MODELING THE IMPACT OF ENERGY SUFFICIENCY ON EUROPEAN INTEGRATED ENERGY SYSTEMS

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ABSTRACT

The Fitfor55 EU package represents a comprehensive suite of policies and regulations introduced by the European Union to align with the Paris Agreement's objectives. In this context, there is a shared drive to decrease greenhouse gas emissions by 55% before 2030, encourage more substantial energy efficiency, and promote the extensive adoption of green energy technologies. Simultaneously, REpowerEU, a bold European initiative, is dedicated to expediting the transition to renewable energy sources. Its overarching aim is to substantially elevate the proportion of renewable energy in Europe's energy matrix, reducing carbon emissions and strengthening energy security across the continent. The European Union clearly aims to attain a greenhouse gas-neutral economy by 2050. Energy sufficiency, frequently overshadowed or muddled with energy efficiency, is a pivotal facet of the energy transition. It pertains to reducing energy usage on both personal and societal scales by embracing less energy-intensive behaviours and routines. Embracing energy-sufficiency strategies carries substantial advantages for the energy transition. These strategies lead to reduced energy demand, resulting in cost savings and reduced requirements for developing new energy infrastructure, thus bearing a positive economic and environmental impact.

Although energy sufficiency is considered in recent studies, its impact on annual costs, emissions, system adequacy and flexibility, and bottlenecks like curtailment and congestion are often overlooked. One reason is the temporal scale; equilibrium models and IAMs typically use a one-year timestep which undermines the network expansion, capacity and flexibility requirements. Another aspect is the spatial scale; most studies focus on a single country, neglecting the effects of interconnections and gas or hydrogen networks. In this study, PyPSA-EUR, a sector-coupled model for optimizing multi-energy systems, is used to scrutinize the energy systems of 28 interconnected European countries. This analysis encompasses the integration of energy-sufficiency measures spanning diverse energy sectors. The findings are subsequently compared with a business-as-usual (BAU) scenario. Remarkably, this study's implementation of energy-sufficiency measures indicates reduced capital investments in generation technologies and grid expansion when compared with the BAU scenario. These results underscore the substantial cost savings and emission reductions achievable through energy sufficiency. Furthermore, the study emphasizes the pivotal role of energy sufficiency in conjunction with energy efficiency and variable renewable energy (VRE) integration in steering the energy transition, compared to pathways focusing solely on energy efficiency and VRE integration.

1 INTRODUCTION

According to the last IPCC WG3 AR6 report Shukla et al. (2022), the world is currently not on track to meet either the 1.5°C or the 2°C climate target. It is of the utmost urgency to start decreasing global

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CO2 emissions soon to remain within the carbon budgets associated with these objectives. To that aim and to understand the levers of action available, global emissions can be decomposed into four factors: the world population, the global consumption per capita, the energy intensity and the carbon intensity. Leaving demographics aside, it is essential to act on (1) the transition to clean energy sources to reduce the carbon intensity, (2) energy efficiency measures to reduce the energy intensity- and (3) the increase in energy sufficiency to reduce the overall consumption per capita. While the two first aspects are the object of abundant literature, much work remains to be done on defining credible scenarios considering energy sufficiency.

Energy sufficiency[1] can be achieved by reducing the consumption of energy services such as lowering the room temperature set points, decreasing the living space per capita for dwellings, or transitioning away from single-occupancy vehicles towards more sustainable alternatives like public transportation or cycling (Ziegler et al., 2021). Sufficiency measures can be implemented by changing societal norms and behaviours or by policy initiatives at the organization, country, or regional level. Although energy sufficiency is not implemented as a policy initiative by the EU Commission, the recent Ukraine war and its impact on energy security clearly outlined the importance of decreasing unnecessary demands in all energy sectors. This is translated in the REPowerEU Plan (*REPowerEU Plan*, 2022), in which member states agreed to decrease gas consumption by 15% in 2022 compared to the previous winter. Similarly, the COVID-19 crisis entailed a major decrease in economic activity which resulted in a significant decrease in consumption and production with an impact on GHG emissions. The main objective of energy sufficiency measures is to attain this reduction by societal transformation and behavior changes rather than a crisis scenario (Kuhnhenn et al., 2020). In such a framework, overconsumption of energy can be reduced while still satisfying the basic energy needs necessary for a decent living Hopkins et al. (2020): most countries are above the final energy threshold necessary for decent living.

