Modeling the impact of energy sufficiency measures in European integrated energy systems using PyPSA-Eur

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Abstract:

The Paris Agreement, in which most countries set the goal to limit global warming to 1.5℃, calls for extensive coordinated efforts across multiple energy sectors. The EU aims at a net-zero greenhouse gas economy by 2050. The two primary focus areas to meet this target are deploying renewable technologies in the energy mix and increasing energy efficiency. Energy sufficiency is an essential aspect of the energy transition that is often overlooked or confused with energy efficiency. It refers to the reduction of energy consumption on individual and societal levels by adopting behaviors and practices that are less energy intensive. The adoption of energy-sufficiency measures can have significant benefits for the energy transition by reducing the overall energy demand, which can, in turn, reduce the need for new energy infrastructure and lower the system costs. In this study, PyPSA-Eur, a generation and transmission optimal expansion and dispatch model, is used to study the energy system of five interconnected countries while accounting for energy sufficiency measures across multiple energy sectors. The outcomes are then compared to a reference case and business-as-usual (BAU) scenario. The sufficiency measures assumed in this study lead to less investment costs in generation technologies and grid expansion compared to the BAU scenario. The findings suggest that energy-sufficiency measures can result in significant cost savings and emission reductions, and energy sufficiency combined with energy efficiency and VRE integration can play a crucial role in the energy transition compared to the pathways considering only energy efficiency and VRE integration.

Keywords:

Energy Sufficiency, PyPSA, Energy Efficiency, Energy System Planning

1. Introduction

According to the last IPCC WG3 AR6 report, the world is currently not on track to meet either the 1.5℃ or the 2℃ climate target. It is of the utmost urgency to start decreasing global CO2 emissions in the near future to remain within the carbon budgets associated with these objectives. To that aim and to understand the levers of action available to us, Kaya's identity [1] usefully decomposes global emissions F into four factors: the world population P, the global consumption per capita G/P, the energy intensity E/G, and the carbon intensity F/E as represented in Equation 1. Leaving demographics aside, it is important 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 first two aspects are the object of abundant literature, much work remains to be done on defining credible scenarios considering energy sufficiency.

$$F = P * (G/P) * (E/G) * (F/E) \quad (1)$$

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 switching to alternatives to public transport or bicycles instead of driving [3]. Sufficiency measures can be implemented by changing societal norms and behaviors 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 demand in all energy sectors. This is translated in the REPowerEU Plan [4], 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

[1] IPCC definition of sufficiency : "Sufficiency policies are a set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries" [2]

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 [5]. In such a framework, overconsumption of energy can be reduced while still satisfying the basic energy needs necessary for a decent living [6]: most countries are above the final energy threshold necessary for decent living. It is noteworthy that some countries have initiated to implementation of sufficiency measures indirectly. In France, the speed limit on national roads was reduced in 2018 from 90 to 80 km/h, although road protection was the driving force behind this choice. The car-free city area in Ghent, Belgium, has grown by nearly 50%. According to a law passed in France in 2013, all workplace and retail lighting must be turned off at midnight [7]. These small steps can become a game-changing initiative if applied extensively and supported by policy initiatives.
Energy sufficiency has been considered in multiple studies in the recent past. Most of the studies use integrated assessment models (IAM) using scenario models to find trajectories for future years, considering the reduction in demand in various sectors. Examples of such modeling tools can be found in [5] and [8]. Energy sufficiency as a demand-side strategy is used in [9] considering what-if scenarios to assess the impact on the long-term sustainability goals. An IAM is also used in [10], where low-demand scenarios are defined. [11] 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 [12]. Modeling sufficiency endogenously using the MESSAGE modeling tool or exogenously using the EnergyPLAN energy modeling tool is used in [13]. The consideration of sufficiency, efficiency, and flexibility to decarbonize energy districts is used in [14]. The TIMES Ireland model is used in [15] to model reduced energy services demand and considers them as macro-economic drivers in the energy system model. Although energy sufficiency is considered as part of energy system models, the impact on annual costs, system adequacy and flexibility, and bottlenecks of the system such as curtailment and congestion are generally ignored, which is very important to consider in the long-term planning and short-term operation studies of energy systems.
In this study, the sector-coupled version of PyPSA-Eur is used to model sufficiency measures in future scenarios. The geographical scope is limited to five interconnected European countries, and 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.

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 scenario [16]. The core workflow of the modeling tool remains consistent with the original model, the sole modification being the substitution of demands. 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 proposed models, methods, and data are released with an open license to ensure transparency and reproducibility of the work [17]; they can be freely downloaded[2].

2.1. CLEVER Sufficiency Scenario

The demand data in this study is based on the CLEVER sufficiency scenario [16]. The scenario was built on a bottom-up approach considering sufficiency, efficiency, and integration of renewable energy. 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 in line with the 1.5℃ 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. In the residential and tertiary sectors, the sufficiency measures mainly encompass lower floor area, and lower energy consumption for space heating and hot water, while the efficiency measures include deep renovations and the use of efficient technologies for heating. 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 sector include low demands for future years with increased efficiency, fuel switch, and recycling. The energy sector includes increased efficiency of technologies and a high share of VRE technologies in the generation fleet.

Industry sector demand reduction in the CLEVER scenario is based on efficiency measures by considering 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

