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Primary Power Analysis of a Global Electrification Scenario

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Abstract: Electrification scenarios dominate most plans to decarbonize the global economy and slow down the unfolding of climate change. In this work, we evaluate from a primary power perspective the impacts of electrifying the power, transport, residential and commercial sectors of the economy. We also investigate the electrification of industrial intense heat processes. Our analysis shows that, in terms of primary power, electrification can result in significant savings of up to 28% of final power use. However, actual savings depend on the sources of electricity used. For intense heat processes, these savings are very sensitive to the electricity sources, and losses of over 70% of primary power can occur during the conversion of heat to electricity and back to heat. Overall, this study highlights the potential benefits and limitations of electrification as a tool for reducing primary power consumption and transitioning to a more sustainable energy system.

Keywords: electrification; power sector; transportation; intense heat processes; sustainable development; energy transition

1. Introduction

The available carbon budget has already been imperiled, while global climate change increasingly dominates our lives [1–3]. Urgent transformation of global energy flows is required to address this insidious polycrisis.

The current dominant paradigm seems to be affordable clean energy and systems that rely on a surplus of renewable energy to justify their low efficiency. However, these systems risk leading societies astray, away from a sustainable future [4,5].

As the vital energy transition unfolds, it presents a unique opportunity to study the major sustainability challenges in real-time [6]. These challenges are complex and involve multiple sectors of our global society. Current infrastructure is rigid, follows a "winners-take-all" approach, and results from a short-term profit-focused vision [7]. Even worse, it is a common practice to ignore the inconvenient environmental, economic, and social *externalities* produced by the current economy [8,9].

The preferred goal towards the decarbonization of global energy systems requires a widespread adoption of renewable power sources. However, blindly pursuing this goal can lead to unachievable scenarios, such as assuming the deployment of more than 50 TW of solar photovoltaics by 2050 [10,11]. Tackling this complex problem requires breaking it down into parts. An initial target is to shut down the most polluting power sources, such as coal [12]. Additionally, intermediate steps, such as the deployment of natural gas, can confer robustness on the transition but could also delay complete transition [13]. Adoption of renewables requires a flexible system [14], but creating and sustaining a completely new power system can be jeopardized by the availability of raw materials [15–18].

Electrification may provide a solution to achieve deep decarbonization and fight climate change [19]. A power transition towards an electrified future driven by renewable sources is very much on the global agenda [4,16,20,21]. Numerous projections towards a sustainable energy system powered by renewables are available [22–24], and different paths

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can be adopted to achieve the same goal [25]. An energy transition changes the dynamics of economic and political interactions at all levels [21,26,27]. However, it is still debatable whether complete electrification is feasible or the best way to tackle current challenges. The hard truth is that we need fossil fuels to subsidize the energy transition [28].

The quantification of power measurements is a complex process that can strongly bias the perceived benefits of electrification, as noted by Giampietro and Sorman [29]. Attempts to express power measurements as a single unit can introduce bias, and Kraan et al. [30] suggest using final power consumption as an alternative to reduce this bias. However, primary energy or power analysis remains an essential tool for assessing the viability of an energy system [29]. *Primary energy per unit time*, or primary power, refers to the energy that enters society before any conversion process occurs. More details on the methods used to quantify primary energy can be found in Section S1 of the Supplementary Information.

Decarbonization is a global task that presents challenges for both developed and developing nations [31]. Waiting for an innovation that decouples GDP and CO_2 emissions is not a viable solution [32], and implementing the available technology can be both effective and disruptive [33].

With this background in mind, we evaluate the alignment between existing political will and the attainable extent of global energy system decarbonization by 2050. We focus on assessing the impacts of our energy transition scenario on the power, transportation, commerce, and residential sectors. Furthermore, we explore the constraints and complexities surrounding the electrification of high-temperature processes. To meet these objectives, we quantify both the nominal power capacity required to facilitate the decarbonization and the tangible energy savings achievable through electrification.

