency (Suff) scenario and a reference (Ref) scenario evaluates differences in energy trajectories, the balance of energy carriers, and the influence of sufficiency and efficiency on overall GHG emissions and system requirements. The study is focused to answer two questions:

- How do energy efficiency and sufficiency drive the progress of the energy transition?
- What is the impact of (energy efficiency + renewable energy) and (energy efficiency + renewable energy + energy sufficiency) on reducing carbon emissions?

2. Modeling Framework

To address these questions, we employ the PyPSA-Eur sector-coupled model and myopic pathway optimization to analyze transitions over time. The Reference scenario follows the default PyPSA-Eur setup [18], incorporating anticipated efficiency improvements across technologies and sectors. The sufficiency scenario uses sectoral demand data from the CLEVER scenario [17], which incorporates sufficiency measures to determine final energy demands for each sector. An overview of how energy sufficiency is integrated into the modeling framework is illustrated in Figure 1.

2.1. Scenarios

The study considers a baseline case for 28 modeled countries; this is used to represent each country's current situation. There is a sufficiency scenario and a reference scenario for comparative analysis, considering net-zero energy systems by 2050 on a regional level. The energy demands in the reference scenario are based on [19] while in the sufficiency scenario energy demands are obtained and adapted from [17]. A single node represents all the countries. However, the United Kingdom, Italy, Spain, and Denmark have two nodes due to additional synchronous areas. The temporal scale is one

[1] IPCC definition of sufficiency: "Sufficiency policies are a set of measures and daily practices that avoid the demand for energy, materials, land, and water while delivering human well-being for all within planetary boundaries" [5]