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

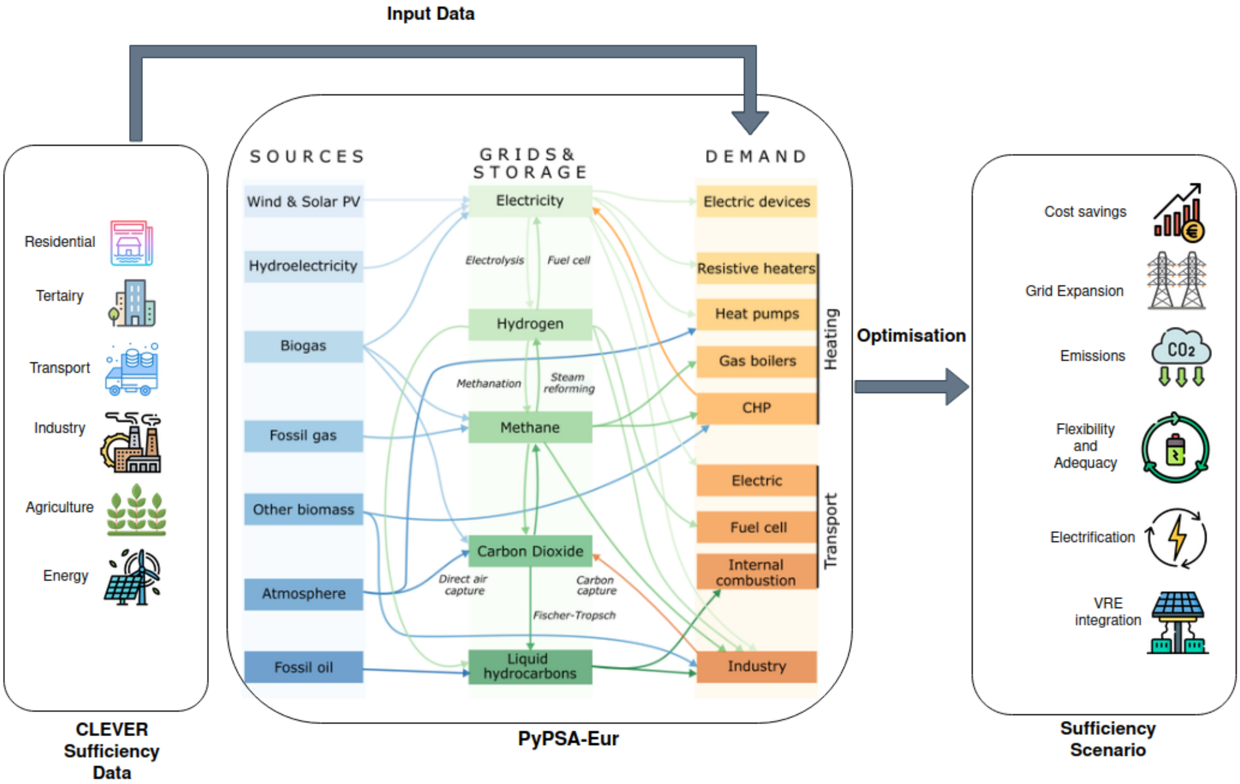

Figure 1: Methodology used in the study to include energy sufficiency (Adapted from [18])

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 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 [19]. In other sectors, sufficiency and efficiency assumptions include, for example, renovating current structures instead of building new ones, increased 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 [18], which is an open-source modeling tool, is used in this study. PyPSA-Eur is a generation and transmission expansion modeling framework for electricity-only and sector-coupled energy systems. 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 [20] 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 Danish Energy Agency [21]. 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 [22] and split into space and water heating. Hydrogen is used in industry to produce direct reduced iron and ammonia. It can also be utilized in stationary fuel cells and in the transport sector. OCGT, CCGT, gas boilers consume methane. Oil demand includes transport fuel, agriculture machinery, and naphtha in the chemical industry, while biomass potentials are taken from [23]. Energy demand for all transport sectors is retrieved from [24]. Industrial energy demand and CO2 emissions are distributed among different energy sectors, which include current and future mitigation strategies. Industrial demand is retrieved from [22], and fuel and process switching is imposed exogenously in the model. The power plant data in PyPSA-Eur is retrieved using the power plant matching library [25] 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

Table 1: Final energy consumption (FEC) per sector in CLEVER sufficiency scenario for year 2050 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	Value	Sufficiency measures	Efficiency measures
Residential	Total space heating	TWh	635.8	(1),(5)	(2),(3),(4)
Residential	Total Hot Water	TWh	126.8	(5)	(3)
Residential	Total Cooking	TWh	57.1	-	(2),(3)
Residential	Total FEC	TWh	993.4	(1),(5),(18)	(2),(3),(4)
Tertiary	Total FEC	TWh	546	(1),(5),(18)	(2),(3),(4)
Transport	FEC road mobility	TWh	353	(11),(15),(14),(13)	(16), (17)
Transport	FEC rail passenger	TWh	52	(11)	(2)
Transport	FEC air travel	TWh	90	(12)	-
Industry	FEC Steel	TWh	181.6	(6),(7)	(3),(8),(9),(10)
Industry	FEC Cement	TWh	31.7	(6),(7)	(3),(8),(9),(10)
Industry	FEC Glass	TWh	14.8	(6),(7)	(3),(9),(10)
Industry	FEC Chemical	TWh	304.3	(6)	-
Industry	FEC Non-Ferrous Metals	TWh	44.5	(6),(7)	(9),(10)
Industry	FEC Food, Beverage and Tobacco	TWh	117.1	(6)	(10)
Industry	FEC paper, pulp and printing	TWh	92.4	(6),(7)	(3),(9)
Agriculture	Total FEC	TWh	85	-	(9),(3)

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 [21].

Objective Function

The objective is to minimize the total annual costs of the system subject to constraints linked to the technologies, to the resources and to the CO2 emissions. The objective function of the linear programming (LP) problem is provided in Equation 2 [26].

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

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. The link specifies energy transport and conversion technologies such as electrolyzer, CHP, fuel-cell, 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. Links represent all the DC transmission lines and conversion technologies. $G_{i,r}$ 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 $f_{k,t}$.

The bounding constraints of the variables used in the problem formulation are shown in Table 2. $\underline{G}_{i,r}$ and $\overline{G}_{i,r}$ are the existing installed capacities and maximum potentials, while the value of $G_{i,r}$ is computed by the optimizer if the technology is considered as extendable. Similarly, the capacities of storage and link or conversion technologies are optimized and constrained. If the extendable option is activated, the solver optimizes the transmission line capacities constrained according to their upper and lower input limits set as parameters. The dispatch of generators and links is also constrained by availability factors due to weather (for VRE technologies) and must-run conditions. $g_{i,r,t}$ and $f_{k,t}$ are the optimized variables describing the operation of the system. Here, $\underline{g}_{i,r,t}$ and $\overline{g}_{i,r,t}$ are a given technology's minimum and maximum capacity factors at each time step. The energy levels $e_{i,s,t}$ at a given time step are constrained by the optimized store capacity $E_{i,s}$, while for hydro, charging and discharging variables are also used in the constraints represented by $h^{+}_{i,s,t}$ and $h^{-}_{i,s,t}$ respectively. Detailed information about the problem formulation can be found in [26].