2. Materials and Methods

The presented methodology defines feasible levels of decarbonization by 2050. Our approach, in accordance with the framework described by Krumdieck [34], is to evaluate transition scenarios by extrapolating historical trends to discern future outcomes constrained by physics and economics. Our robust approach begins with the foundational unit of primary power and identifies viable technological substitutions across the power, transportation, commerce, and residential sectors. These primary power replacements are then evaluated for their potential efficiency improvements and quantifiable power savings.

The 2018 data for the power baseline precede the COVID-19 pandemic, and therefore represent a *business as usual* scenario. The 2020–2022 data are pandemic-influenced, and introduce bias. For reference, between 2018 and 2022, solar and wind energy increased their share slightly, while nuclear and hydro decreased. Meanwhile, the share of fossil fuels reduced from 84% to 83% [35]. This marginal shift is expected to have a negligible impact on the presented outcomes.

2.1. Primary Energy

We estimate the primary energy consumed to generate electricity using heat efficiency. Heat efficiency gives the ratio of how much primary energy is consumed to produce electricity. The EIA [36] provides the gross heat content of electricity for power plants in the United States (US). The heat efficiency can be calculated as [37]:

$$\text{Heat Efficiency} = \frac{\text{Heat Content of Electricity}}{\text{Heat Rate}} \quad (1)$$

The heat content of electricity is 3412 Btu/kWh, while the heat rate is the amount of heat (gross heat content or high heat value) used by a power plant to produce one kWh of electricity, usually expressed in Btu kWh^{-1}. In this study, the heat efficiency values are adopted from the US power plants [38–40].

Heat efficiency is important because it allows us to track the primary energy consumed to generate electricity. Once we know the heat efficiency and the electricity generated, the primary energy equivalent can be calculated as [37]:

$$\text{Primary Energy} = \frac{\text{Net Electricity Generation}}{\text{Heat Efficiency}} \quad (2)$$

Net electricity generation excludes the energy consumed by the power plant [36].

2.2. Technology Replacement

2.2.1. Power Sector

A literature review covering power plants under construction, planned and forecasted by agencies and governments at a global and national level, was conducted to estimate the potential resources for power generation for each primary resource. From the information available in the literature and the current deployment of technologies, we obtained a global projection for 2050. From a logistic fitting, based on the works of Hubbert [41], the projection of the installed capacity was estimated as:

$$\text{Capacity (Year)} = \frac{\text{Max Capacity}}{1 + e^{-\text{Growth Rate (Year - Midpoint Year)}}} \quad (3)$$

The midpoint in Equation (3) refers to the year that half of the nominal capacity is predicted to have been installed.

Detailed information on the current installed capacity, installation under construction, plan, forecasts by agencies/governments, and our projections for 2050 are available in Section S2 of the Supplementary Information. For each resource, the following information was considered in our projection:

- **Biomass:** EIA [42] points out that the electric sector mainly uses wood and biomass-derived waste (“waste is a human concept because nature knows of no waste [43]).” to produce electricity. An important observation is that biomass “waste” includes energy crops, which are tree plantations, not waste [44]. Forecasts from IRENA [45] envision 384 GW, IEA [46] 732 GW. Our projection starts from a logistic fit from the currently installed capacity [36] and assumes that the equivalent of 20% of the industrial forest is destined to be fuel-wood. The current area dedicated to industrial forestry is 293 Mha [47].
- **Geothermal:** Currently, there are approximately 12 GW of installed capacity [36,48]. World Bank [49] estimates a potential of 80 GW. Through the adoption of more advanced techniques, such as enhanced geothermal systems, the installed capacity might reach up to 256 GW [50]. A current market outlook by the IEA shows that major geothermal power expansion has occurred in several countries (Indonesia, Kenya, and Turkey) [51]. From the plans and projections by the leading countries, i.e., Indonesia, Kenya, Mexico, New Zealand, Philippines, Turkey, and the US, we could expect a doubling in the nominal capacity installed in the next ten years [52–58]. Our account excludes geothermal for direct use because this technology does not generate electricity. However, direct use of geothermal has been targeted by many countries, such as China [59]. For geothermal, there is a lack of reliable information and certainty on long-term projections. However, from the current capacity and political scenario, we expect an expansion trend to continue through 2050, and a nominal capacity of 50 GW might be installed.
- **Hydro:** Under-construction, planned, and forecasted capacities for hydropower were investigated. The under-construction and planned capacities are currently 688 GW [60]. Recent data show that the under-construction capacity is 233 GW, and the planned capacity is 491 GW [61]. It is important to mention that these data do not include hydropower plants smaller than 1 MW, and there is a proliferation of small hydropower plants. Therefore, the actual potential could be in the range of 230 GW [62,63]. Mini-hydropower plants (up to 1 MW) and micro-hydropower plants