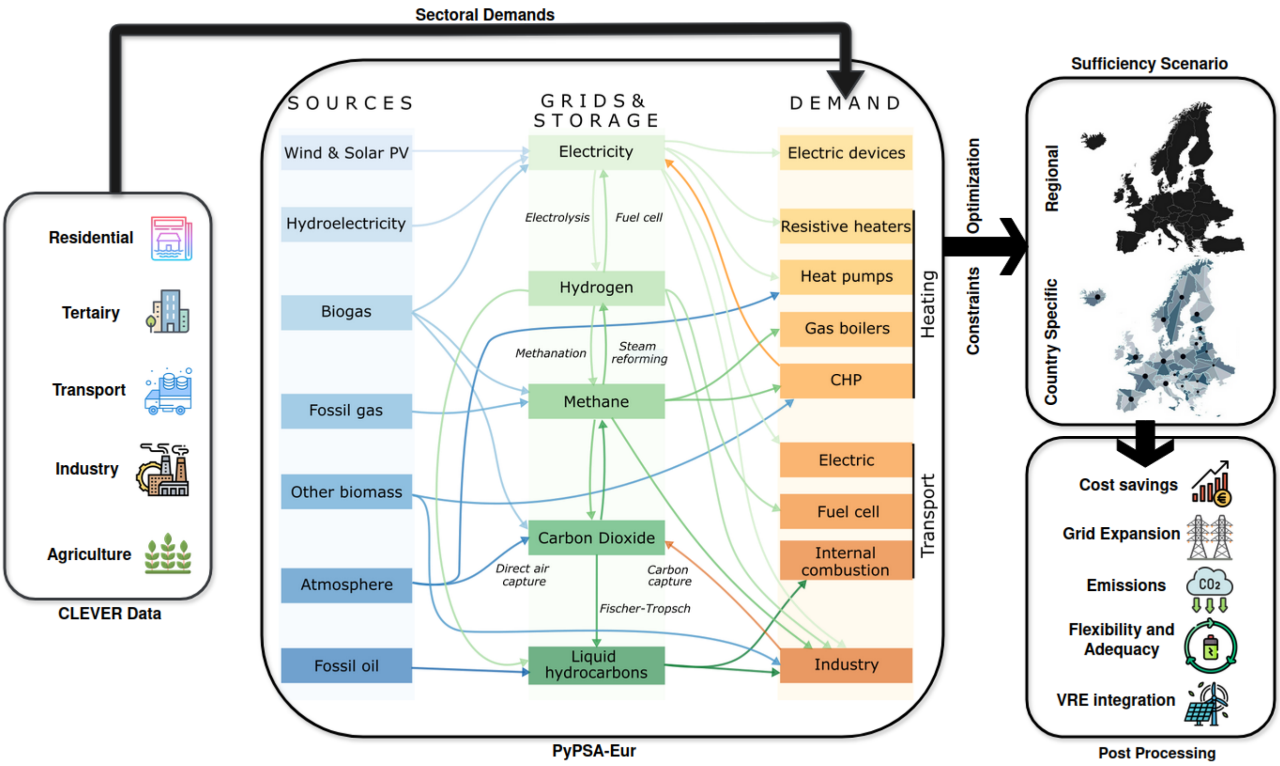

Figure 1: Schematic view of the modeling framework for the sufficiency scenario adapted from [18]. The final energy demands for the residential, tertiary, transport, industry, and agriculture sectors derived from the CLEVER scenario [17] are incorporated in the PyPSA-Eur.

year with a 1-hour resolution. For the simulations, the myopic scenario building is used to analyze the progressive changes within a network, such as those occurring along a transition pathway. In the myopic pathway optimization capacities installed at any given year remain operational within the network until they reach the end of their designated lifetimes. In the sufficiency scenario, only process emissions from industry and CO2 produced by biogas can be captured and used for P-to-X utilization. The assumed values for LULUCF are taken from [17] and are modeled as carbon sinks for both reference and sufficiency scenarios. The maximum extension of transmission lines for both scenarios is limited to 50% of the previously installed capacity for each 10-years planning horizon. This limitation considers the time constraints on planning and deploying the additional capacities to transmission lines, especially interconnections. A global CO2 constraint of -55% for 2030, -85% for 2040, and -100% for 2050 compared to CO2 emissions in 1990 is considered, which comply with both short and long-term EU targets. Country-specific CO2 constraint also considers -55% for 2030, -85% for 2040 reduction for each country but -95% for 2050; this relaxes the optimization at the country level and unlocks solidarity between member states: large countries with higher negative emission potentials can absorb excess emissions from more densely populated countries in order to reach an overall 100% reduction. More details about the scenarios configuration are shown in the Table 1 and further information is available in [19].

2.2. Optimization model

The optimization aims to minimize the system's total annual costs while adhering to technologies, resources, and CO2 emission constraints. The objective function for the linear programming (LP)

Table 1: Configuration details of scenarios

Scenario	Baseline	Reference			Sufficiency		
Year	2020	2030	2040	2050	2030	2040	2050
Technologies	Current	All	All	All	No CCS	No CCS	No CCS
Sequestration (Mtons)	0	200	200	200	0	0	0
Transmission Expansion (%)	0	50	50	50	50	50	50
LULUCF (Mtons)	438	438	485	509	438	485	509
EV Share (%)	0	25	60	85	25	60	85
Fuel Cell vehicles share (%)	0	5	10	15	5	10	15
Maritime hydrogen share (%)	0	0	30	50	0	30	50
Maritime methanol share (%)	0	30	40	50	30	40	50
District heating share (max 25%)	Current	30	60	100	30	60	100

problem is provided in Equation 2.

$$\min_{G,E,P,F,g} \Bigg[\sum_{i,r} c_{i,r} \cdot G_{i,r} + \sum_{i,s} c_{i,s} \cdot E_{i,s} + \sum_{\ell} c_{\ell} \cdot P_{\ell} + \sum_{k} c_k \cdot F_k + \sum_{t} w_t \cdot \left(\sum_{i,r} o_{i,r} \cdot g_{i,r,t} + \sum_{k} o_k \cdot f_{k,t} \right) \Bigg] \tag{2}$$

Where, i, r, s, ℓ, k, and t denote the indices for bus, generator technology, storage technology, transmission line, link, and time step, respectively. In this model, a line component corresponds to an AC transmission line, while a link corresponds to a component with controllable power flow, such as bidirectional HVDC links, unidirectional lossy HVDC links, AC/DC network converters, heat pumps, CHPs, and more. The annualized capital costs for generator and storage technologies at bus i are represented by $c_{i,r}$ and $c_{i,s}$, respectively. Similarly, c_ℓ and c_k denote the annualized capital costs for transmission lines and links. The variables $G_{i,r}$ and $E_{i,s}$ indicate the generator and storage technology types and capacities at bus i, while P_ℓ and F_k represent the capacities of transmission lines and links. The time-step weightings, w_t, are set to 1 for a one-hour resolution in the simulation. The variable operating costs for generator dispatch $g_{i,r,t}$ and link dispatch $f_{k,t}$ are denoted by $o_{i,r}$ and o_k respectively.