The computed overnight capital costs are converted into net present costs by annualizing them over the eco-

Table 2: Constraints used in the problem formulation

Type	Constraint
Generation Capacity	$\underline{G}_{i,r} \leq G_{i,r} \leq \overline{G}_{i,r}$
Storage Capacity	$\underline{E}_{i,s} \leq E_{i,s} \leq \overline{E}_{i,s}$
Transmission Capacity	$\underline{P}_{\ell} \leq P_{\ell} \leq \overline{P}_{\ell}$
Link capacity	$\underline{F}_{k} \leq F_{k} \leq \overline{F}_{k}$
Generator Dispatch	$\underline{g}_{i,r,t} G_{i,r} \leq g_{i,r,t} \leq \overline{g}_{i,r,t} G_{i,r}$
Link Dispatch	$\underline{f}_{k,t} F_{k} \leq f_{k,t} \leq \overline{f}_{k,t} F_{k}$
Store Capacity	$0 \leq e_{i,s,t} \leq E_{i,s}$
Hydro Storage	$0 \leq h^{+}_{i,s,t} \leq H_{i,s}$
-	$0 \leq h^{-}_{i,s,t} \leq H_{i,s}$

nomic lifetime n. This conversion is achieved by applying the annuity factor a, which takes into account a discount rate r as shown in Equation 3.

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

3. Reference case, sufficiency, and BAU scenarios

The study considers a reference case for modelled countries representing the current energy systems based on 2020 values. There are two sufficiency scenarios and a business-as-usual or BAU scenario for comparative analysis, all considering net-zero energy systems by 2050 as shown in Figure 2.

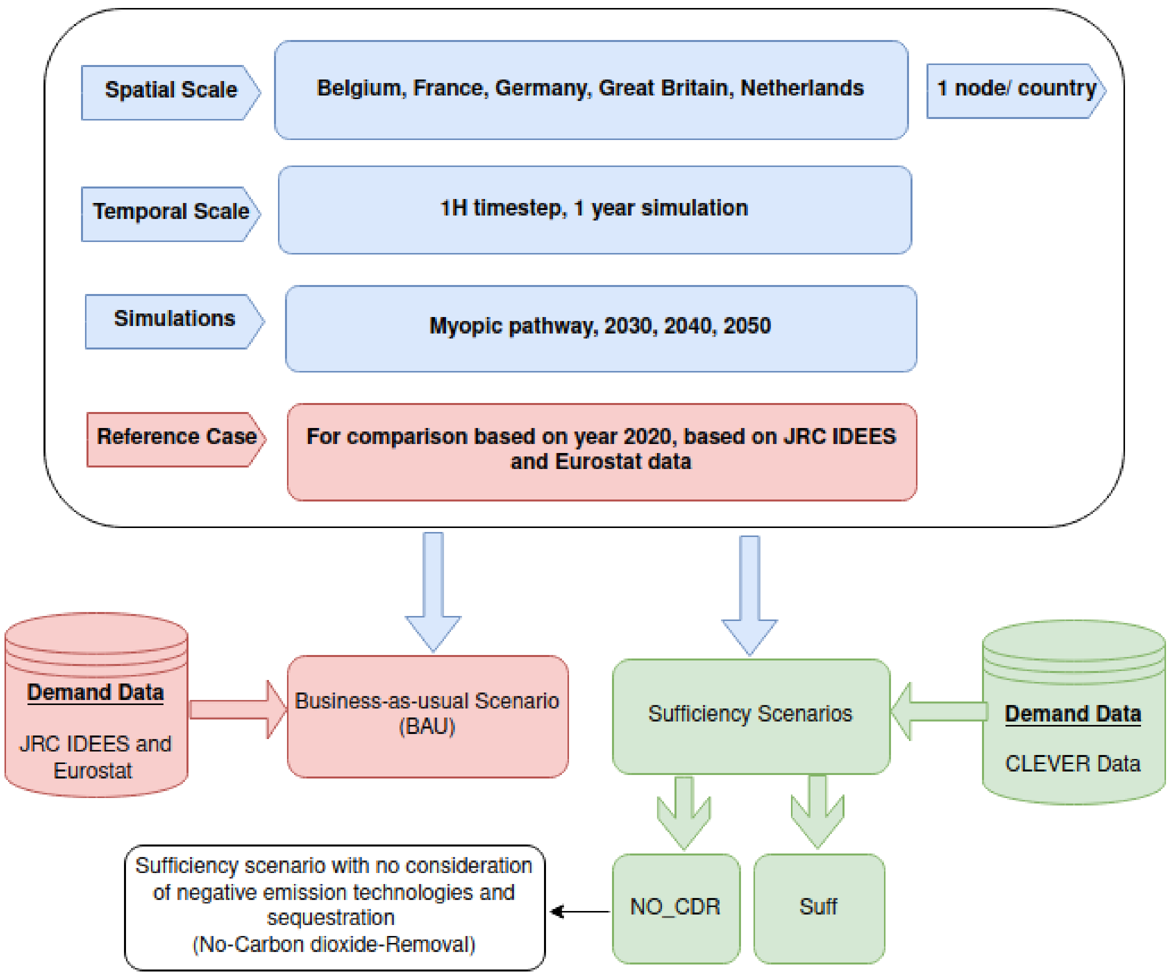

Figure 2: Scenarios considered in the study

The demands for all sectors in the reference case and BAU scenario use default PyPSA-Eur data retrieved from JRC-IDEES and Eurostat. The sufficiency scenarios demand data is based on the CLEVER scenario [16]. The spatial resolution of the initial study is based on five interconnected countries: Belgium, France, Germany, Netherlands, and Great Britain. All the countries are represented by a single node except for Great Britain, which is represented by two nodes with the inclusion of Northern Ireland. The temporal scale is one year with a 1-hour resolution. For the simulations, the myopic scenario building of PyPSA-Eur is used to analyse the progressive changes in the transition path.
The important parameters and constraints used in the study are presented in Figure 3. The suff scenario considers CCS options while NO-CDR considers no carbon removal options in the optimisation, only process emissions from industry are allowed to be captured and used for P-to-liquid utilisation. However, for the capacities of generation technologies, the assumed capacities in the CLEVER are not considered, except for a nuclear phase-out in 2050. Also, the negative emission technologies which are not part of the CLEVER scenario are also considered for only suff scenario, which include direct air capture (DAC) and bio energy carbon capture and sequestration (BECCS). The assumed values for land use, land-use change and forestry (LULUCF) are included in the sufficiency scenarios based on CLEVER assumptions by considering a carbon sink in the model. VRE technologies are only constrained by the maximum available capacities. There is also no constraint used for the maximum extension of transmission lines for both sufficiency and BAU scenarios. However, for reference case, the transmission line capacities are kept at current system values. For reference case there is no co2 constraint used while for BAU, suff and NO-CDR scenario a limit of -55% for 2030, -85% for 2040 and -100% for 2050 compared to carbon emissions in 1990 is considered.