Energy sufficiency has been considered in multiple studies in the recent past. Most of the studies use equilibrium and integrated assessment models (IAMs) to find trajectories for future years, considering the reduction in demand in various sectors. Examples of such modeling tools can be found in (Kuhnhenn et al., 2020) and (*EUCALC*, 2020). Energy sufficiency as a demand-side strategy is used in Tomer et al. (2021) considering what-if scenarios to assess the impact on the long-term sustainability goals. An IAM is also used in Grubler et al. (2018), where low-demand scenarios are defined. Eerma et al. (2022) uses a German case study to analyze the impact of behavior change to achieve a fully renewable energy system. Energy demand reduction options for the United Kingdom are considered in (John et al., 2021). Modeling sufficiency endogenously and exogenously is used in (Boye et al., 2022). The consideration of sufficiency, efficiency, and flexibility to decarbonize energy districts is used in (Silvia & Lorenzo, 2021). The TIMES Ireland model is used in Gaur et al. (2022) to model reduced energy services demand and considers them as macroeconomic drivers in the energy system model. A behavior change scenario is used in FPS (2021) to investigate the investment needs for Belgium in 2050. Although energy sufficiency is considered part of energy system models, the impact on annual costs, system adequacy and flexibility, and system bottlenecks such as curtailment and congestion are generally ignored; one reason for this is the temporal scale to investigate the complex energy systems, the equilibrium models and IAMs generally use 1-year timestep in studies which undoubtedly undermines the capacity requirements and network expansion. Another reason is the spatial scale; most energy system models considering energy sufficiency in the studies are limited to a single country, which undermines the impact of interconnections and gas or hydrogen networks.

This study uses the sector-coupled version of PyPSA-EUR to model sufficiency measures in future scenarios. The geographical scope is limited to 28 interconnected European countries, and one-hour timesteps for a whole year is used as a temporal scale. A comparative analysis of the sufficiency scenario is carried out with a business-as-usual (BAU) scenario to analyze the differences between energy trajectories, the balance between different energy carriers, and the impact of sufficiency on overall GHG emissions.

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[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" (Shukla et al., 2022)

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2 METHODOLOGY

Figure 1 provides an overview of the methodology used in this study and the inclusion of energy sufficiency in PyPSA-EUR. The energy-efficient and energy-sufficient demands for residential, tertiary, transport, industry, and agriculture sectors are based on the CLEVER EU scenario (*CLEVER Scenario*, 2023). In such a system, electricity consumption is reduced because of the overall decrease in the consumption of goods and services, but also increased because of the electrification of relevant sectors such as transportation, heating and cooling. The system is optimized using the myopic pathway optimization of PyPSA-EUR until 2050, with the constraint of remaining within the 1.5°C carbon budget (26-28 GtCO2). The myopic pathway tracks changes in an energy system during a transition path, with capacities installed in a given year treated as pre-installed capacities in subsequent years until their operational lifetime expires. The results are then analyzed to assess the impact of the sufficiency and efficiency measures on grid expansion, system costs, emissions, flexibility requirements, electrification, and VRE integration. The study considers a sufficiency scenario and a business-as-usual or BAU scenario for comparative analysis (the primary difference between both is energy demands), considering net-zero energy systems by 2050 on a European level. The sufficiency scenario considers no carbon removal options in the optimisation; only process emissions from industry are allowed to be captured and used for power-to-liquid utilisation.

The proposed models, methods, and data are released with an open license to ensure transparency and reproducibility of the work Pfenninger et al. (2017); they can be freely downloaded[2].

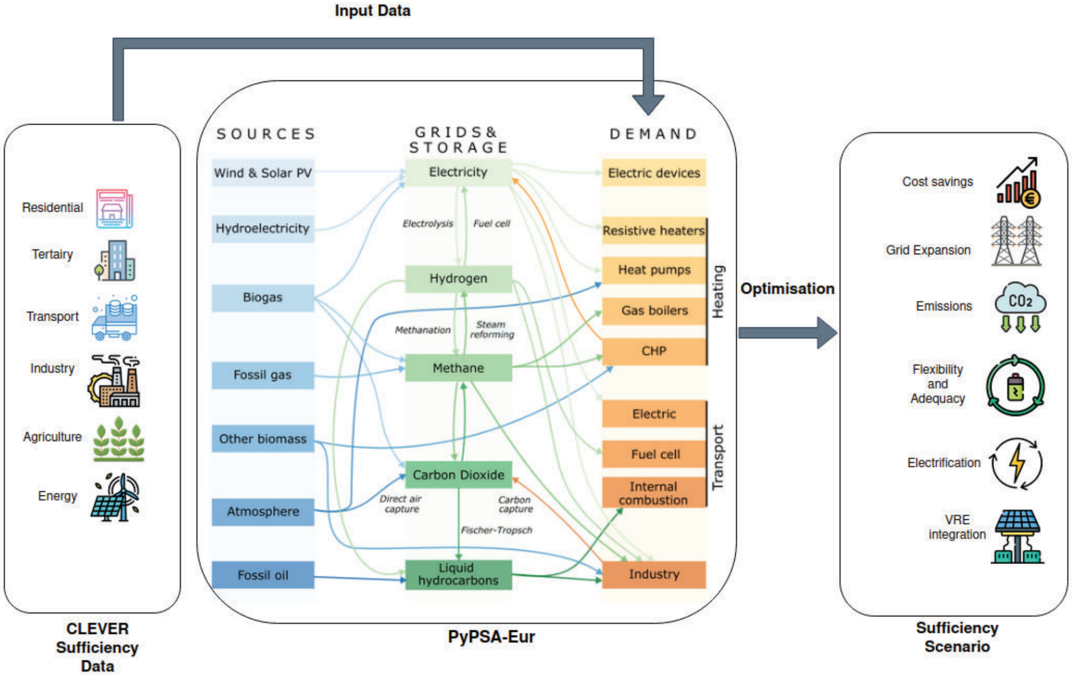

Figure 1: Methodology used in the study to include energy sufficiency (Adapted from(*PyPSA-EUR*, 2024))