The computed capital costs are annualized over the economic lifetime n using the annuity factor a, which accounts for the discount rate r, as shown in Equation 3.

$$a = \frac{1 - (1 + r)^{-n}}{r} \tag{3}$$

The optimization process incorporates a range of constraints to ensure accuracy and feasibility. These include general technology-specific constraints for generators, storage units, transmission lines, energy flow balances, etc. Other constraints are more study-oriented, such as those limiting transmission line expansion, CO2 emissions and sequestration, technology capacity expansion, etc. Detailed information about the mathematical formulation and application of constraints is available at [20, 21].

Constraints specific to the present study are also added to the model. Equation 4 shows the carbon limit constraint that sets a country-specific carbon limit for each country. It is used in addition to the global carbon limit constraint for the whole region. The reason for using this additional constraint is that the Land use, land-use change, and forestry (LULUCF) sector is considered as a carbon sink in this study, and if we use a carbon sink on the regional level, then, for example, the LULUCF sector of Finland, which in general contributes to the energy systems in Finland is also utilized by high emitting countries in the model. Therefore, two carbon limitation constraints are used in this study: the global, which considers the carbon budget on a regional level, and the Equation 4, which considers the carbon budget on the country level.

$$\sum_{country} e_{i,r,k,t} - \sum_{country} e_{neg,t} \leq CO2_{country} + LULUCF_{country} \tag{4}$$

Where, $e_{i,r,k,t}$ computes the total carbon emission for each country. $e_{neg,t}$ computes the total carbon emissions removed by negative emission technologies like DACCS and BECCS. $CO2_{country}$ is the total carbon budget for each country, $LULUCF_{country}$ is the country specific LULUCF potentials.
The techno-economic assumptions used in the optimization are derived from data published by the Danish Energy Agency[22]. Future capital costs of technologies are estimated using learning curves, and anticipated efficiency improvements are also considered to ensure more realistic cost projections. The proposed models, methods, and data are released under an open license to ensure transparency and reproducibility of the work [23]. They are openly available Repository.

3. Results and Discussion

Figure 2 illustrates the cumulative carbon emissions from 2020 to 2050 for the reference and sufficiency scenarios. From 2020-2050, in the reference scenario, the 28 European countries cumulatively emit 27.5 Gtons CO2, while in the sufficiency scenario, the emissions total 19 Gtons. The major impact of sufficiency measures can be seen in the emissions of transport sectors, where the land-based carbon emissions from transport are reduced by 45%, aviation by 48%, and maritime by 31% compared to the reference scenario. Furthermore, the cumulative CO2 emissions indicate that in the reference scenario, negative emission technologies like DACCS and BECCS are required to reach net zero, with a total of 4.3 Gtons removed by 2050; this requires a sequestration potential of 200 Mtons per year in underground or offshore facilities, while the sufficiency scenario achieves lower emissions without the utilization of negative emission technologies. It is important to consider the following limitations of carbon dioxide removal and sequestration technologies:

- The underground carbon sequestration potential in Europe is substantial [24] and higher than the conservative assumptions used in this study. These assumptions are taken to account for the unequal distribution of geologic storage resources across Europe, involving that many countries will be unable to store their carbon dioxide domestically. This requires cross-border collaboration for carbon storage.
- Another limitation is the speed of deployment, currently, only Norway and Croatia have large scale operational CCS facilities in Europe. The ongoing projects of carbon sequestration in Europe [25] indicate substantial deployment by 2030, however, it will require rapid infrastructure development and a carbon network across Europe.
- The market readiness level of negative emission technologies and the associated costs is also a major problem, both BECCS and DACCS are in early stages of commercial development and require substantial subsidies [26]. Finally, BECCS relies on sustainable biomass availability for large-scale implementation, while DACCS requires substantial energy inputs, including heat and electricity.