Scenario	Reff	BAU			Suff			NO_CDR		
Technology Constraints	Current system	---			---			No CCS + process emissions CC		
Year	2020	2030	2040	2050	2030	2040	2050	2030	2040	2050
CO2 Budget (%)	--	-55	-85	-100	-55	-85	-100	-55	-85	-100
Shipping methanol Share (%)	--	30	70	100	30	70	100	30	70	100
LULUCF (Mtons)	55.8	55.8	55.8	55.8	81.3	90.8	95	81.3	90.8	95
Transmission line expansion	0	--	--	--	--	--	--	--	--	--

Figure 3: Parameters and constraints used for considered scenarios

Figure 4 presents an overview of energy demands across various sectors in the reference case, BAU, and sufficiency scenarios. In the BAU scenario, electricity demand gradually increases until 2050 due to the growth of the electric vehicle fleet in the transport sector and increased electrification in the industrial sector. In both sufficiency scenarios, electricity demand experiences a slight increase by 2050 compared to the reference scenario. The distribution sector sees a gradual decrease in electricity use due to sufficiency measures, including reduced electricity consumption per capita. Increased electrification is noticeable in the residential and tertiary sectors electrified heat demands, while electricity demand in the industrial sector rises due to increased electrification in various industrial sectors. Even with an 85% EV share, the transport sector's demand decreases in the sufficiency scenarios due to factors like reduced per capita passenger- kilometres. An essential distinction arises in energy requirements for oil and heat. In the heating sector, sufficiency measures such as lowered temperatures for space heating and reduced energy consumption for domestic hot water lead to decreased usage. Similarly, the sufficiency scenarios show a gradual decline in aviation fuel consumption within the oil sector, driven by fewer passenger kilometers and a shift towards rail travel. Non-energy demand in the BAU scenario remains constant, considering the use of oil for feedstock production. In both sufficiency scenarios, a significant portion of non-energy demand is replaced by hydrogen. When considering sufficiency measures across all modeled sectors, the combined energy demand for Belgium, France, Germany, Great Britain, and the Netherlands totals 3656 TWh by 2050. In comparison, the reference case indicates a total energy demand of 7564 TWh, while the BAU scenario indicates a demand of 6061 TWh. This underscores the significant impact of sufficiency measures in reducing energy demands and promoting environmental sustainability.