2.1 The CLEVER Scenario

The CLEVER scenario *CLEVER Scenario* (2023) is built on a bottom-up approach considering sufficiency, efficiency, and integration of renewable energy. Energy sufficiency is considered a primary step, followed

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[2] https://github.com/UmairTareen/pypsa-eur

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by energy efficiency and renewable energy Cabeza et al. (2022). The national-level scenarios were first defined by quantifying the energy consumption at the national level, considering the minimum consumption level by prioritizing essential needs, which include the sufficiency assumptions. The national sufficiency scenarios were then harmonized to allow aggregation and comparison. In the last step, all scenarios were integrated to build a European sufficiency pathway aligned with the 1.5°C objective. The model computes incremental changes in energy demand every year, including demands for residential, tertiary, transport, industry, agriculture, and energy sectors. A summary of the most relevant sufficiency assumptions is provided in Table 1. The sufficiency measures in the residential and tertiary sectors mainly encompass lower floor areas and lower energy demand for space heating and hot water. The efficiency measures include deep renovations and the use of efficient technologies for heating. However, the embodied emissions associated with efficiency measures like deep renovation of building stock are not considered. In the transport sector, the sufficiency measures include increased occupancy, increased rail travel, decreased air travel, and reduced passenger kilometers for road mobility. The industrial and agriculture sectors include low demands for future years with increased efficiency, fuel switch, and recycling. The energy sector includes increased technology efficiency and a high share of VRE technologies in the generation fleet.

Table 1: Final energy consumption (FEC) per sector in CLEVER sufficiency scenario for 28 modeled countries for the year 2050 compared with 2020 with main sufficiency and efficiency assumptions

(1) Reduced Floor area
(2) Share of carriers
(3) High efficiency technologies
(4) Deep renovation
(5) Lower energy consumption per capita
(6) Lower production demand
(7) Downscaling of goods
(8) Improved materials
(9) Fuel substitution
(10) Recycling
(11) Distance traveled per capita
(12) Air distance traveled per capita
(13) Active mobility share
(14) Collective transport share
(15) Car occupancy
(16) EV share
(17) Car efficiency
(18) Lower specific electricity usage per capita

Sector	Demand type	Unit	2020	2050	Sufficiency measures	Efficiency measures
Residential	Total space heating	TWh	2237	1211	(1),(5)	(2),(3),(4)
Residential	Total Hot Water	TWh	504	259	(5)	(3)
Residential	Total Cooking	TWh	175	129	-	(2),(3)
Residential	Total FEC	TWh	3464	1985	(1),(5),(18)	(2),(3),(4)
Tertiary	Total FEC	TWh	1761	1051	(1),(5),(18)	(2),(3),(4)
Transport	FEC road mobility	TWh	2208	391	(11),(15),(14),(13)	(16), (17)
Transport	FEC rail passenger	TWh	62	96	(11)	(2)
Transport	FEC air travel	TWh	654	187	(12)	-
Industry	FEC Steel	TWh	571	332	(6),(7)	(3),(8),(9),(10)
Industry	FEC Cement	TWh	166	87	(6),(7)	(3),(8),(9),(10)
Industry	FEC Chemical	TWh	661	480	(6)	-
Industry	FEC Non-Ferrous Metals	TWh	142	111	(6),(7)	(9),(10)
Industry	FEC Food, Beverage and Tobacco	TWh	356	220	(6)	(10)
Industry	FEC paper, pulp and printing	TWh	408	282	(6),(7)	(3),(9)
Agriculture	Total FEC	TWh	358	206	-	(9),(3)

Industry sector demand reduction in the CLEVER scenario is based on efficiency measures that consider fuel substitution, material substitution, and technological gains to decrease the energy intensity of industrial processes. The sufficiency policies include gradual downscaling of industrial goods production due to lower demand at the consumer level. In cement production, for example, a 48% reduction is assumed for 2050. The energy intensity of cement production is assumed to be lowered by 18% due to technological innovation and material and fuel substitution. In the steel industry, sufficiency and efficiency measures reduce energy consumption by 52% and production by 26% by 2050. Sufficiency measures in the steel industry include a decrease in new engineering structures, less waste in construction, less demand for heavy

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vehicles and other vehicles in the transport industry due to vehicle sharing, and increased lifetime. The primary steel production route is assumed to be replaced by direct reduced iron (DRI) in 2050. Detailed information about the industrial demand assumptions for other industrial sectors can be found at (Toledano et al., 2018). In other sectors, sufficiency and efficiency assumptions include, for example, renovating current structures instead of building new ones, increasing co-housing, and decreasing the construction of new road networks due to increased rail travel.