In both scenarios, biomass and LULUCF play a major role in achieving a net-zero target by 2050. The biomass potentials considered in both scenarios align with findings from available literature [27]. For both reference and sufficiency scenarios, the annual LULUCF potential is assumed to be 509 Mtons for 28 modeled countries by 2050 adapted from [17]. However, non-energy GHG emissions from LULUCF and agriculture sectors are not accounted for in the study resulting in higher potential estimates compared to other studies [28, 29] that account for these emissions. Historical data on EU land-use sector indicates a decline in LULUCF potential in recent years [30], however, the revised EU regulation on land-use [31] is a major step in future developments in this sector. Future work will address non-energy GHG emissions, particularly from LULUCF and agriculture sectors, to provide a more comprehensive analysis.

The cumulative net emissions in the reference scenario do not align with Europe's carbon budget based on population share (12-25 Gtons), for a 50% probability of limiting global warming to 1.5°C (IPCC medium C1a scenario [32]). This indicates that, without sufficiency measures, the EU needs more ambitious net negative targets by 2050 to remain in the carbon budget. In the reference scenario, this carbon budget is consumed by 2040, requiring increased investments in negative emission, VRE, and flexibility technologies.

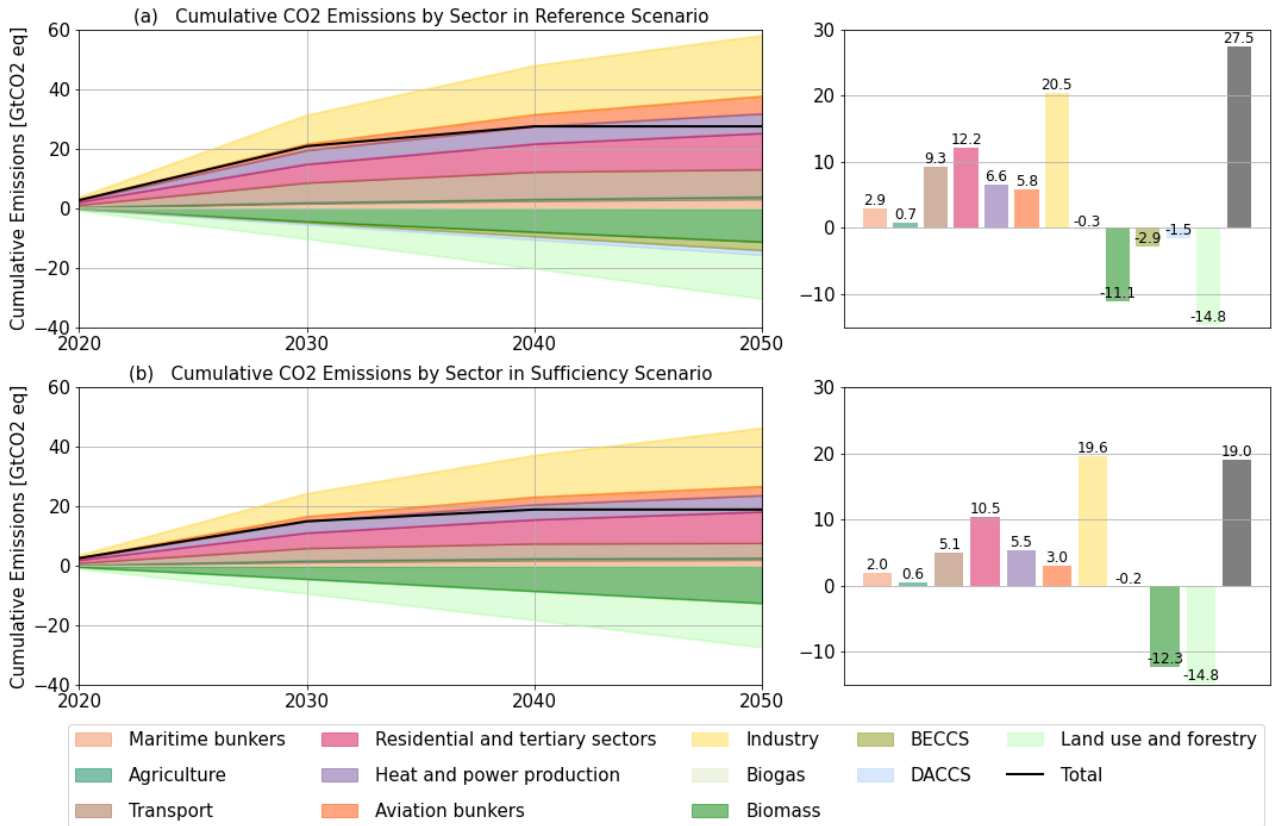

Figure 2: **a,b** shows total cumulative emissions for the reference and sufficiency scenarios. The area chart shows the trajectory of the total cumulative emissions with the share of each sector. The bar chart shows the total contribution of all sectors in cumulative emissions.

Figure 3 presents the Sankey diagrams comparing the reference and sufficiency scenarios for the year 2050. The results reveal a 24% reduction in useful energy in the sufficiency scenario relative to the reference scenario. This reduction highlights the multifaceted benefits of energy sufficiency. Firstly, by reducing energy demand, the sufficiency scenario leads to smaller required capacities for generation technologies, which, in turn, significantly lowers investment costs. Secondly, operational costs are reduced due to decreased consumption of primary resources, contributing to long-term economic efficiency. Most importantly, the transition to a sufficiency-based approach facilitates the deployment of renewable energy technologies. As the demand for energy decreases, there is a corresponding reduction in required generation capacities, which also results in less land use and material requirements. This underscores the environmental benefits of energy sufficiency when integrated with efficiency improvements and a higher share of renewables, positioning it as one of the most viable options for achieving a sustainable energy transition.