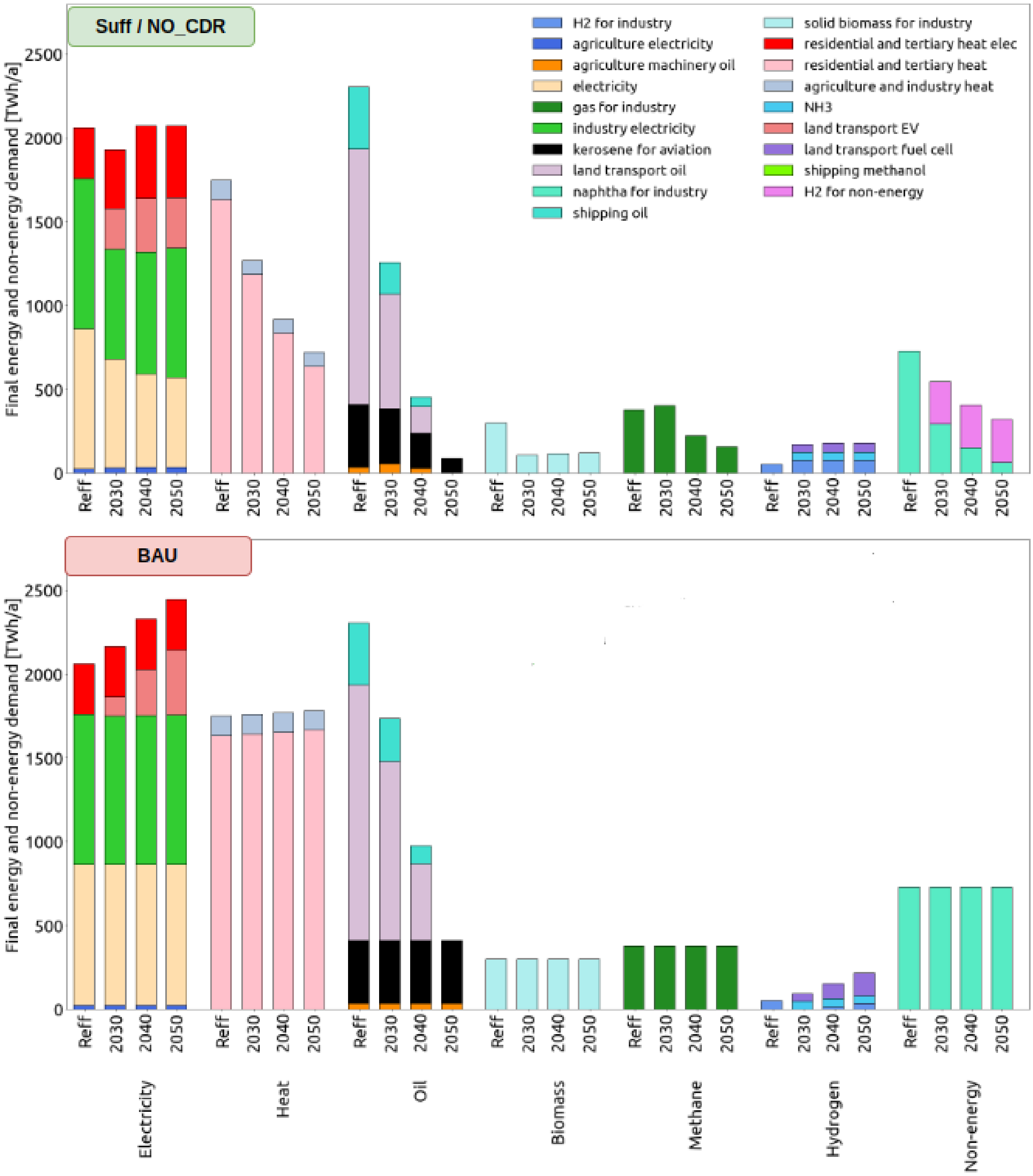

Figure 4: Sectoral demands per energy carrier for BAU and sufficiency scenarios

4. Results and Discussion

This section presents the findings and analysis of the sufficiency scenario in comparison to the BAU scenario. Figure 5 illustrates the expansion of the grid and the total installed capacities for five simulated countries. The reference case displays the historical installed capacities in 2020, considering the existing grid connections between these 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 reference case, the combined transmission line capacities for both AC and DC transmission lines are 57 GW. In the BAU scenario, the total transmission line capacities for AC and DC lines from the transition path from 2030 to 2050 are 185 GW. For the Suff and NO-CDR scenarios, these capacities are 107 GW and 112 GW, respectively. 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 wind are 1577 GW, 945 GW, and 134 GW, respectively. In comparison, the suff scenario requires lower capacities of 937 GW, 553 GW, and 68 GW for solar, onshore wind, and offshore wind while for NO-CDR the capacities for these VRE technologies are 964 GW, 578 GW and 68 GW respectively. Regarding flexibility needs in terms of hydrogen storage, the BAU scenario necessitates 60 TWh, whereas the suff requires a reduced capacity of 22 TWh and NO-CDR requires 32 TWh. In addition, the sufficiency scenario exhibits significantly lower requirements for P2X (Power-to-X) technologies compared to the BAU scenario. DAC capacities are 9286 ton/h for the BAU, and suff scenario requires no DAC capacity. These results emphasize the substantial impact that demand reduction can have on future energy systems.

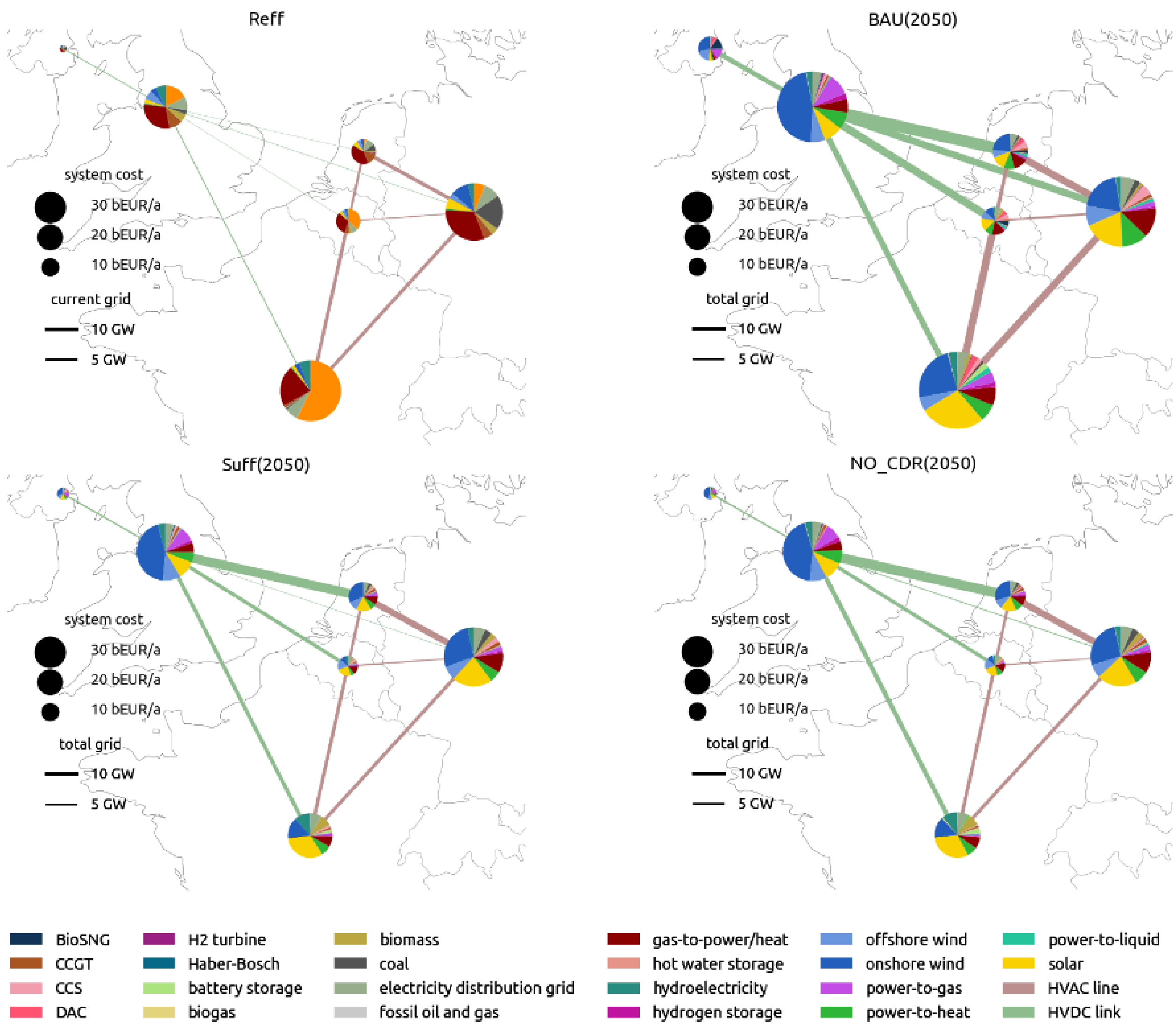

Figure 5: Grid expansion and installed capacities per technology for considered scenarios

Figure 6 provides a visual representation of power dispatch during a summer week and heat dispatch during a winter week for the Suff and BAU scenarios in the year 2050. In this future scenario, Combined Cycle Gas Turbine (CCGT) power generation primarily serves as a flexibility option due to the increasing use of Variable Renewable Energy (VRE) technologies. The BAU scenario experiences higher curtailment compared to the Sufficiency scenario. This is because the BAU scenario relies on larger VRE capacities to meet all demands, whereas the Sufficiency scenario implements measures to reduce overall demands, leading to more efficient resource utilization. The power dispatch graph highlights the impact of sufficiency measures on the capacity requirements of different generation technologies. This emphasizes that focusing solely on efficiency and VRE integration may not be sufficient for highly efficient energy systems in the future. Additionally, Figure 6 illustrates the heat dispatch during the first week of February. The impact of sufficiency measures on heat demand reduction is evident when comparing it with the BAU scenario. The power-to-heat dispatch also shows that sufficiency measures, combined with efficiency improvements, can reduce the extra burden on electricity networks during winter.