2.2 PyPSA-EUR

The sector-coupled version of PyPSA-EUR, which is an open-source modeling tool, is used in this study. The sector-coupled version considers demands from various energy sectors (residential, tertiary, industrial, transport, agriculture) depending on the scope of the study. VRE generation and capacity calculations use Atlite Hofmann et al. (2021) to compute the maximum generation capacities considering the CORINE land-use database, excluding the natural protection areas specified in the Natura 2000 dataset. All the transmission lines are aggregated to 380kV for simplicity, and DC load flow equations are used. The technology and cost assumptions use the data published by the Danish Energy Agency. The capital costs of technologies for future years are assumed considering the learning curve, while better efficiencies are also considered for future years to have more realistic cost assumptions. The annual heat demands are taken from Ming et al. (2017) and split into space and water heating. The biomass potentials are taken from (Ruiz, 2019). Industrial energy demand and CO2 emissions are distributed among different energy sectors, which include current and future mitigation strategies. The power plant data in PyPSA-Eur is retrieved using the power plant matching library Fabian et al. (2019) and includes complete information about power plants and hydro capacities. Electricity demand profiles are retrieved from the OPSD data published by ENTSO-E. The demands for all sectors are retrieved from JRC-IDEES and Eurostat for sector-coupled studies. All the other parameters, which include electric vehicles, fuel cell vehicles, and ICE, share in transport, heat demand reduction due to renovation, shipping fuel shares, and steel and aluminum industry primary and secondary routes share are set exogenously in the model. Detail information about supply and demand is available at (*PyPSA-EUR*, 2024).

Objective Function

The objective is to minimize the total annual costs of the system, which is subject to constraints linked to the technologies, resources, and CO2 emissions. The objective function of the linear programming (LP) problem is provided in Equation 1.

$$\min_{G,E,P,F,g}\left[\sum_{i,r} c_{i,r}.G_{i,r} + \sum_{i,s} c_{i,s}.E_{i,s} + \sum_{\ell} c_{\ell}.P_{\ell} + \sum_{k} c_{k}.F_{k} + \sum_{t} w_{t}.\left(\sum_{i,r} o_{i,r}.g_{i,r,t} + \sum_{k} o_{k}.f_{k,t}\right)\right] \tag{1}$$

Where i, r, s, ℓ, k, and t are the indices relative to the bus, generator technology, storage technology, transmission line, link, and time-step, respectively. In the PyPSA framework, the link component is versatile and used for elements with controllable power flow, including bidirectional HVDC links, unidirectional lossy HVDC links, AC/DC network converters, heat pumps, CHPs, etc. $c_{i,r}$ and $c_{i,s}$, are the annualized capital cost for generator and storage technologies at bus i, c_ℓ and c_k are the annualized capital cost for transmission lines and links. $G_{i,r}$ and $E_{i,s}$ are the generator and storage technology type and capacities at bus i. P_ℓ and F_k are the transmission line and links capacities. w_t is the time-step weightings equal to 1 if a one-hour resolution is selected for simulation. $o_{i,r}$ is the variable operating cost of generator dispatch $g_{i,r,t}$ and o_k is the variable operating cost of link dispatch $f_{k,t}$. Detailed information about the problem formulation can be found in (Victoria et al., 2022).

The computed capital costs are annualized over the economic lifetime n. This conversion is achieved by

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applying the annuity factor a, which considers a discount rate r as shown in Equation 2.

$$a = \frac{1 - (1 + r)^{-n}}{r} \tag{2}$$

3 RESULTS AND DISCUSSION

The study considers a reference case for 28 modeled countries representing the current energy systems based on 2020 values. There is a sufficiency scenario and a business-as-usual scenario for comparative analysis, considering net-zero energy systems by 2050. All the countries are represented by a single node. However, the United Kingdom, Italy, Spain, and Denmark have two nodes due to additional synchronous areas. The temporal scale is one year with a 1-hour resolution. For the simulations, the myopic scenario building of PyPSA-EUR is used to analyze the progressive changes in the transition path. In the sufficiency scenario, only process emissions from industry can be captured and used for P-to-X utilization. However, the assumed capacities in the CLEVER scenario are not considered for the capacities of generation technologies. The assumed values for land use, land-use change, and forestry (LULUCF) are included in the sufficiency scenario based on CLEVER assumptions by considering a carbon sink in the model. VRE technologies are only constrained by the maximum potentials computed by Atlite. The maximum extension of transmission lines for both sufficiency and BAU scenarios is limited to 50% for each planning horizon. This limitation is used to consider the time constraints on planning and deploying the additional capacities to transmission lines, especially interconnections. For both BAU and sufficiency scenarios, a constraint of -55% for 2030, -85% for 2040, and -100% for 2050 compared to CO2 emissions in 1990 is considered. An additional CO2 constraint is also applied on the country's level. For the year 2050, a -95% emissions constraint is applied for each country in addition to -100% on the EU level. For better representing the energy systems on a country level, an equity constraint is also used in the study which ensures that at least 70% of the power generation is generated locally by each country. These additional constraints ensure that energy systems of countries that have high LULUCF potentials but small economies are not impacted in the optimization process by EU-level emissions constraint.