Furthermore, the impact of energy sufficiency extends to system-wide performance, where we observe a 50% reduction in overall system losses. This result emphasizes that while energy efficiency improvements are vital, they alone will not suffice to meet climate targets. Achieving the necessary emissions reductions requires addressing the complex interactions between all energy vectors, particularly those in demand sectors, which still heavily influence overall system efficiency.

The Sankey diagram provides a comprehensive visualization of the differences in energy requirements between the reference and sufficiency scenarios, offering deeper insights into the impact of energy sufficiency on future energy systems. One of the most striking differences is observed in electricity generation, where the reference scenario demands 8,618 TWh of generation capacity, whereas the sufficiency scenario requires only 4,618 TWh. This substantial reduction of approximately 47% highlights the immense potential for investment and operational savings in power generation technologies and grid infrastructure. A lower electricity demand translates into fewer new power plants, reduced fuel consumption, and minimized expansion costs for transmission and distribution networks.

A similar trend is seen in fossil fuel consumption, where the reference scenario relies on 982 TWh of fossil oil, while the sufficiency scenario drastically cuts this down to just 246 TWh, a 75% reduction. In the case of fossil gas, consumption remains relatively similar across both scenarios, indicating its continued role in the energy mix. However, a critical distinction emerges in the need for negative emission technologies: the reference scenario requires an additional 102 TWh of electricity and heat inputs for Direct Air Carbon Capture and Storage (DACCS) to offset emissions, whereas the sufficiency scenario eliminates this need entirely, demonstrating a more sustainable and self-sufficient energy system.

Overall, the analysis underscores that energy sufficiency measures yield positive impacts across all sectors, reducing both the final energy demand and the reliance on costly and carbon-intensive technologies. By optimizing energy use and reducing unnecessary consumption, the sufficiency scenario not only enhances system efficiency but also significantly lowers environmental impact, paving the way for a more resilient and sustainable energy future. A detailed comparison of energy flow across both scenarios, along with the situation in 2020, is presented in Table 2. In 2020, energy losses accounted for more than 50% of the primary energy supply. In the reference scenario, these losses are reduced to 33% due to the higher efficiency of the electrification pathway, which is predominant in 2050, whereas fossil fuels are the main energy vector in 2020. The sufficiency scenario mainly acts on the amount of useful energy, which in turns decreases the final and the primary energy consumptions.