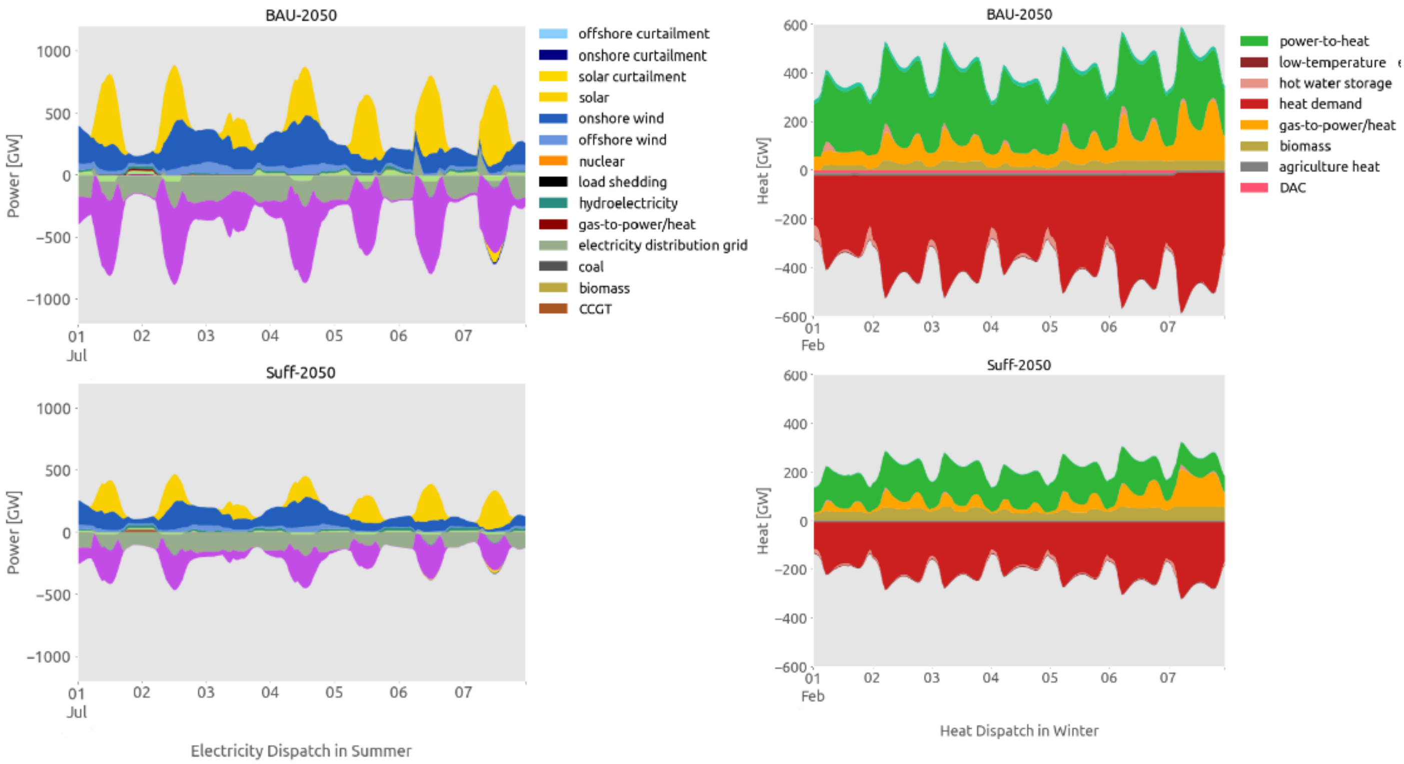

Figure 6: Power and Heat Dispatch

Figure 7 displays the total annualized investments in various technologies, including VRE, storage, transmission lines, gas pipelines, and P2X technologies, for the suff, NO-CDR, and BAU scenarios. In the suff and NO-CDR scenario, the annual investments in hydrogen storage and pipelines amount to 1.84 billion €/y and 2.1 billion €/y, respectively compared to 3.91 billion €/y in BAU scenario. For transmission lines and gas pipelines, the annual investments are 3.85 billion €/y and 3.94 billion €/y respectively for suff and NO-CDR scenarios while BAU scenario requires 6 billion €/y. Regarding battery storage, the BAU scenario also entails higher investment costs compared to both sufficiency scenarios, amounting to 1.65 billion €/y. Similarly, the investments in P2X and VRE technologies are significantly lower in the sufficiency scenarios compared to the BAU scenario. In summary, Figure 7 illustrates that the sufficiency scenarios requires less investment in P2X and VRE technologies compared to the BAU scenario.

As indicated in Figure 8, the total annual costs for the modelled countries in the reference case amount to 501 billion €/y. However, for the suff, NO-CDR and BAU scenarios, these costs are reduced to 271 billion €/y, 275 billion €/y and 430 billion €/y, respectively. In the NO-CDR scenario, as there is no consideration of CCS technologies, the total system costs are a little bit higher than in the suff scenario due to more investment in VRE, flexibility and storage technologies. The lower annual costs in the sufficiency scenarios are attributed to the implementation of 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.