Figure 2 provides an overview of energy demands in the BAU, and sufficiency scenarios. The sufficiency scenario considers the sufficiency and efficiency assumptions to reduce the overall demands presented in Table 1, while the BAU scenario only considers the efficiency improvements used by the default PyPSA-EUR configuration. In the BAU scenario, electricity demand rises gradually until 2050 due to electric vehicle fleet growth and increased industrial electrification. In the sufficiency scenario, electricity demand sees a slight increase by 2050, with reduced distribution sector use and increased residential and tertiary electrification.

The transport sector's demand decreases in the sufficiency scenario, even with an 85% EV share, due to reduced per capita passenger-kilometers. Notable declines in heating and aviation fuel consumption are observed, driven by lower energy consumption per capita, reduced hot water energy use, fewer passenger kilometers traveled by air, and a shift towards rail travel. A large portion of Non-energy demand in the sufficiency scenario is replaced by hydrogen. When considering sufficiency measures across all modelled sectors, the combined energy demand for 28 EU countries totals 7007 TWh by 2050. In comparison, the BAU scenario indicates a demand of 10,554 TWh. This underscores the significant impact of sufficiency measures in reducing energy demands and promoting environmental sustainability.

Figure 3 illustrates the expansion of the grid and the total investment costs for capacities for 28 simulated countries. Both the BAU and sufficiency scenarios involve grid expansion, with additional capacities added to the interconnections, encompassing both AC and DC categories. In the BAU scenario, the total transmission line capacities for AC and DC lines from the transition path from 2020 to 2050 are 456 GW. For the sufficiency scenario, these capacities are 402 GW. These findings indicate that demand reduction plays a crucial role in decreasing new investments in transmission lines. The comparison between the sufficiency and BAU scenarios also reveals that sufficiency measures lead to lower capacity requirements for generation and storage. In the BAU scenario, the installed capacities for solar, onshore wind, and offshore

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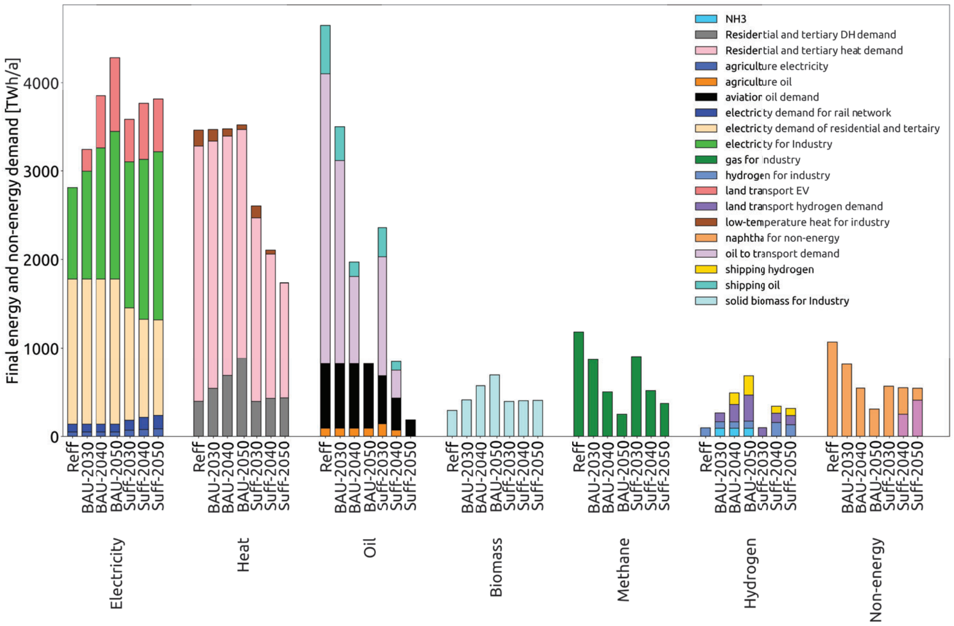