Table 2: Comparison of energy flows in reference and sufficiency scenarios to 2020

Energy (TWh)	Baseline (2020)	Reference (2050)	Sufficiency (2050)
Primary energy	17489	13404	8392
Final energy	15364	11826	7391
Useful energy	8665	7697	5834
Losses	8888	4495	2272

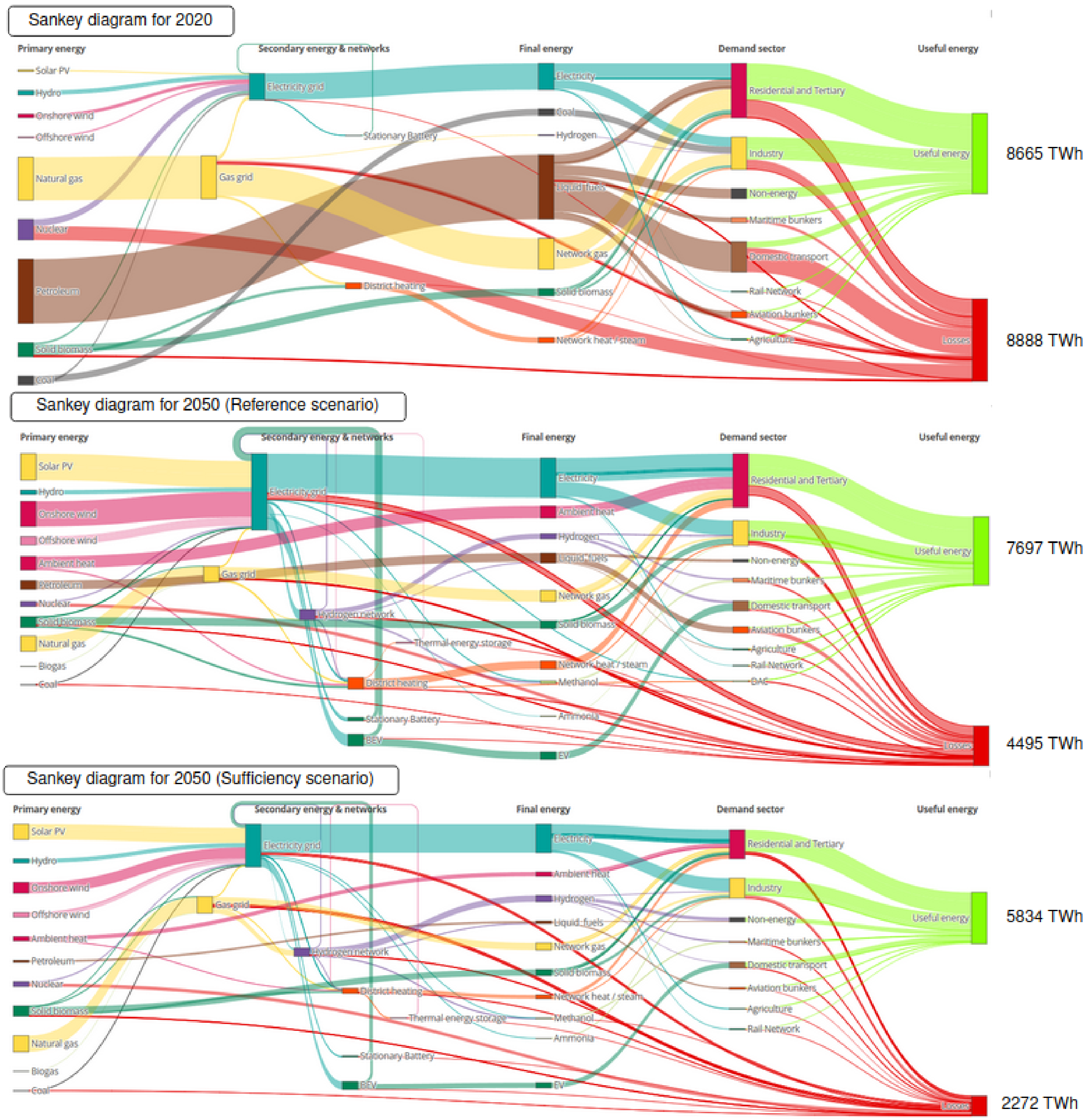

Figure 3: Sankey diagrams in the year 2020 and 2050 for the reference and sufficiency scenarios.