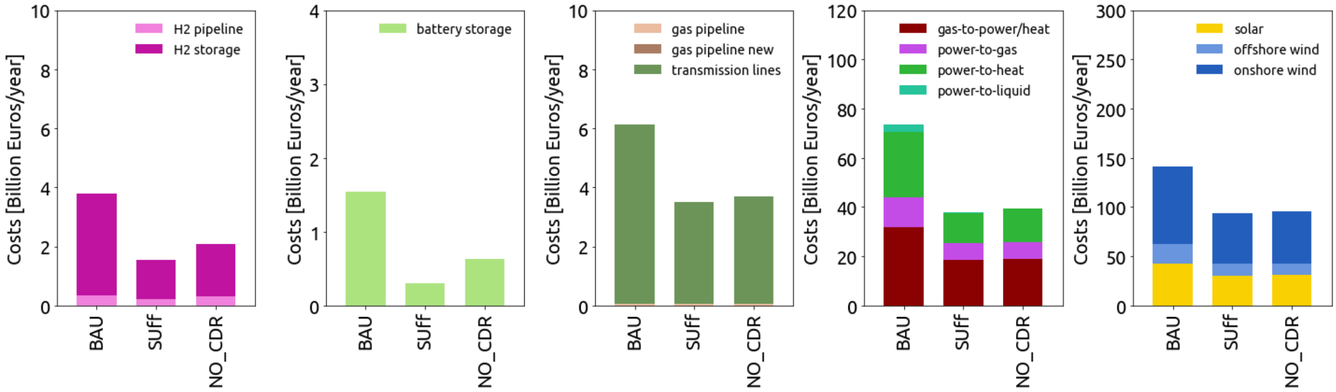

Figure 7: Investments in VRE and flexibility technologies

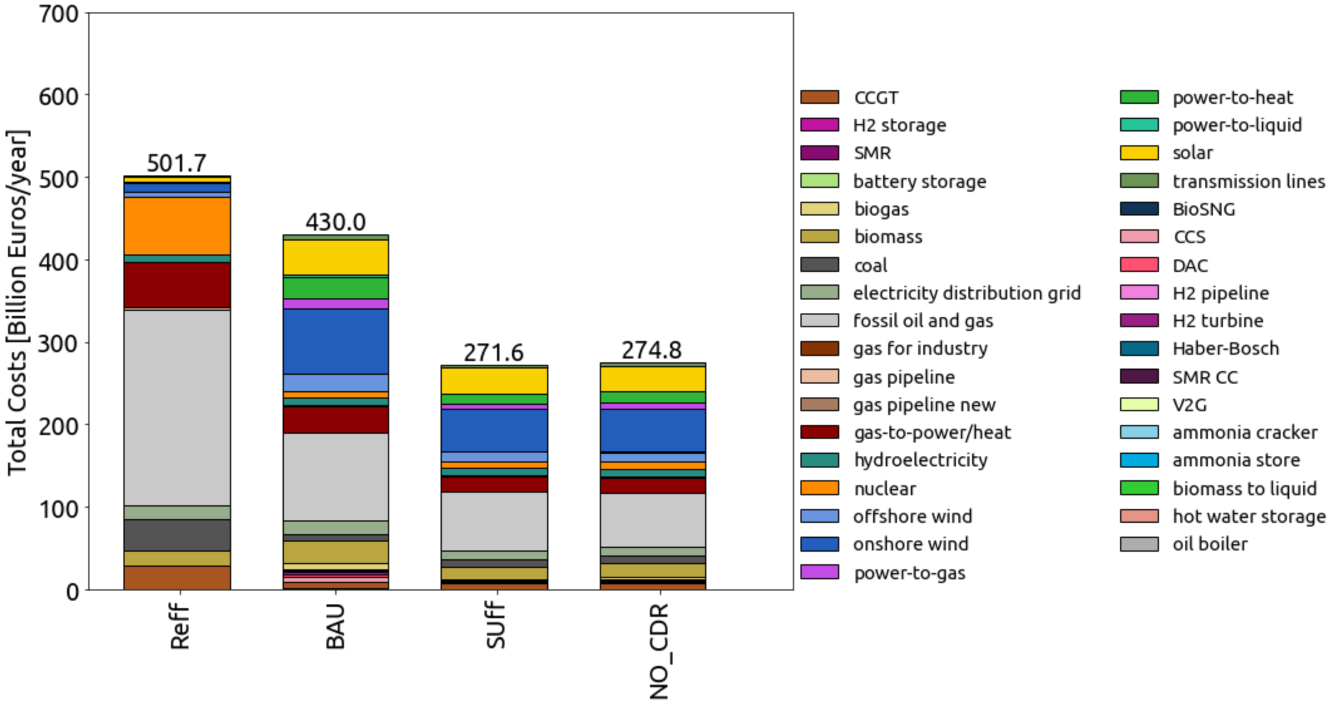

Figure 8: Total annualized costs in the reference case, sufficiency, and BAU scenarios

Figure 9 illustrates the Sankey diagram for the NO-CDR scenario in 2050. The diagram showcases the energy flow and contributions from various technologies. In terms of electricity generation, wind onshore and offshore technologies are the main contributors, providing 1912 TWh of energy to the grid. They are followed by solar energy, contributing 546 TWh. To ensure grid flexibility, CCGT and OCGT power plants generate 23 TWh. In the NO-CDR scenario, 731 TWh of electricity is consumed by electrolyzers, which produce hydrogen. This hydrogen is then either utilized directly by demands or transformed into methanol and liquid fuels through the Fischer-Tropsch process. To support the grid and store energy, vehicle-to-grid (V2G) systems and battery storage contribute 55.5 TWh and 64.5 TWh of energy respectively. In the heating sector, biomass and fossil gas-based Combined Heat and Power (CHP) plants generate 76 TWh. However, heat pumps emerge as the leading technology, producing 301 TWh to meet heating demands.

Figure 10 shows the CO2 Sankey diagram showcasing the CO2 emissions flow within a net-zero system in the NO-CDR scenario. The diagram highlights the sources of CO2 emissions, as well as the processes involved in their capture and storage. Among the contributors to CO2 emissions, fossil gas plays a significant role, accounting for 27.6 Mton/y. These emissions stem from industrial processes, CCGT and various boiler technologies. The shipping sector also contributes to CO2 emissions, with 24.6 Mton/y originating from methanol usage. Additionally, 57 Mton/y of CO2 emissions result from industrial processes. To reduce these emissions, different technologies are utilized. Process emissions, totaling 53.1 Mtons, are captured through post-process carbon capture techniques, encompassing the cement industry and heat processes in the industrial sector.