Figure 2: Sectoral demands per energy carrier for BAU and sufficiency scenarios

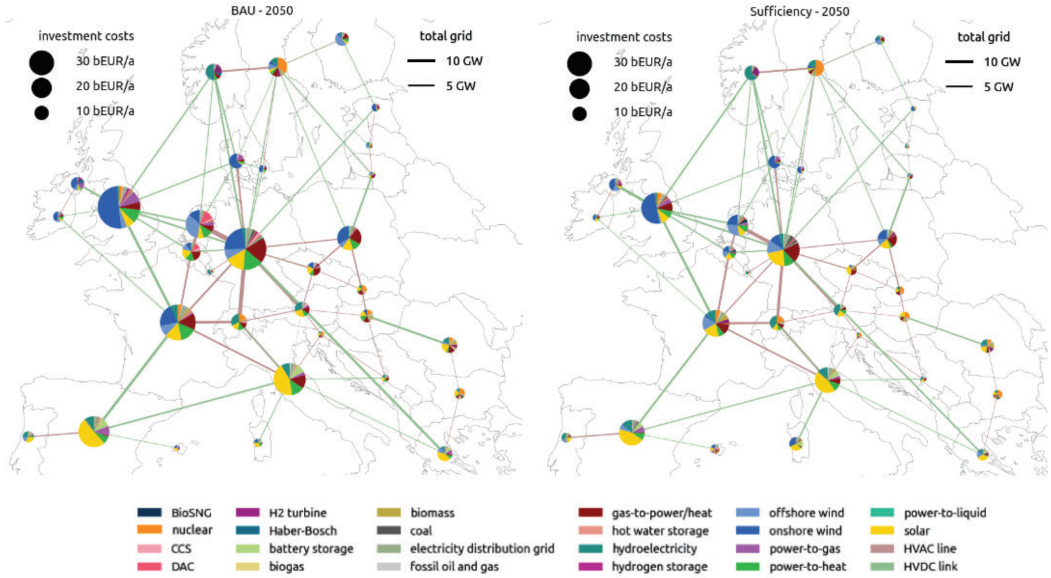

Figure 3: Grid expansion and installed capacities per technology for considered scenarios

wind are 2498 GW, 1042 GW, and 210 GW, respectively. In comparison, the sufficiency scenario requires lower capacities of 1784 GW, 538 GW, and 145 GW for solar, onshore wind and offshore wind. Regarding flexibility needs in terms of hydrogen storage in the BAU scenario is 19 TWh, while for sufficiency scenario the hydrogen storage requirements are 5.6 TWh. For electrolysis capacity requirements, the BAU scenario requires 482 GW, whereas the sufficiency requires a reduced capacity of 195 GW. In addition, the sufficiency scenario exhibits significantly lower requirements for P2X (Power-to-X) technologies compared to the BAU scenario. The BAU scenario also indicates huge investments in negative emission technologies

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while in sufficiency scenario no such investments are needed. These results emphasize the substantial impact that demand reduction can have on future energy systems.

Figure 4 shows the cumulated emissions for the transition period from 2020 to 2050 for both BAU and sufficiency scenarios. The cumulated emissions for 28 countries in the BAU scenario are 27.5 Giga tons, while for the sufficiency scenario, the emissions are 20.6 Giga tons. In the BAU scenario, the cumulated emissions align with the carbon budget for EU based on a population share, with a 50% probability of reaching the 1.5C° scenario. However, most of the carbon budget is consumed by 2040, and considerable investments in negative emission, VRE, and flexibility technologies are required to remain within the carbon budget. The cumulated emissions in the sufficiency scenario indicate that if behavior changes are applied and the overconsumption of energy is reduced, achieving the climate targets is more feasible with reduced investments in infrastructure and capacities.