Figure 4a illustrates the total energy curtailment of variable renewable energy (VRE) technologies. Curtailment refers to the portion of energy generated by VRE sources, such as wind and solar power that cannot be utilized, stored, or transmitted due to system constraints. As a result, this energy is effectively wasted and not integrated into the power grid. In the reference scenario, the curtailment of VRE technologies increases with their growing share in the electricity mix. This trend highlights significant challenges in grid flexibility and the underutilization of renewable energy assets, limiting the efficiency and reliability of the energy system. By contrast, the energy sufficiency scenario demonstrates a marked reduction by a factor of 3 by 2040 and 2 by 2050 compared to the reference scenario in VRE curtailment. This suggests that sufficiency measures contribute to more resilient and efficient energy systems, enabling a higher integration of renewable energy while minimizing waste.
Figure 4b illustrates the projected evolution of average per capita carbon emissions across all considered countries, assuming a constant population for future years. The results highlight the significant impact of energy sufficiency in reducing individual carbon footprints over time.

The analysis also reveals consistently high per capita carbon emissions in Nordic countries and Switzerland under both scenarios. These countries, despite having relatively small populations, exhibit high energy consumption due to their cold climates and energy-intensive industries, which contribute to sustained carbon emissions.

Figure 4c presents a comparative analysis of the average energy prices for electricity, hydrogen, and district heating across different planning horizons. The results highlight the long-term cost benefits of energy sufficiency measures in shaping a more efficient and affordable energy system. By 2050, the wholesale prices in the sufficiency scenario exhibit notable reductions compared to the reference scenario, with a 12% decrease in electricity prices, a 13% reduction in hydrogen prices, and a significant 36% drop in district heating costs.

The decline in electricity prices can be attributed to a more balanced and optimized energy demand, which reduces grid infrastructure requirements and efficient utilization of variable renewable energy sources which helps to lower marginal generation costs, ultimately benefiting consumers with reduced electricity prices. The most notable cost reduction is observed in district heating networks, where the sufficiency scenario results in a 36% decrease in average prices. This can be explained by enhanced energy efficiency and sufficiency measures in buildings, better thermal storage integration, and the adoption of efficient heating technologies, all of which contribute to lowering the demand for high-cost heat generation. The results suggest that energy sufficiency strategies not only reduce emissions but also play a crucial role in making energy more affordable for households and industries, fostering a more sustainable and cost-effective energy transition.