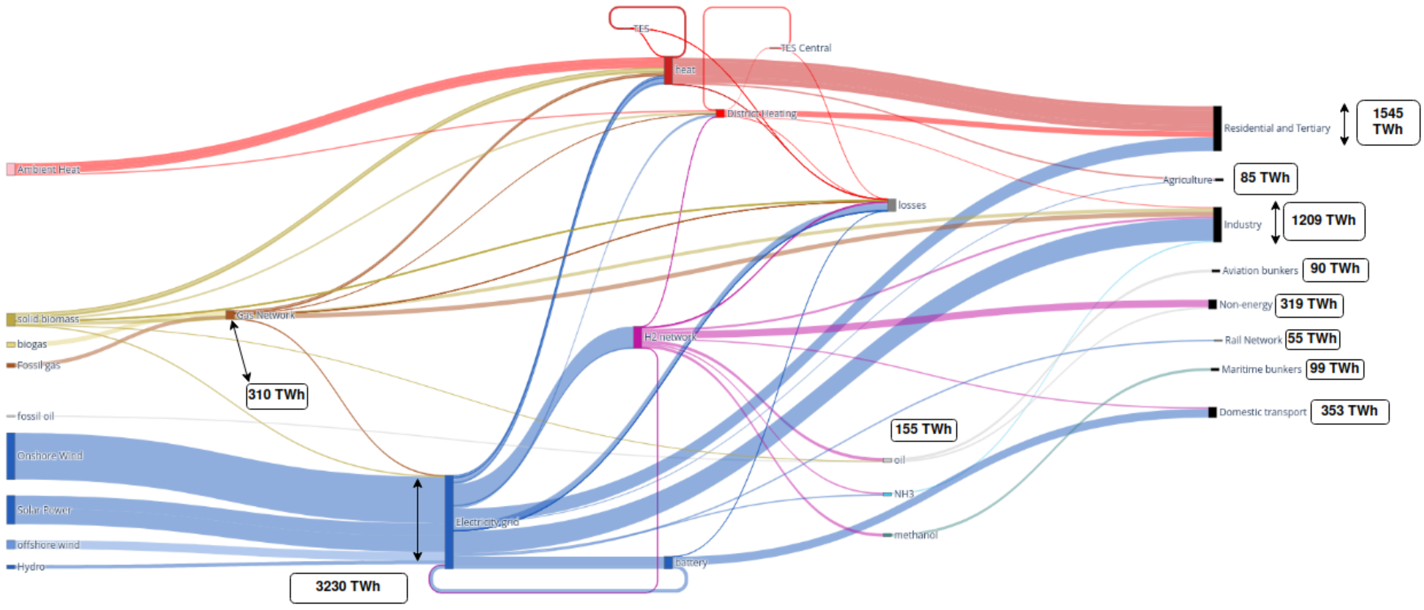

Figure 9: Sankey diagram of NO-CDR scenario for year 2050

The diagram also indicates that 95 Mton/y of CO2 are stored in LULUCF sector. These values align with the assumptions made in the CLEVER sufficiency scenario, highlighting the role of forests in CO2 storage.

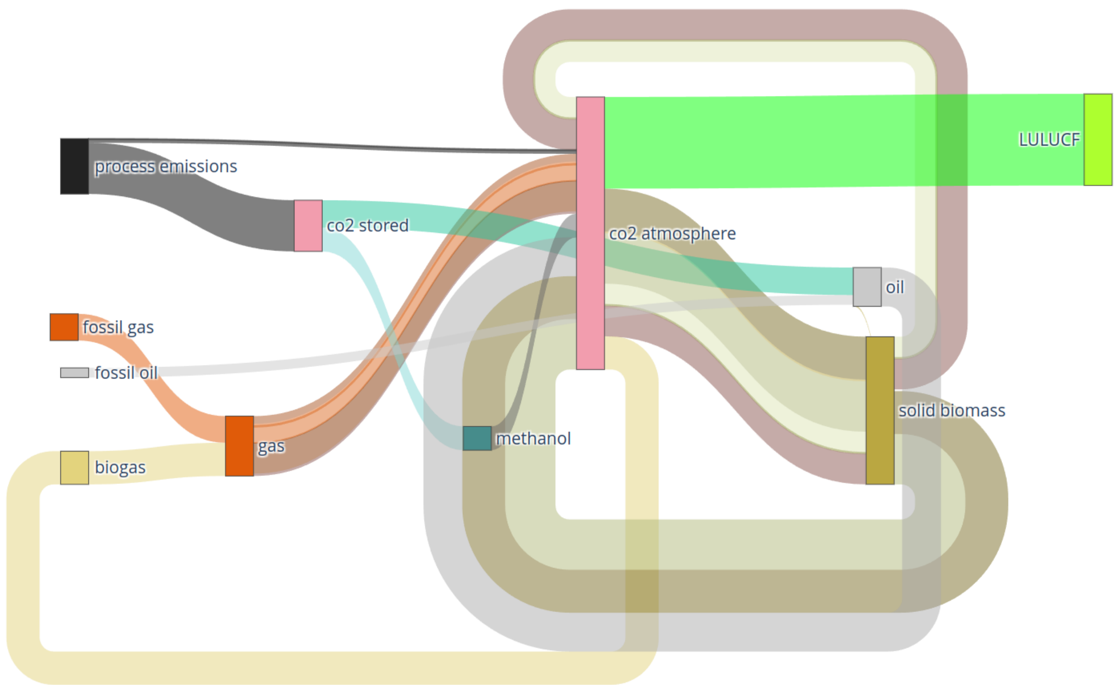

Figure 10: CO2 Sankey diagram for NO-CDR scenario for year 2050

5. 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. By incorporating energy sufficiency considerations, a more comprehensive approach to sustainable energy planning can be achieved.

The results indicate that by the implementation of sufficiency measures and the associated demand reduction it is possible to achieve the 1.5C° climate target without the CCS and nuclear technologies. The results also show that implementing energy sufficiency measures leads to significant cost savings by reducing energy demand across various energy sectors. This 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. The results also indicate that 100% energy independence can be achieved for the modelled countries by the implication of sufficiency measures.

Future improvements to the model include adding scenarios with no transmission line expansion to evaluate further the impact of sufficiency in net zero emissions and grid expansion. Sensitivity analyses to quantify the impact of uncertain parameters and cost-benefit analyses to have a clearer view of cost savings and economic feasibility are also part of future improvements. Future improvements also include having a detailed analysis of the adequacy of the system. The next step includes considering all EU-27 + UK in the study to get a complete picture on a regional level of how energy sufficiency impacts the integration of renewable energy technologies, carbon emissions, the adequacy and flexibility of the system, and the trajectory of energy carriers that can result in net-zero economies in the future.

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