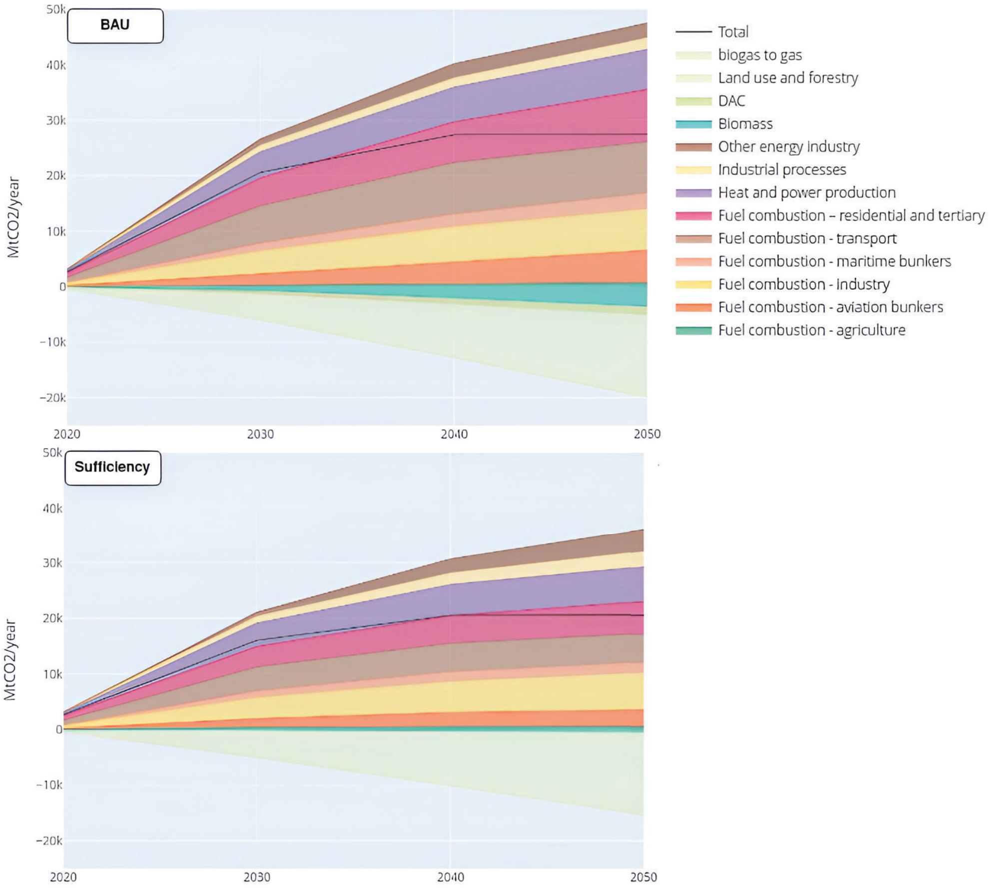

Figure 4: Cumulated CO2 emissions in BAU and sufficiency scenarios

Figure 5 shows the total annual costs required to reach climate neutrality by 2050. In the BAU scenario, where only efficiency measures are applied, the annual costs are very high compared to the sufficiency scenario. The lower annual costs in the sufficiency scenario are attributed to implementing sufficiency and efficiency measures across the considered sectors. These measures effectively reduce the capacity requirements and subsequently lower the operational costs due to reduced demands. If we consider the cumulated costs from 2023- 2050 for both scenarios, the BAU scenario cumulated costs are 13.7 trillion euros, while for the sufficiency scenario, it is 10.2 trillion euros; this indicates enormous savings can be achieved if energy sufficiency measures are applied across all energy sectors. The sufficiency measures implemented with VRE integration and energy efficiency are the most economically and technically feasible options to be climate neutral by 2050. However, it requires considerable societal and behavior changes on individual and societal levels, reinforced by policy measures on the EU level.

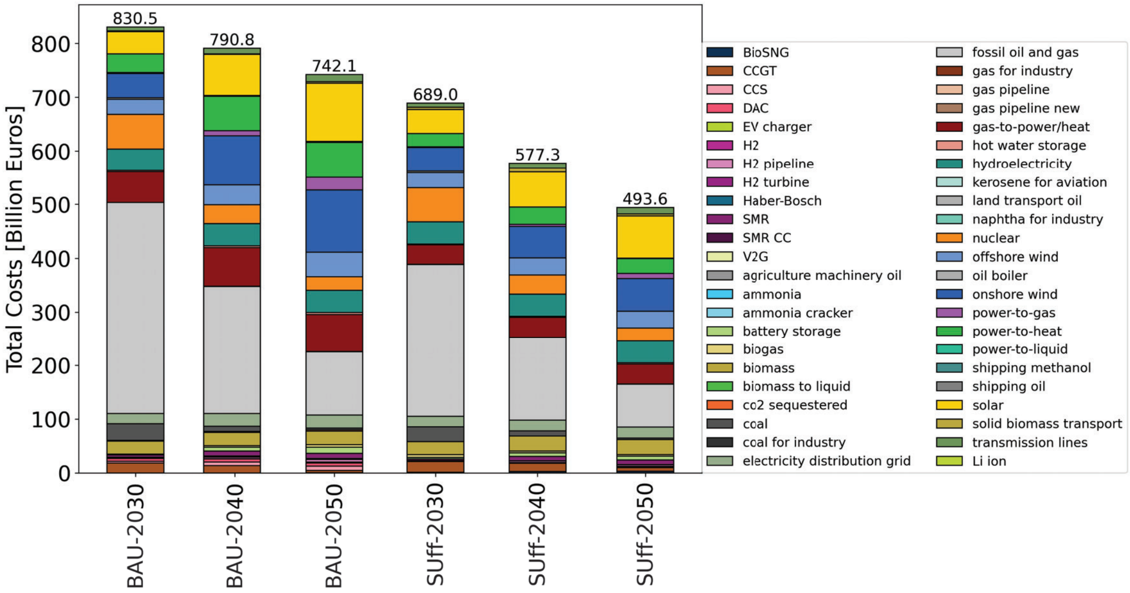

Figure 5: Annual investment and operational costs for BAU and sufficiency scenarios

Figure 6 illustrates the Sankey diagram for the BAU and sufficiency scenarios in the year 2050. The diagram showcases the energy flows from source to demand sectors and contributions from various technologies. In the BAU scenario, 1881 TWh of natural gas and 982 TWh of petroleum imports are required. However, the BAU scenario also requires 53 TWh from biogas in the gas grid, 151 TWh of e-fuels provided by Fischer-Tropsch, and 1159 TWh of hydrogen. In the sufficiency scenario, the natural gas imports are 1839 TWh, and petroleum imports are 260 TWh, with 31 TWh from biogas and 63 TWh from e-fuels. The electricity grid in the BAU scenario generates 9000 TWh of electricity, while in the sufficiency scenario, it is limited to 6187 TWh; this signifies the capacity requirements for flexibility in highly VRE-concentrated energy systems of the future, which sufficiency measures can minimize. The impact of sufficiency measures can also be seen in the hydrogen network, district heating, and EV demand requirements. However, there is still a large portion of natural gas imports in the sufficiency scenario, which indicates that the country-level CO2 constraint can be lowered further for all countries.