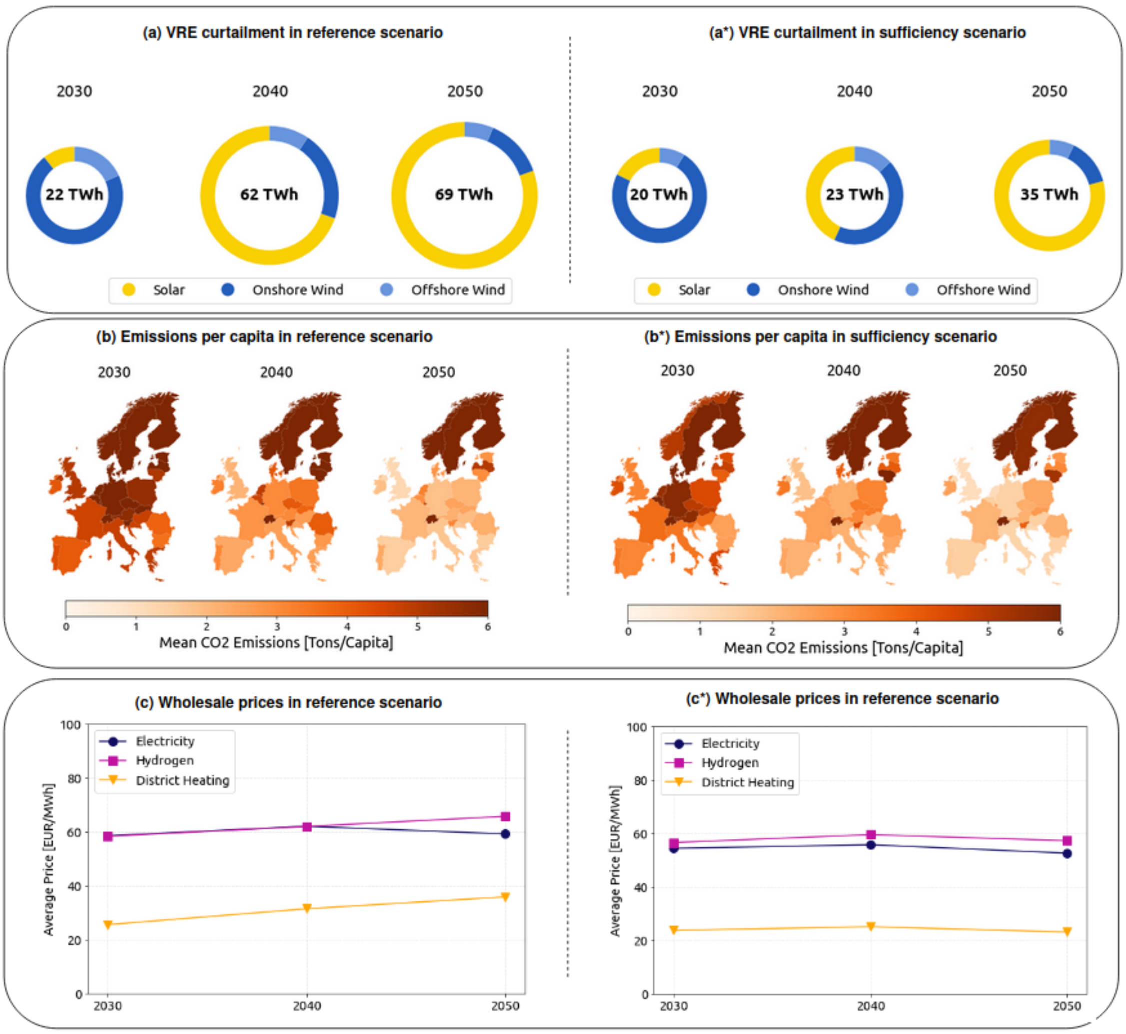

Figure 4: Key performance indicators comparison for the reference and sufficiency scenarios.

4. Conclusion

Our study highlights the significant benefits of energy sufficiency in the energy transition and the importance of reducing non-essential energy demands across various sectors. The model we used also demonstrates the integration of energy sufficiency into an established energy system model like PyPSA-Eur, which provides a comprehensive and highly temporally resolved view of the future sector-coupled energy systems at both regional and national levels. The study currently incorporates the demand reductions exogenously into the model. The next step in improving the model is to use endogenous modeling of sufficiency measures across the residential, tertiary, and transportation sectors. Demand reduction in these sectors requires significant structural/behavioral changes at the individual and societal levels, which is complex but has a high impact as demonstrated in this work. Overall, the results show the significant advantages of energy sufficiency in reaching energy independence at the EU level, ranging from cost savings to reduced capacity requirements and a lower carb on footprint. Implementing sufficiency measures makes it more feasible to achieve the climate targets without the need for investments in nuclear and CCS technologies. In addition, it also reduces the requirement for power generation, flexibility, and storage systems. The low capacity requirements have two benefits: which are low investment costs and reduced land-use and material requirements for VRE installations. The results indicate efficiency measures decrease the overall system losses, from over 50% today to 33% of primary energy in 2050, implementing sufficiency measures further decrease the losses by 6%.

The comparison of energy efficiency and energy sufficiency in our scenarios show that sufficiency measures achieves a 30% reduction in emissions and a 50% decrease in overall system losses at the regional level compared to only implementing the efficiency measures due to reduced energy consumption. The results also underscore that the electricity grid requires further expansion, and hydrogen remains an important energy vector for achieving deep decarbonization. The JRC report [33] estimates a seven times increase in flexibility requirements in the European region by 2050. Our results show that sufficiency measures reduce the need for flexibility requirements; in storage technologies, the required reductions are more than 60%, while in grid infrastructure, the capacities are reduced by 15% in interconnections and more than 50% in hydrogen pipelines compared to the reference scenario.

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