Overall, the results show tremendous benefits of energy sufficiency in the energy transition, from cost savings to fewer capacity requirements and reduced carbon footprint. However, it requires behavior change on the personal and societal levels reinforced by policy measures on the country and regional levels. The social acceptance of these measures is of utmost importance, and it can be made more attractive if economic incentives are initiated for lower energy consumption. Awareness initiatives hold significant potential in effectively communicating messages to the broader public. The impact on economies on the country and regional levels is out of the scope of this study. However, Sufficiency can align with economic growth, as illustrated globally by the IPCC's Shared Sustainable Pathway (SSP1) (Rogelj et al., 2018). Also, limiting global warming to 1.5°C is crucial, and there is a need to weigh the economies not only on GDP parameters but also on environmental sustainability, quality of life, equity, and alignment with the planetary boundaries.

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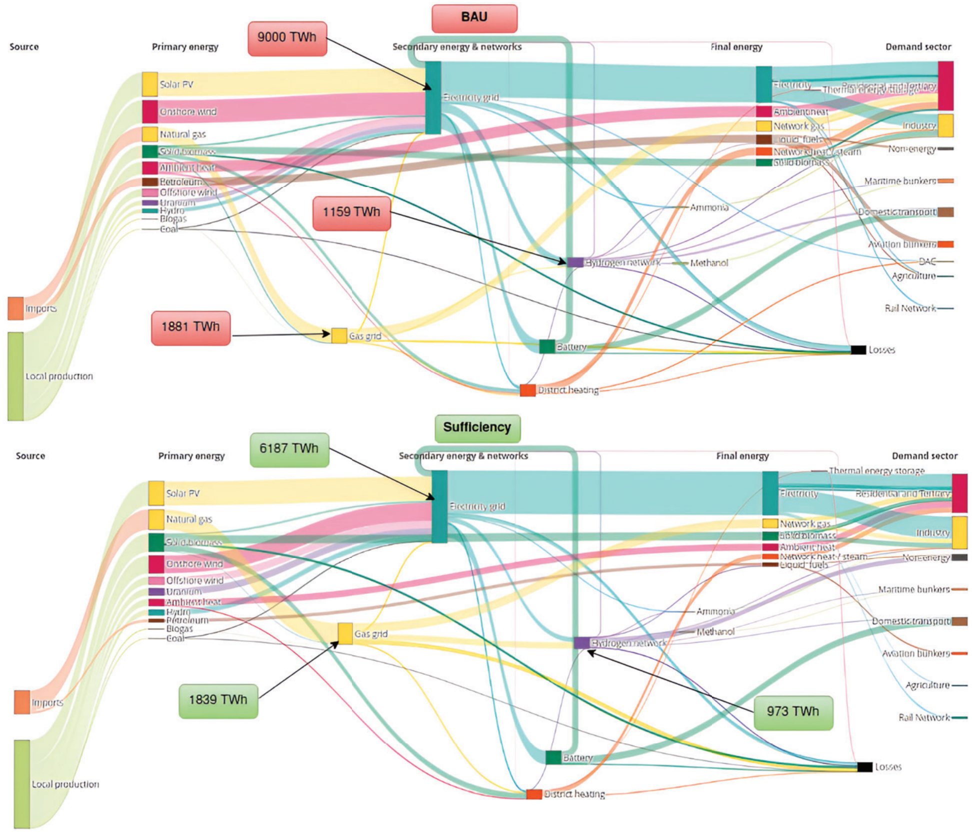

Figure 6: Sankey diagram for BAU and sufficiency scenarios for 2050

4 CONCLUSION

This study emphasizes the significance of energy sufficiency in driving the energy transition and underscores the advantages of reducing non-essential demands across diverse energy sectors. The utilization of the model enables the integration of energy-sufficiency measures alongside efficiency improvements and renewable energy technologies in long-term planning studies. A more comprehensive approach to sustainable energy planning can be achieved by incorporating energy-sufficiency considerations. The future improvements in the model include cost-benefit analyses to have a clearer view of cost savings and economic feasibility and sensitivity analyses to quantify the impact of uncertain parameters.

The results indicate that by the implementation of sufficiency measures and the associated demand reductions, it is possible to achieve the 1.5C° climate target without investments in the CCS and nuclear technologies. The demand reduction positively impacts CO2 emissions and reduces the need for extensive capacity requirements for both generation and storage technologies. Consequently, this translates to reduced land utilization for the installation of VRE technologies, thereby promoting material usage reduction as well. Nonetheless, it demands a change in behavior at both the individual and societal levels, bolstered by policy measures at the national and regional levels. Results also indicate that, despite a lower overall energy consumption and lower associated CO2 emissions, interconnections and flexibility resources remain primordial. The electric grid, for example, requires further deployment, and hydrogen remains a significant energy vector for advanced decarbonization levels. The sufficiency scenario, however, allows for drastically reduced investment costs for these technologies compared to a BAU scenario without investments in negative emission technologies. However, this is associated with developments in the LULUCF sector on the country level.

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