(up to 100 kW), usually contribute to the regional or national grids [64]. Hydropower plants below 1 MW are not commonly reported, which makes it hard to make a good estimate of the power capacity of this category [60]. Overall, it is estimated that the technically feasible hydropower capacity to be installed could be up to 4000 GW [65]. The climate deregulation-related mega-droughts on all continents and the fast melting glaciers in the Himalayas can upend these hydropower expansion plans.

- **Nuclear:** The installed, under-construction, planned, and forecasted capacity for nuclear power plants was investigated. The current nominal capacity under construction is 53 GW [66,67]. The planned capacity to be added is 104.6 GW. Furthermore, an additional 225.3 GW has been proposed [68]. It is important to emphasize that there is a growing number of countries classified as "emerging countries" that are interested in installing nuclear power. These countries are initially studying the feasibility and identifying partnerships to provide the technology (mainly with China and Russia) [69]. Nuclear power represents a great alternative to supply the power needs with the requirement of a carbon-free economy. It will not be surprising if the installed capacity significantly exceeds the more optimistic forecast by 2050.
- **Solar:** Installed, under-construction, and forecasted solar power capacities were investigated. Solar photovoltaic power generation is growing fast and is aligned with sustainable development goals [70]. The nominal capacity installed has been expanding at a rate close to 100 GW/yr [71]. Major projects currently under construction have a nominal capacity of 160 GW [72]. As solar photovoltaic expansion is still at an early stage, the data can fit any model, from the most conservative to an overly ambitious one. We observe that in the 2018 forecast IEA [73], 5000 GW was foreseen by 2050; however, in 2021, the IEA [74] predicted 15,000 GW by 2050. The latest estimate is three times the previous estimate. This difference is not associated with a significant array of deployment or manufacturing capacity changes. Still, it is a reaction to the pressing need for a power transition to avoid the collapse of our civilization due to climate change [3,4,16]. However, a forecast unbounded by reality can do more harm than benefit because it is selling a solution that is unlikely to be achieved and prevents the implementation of more effective measures [5]. From the current installed capacity and deployment rates, we envision 3000 GW of solar photovoltaics by 2050, keeping the current trends in deployment and avoiding overly ambitious estimates.
- **Wind:** The installed, under-construction, planned, and forecasted capacity for wind power was investigated. According to the IEA [75,76], more effort is needed to deploy onshore and offshore wind power. In the last twenty years, the expansion of wind power has been close to 50 GW/yr [77]. Major projects, under construction and planned, have a nominal capacity of 350 GW [78]. Similar to solar photovoltaics, the urgent need for a power transition is reflected in these forecasts. In 2018, there was an IEA report [79] forecasted 3000 GW by 2050; in the most recent report [74], this estimate jumped to 8500 GW. Besides the clear need for the power transition, no justifications or changes support this increment of the forecasted values. From the current capacity and deployment rates, we expect an additional 2000 GW of wind power in 2050, which can be considered an ambitious target based on the current trends.

2.2.2. Transport Sector

We considered the full replacement of the internal combustion engine (ICE) with electric vehicles (EV) or fuel cell vehicles (H_2). Data for ICE were based on eight models from the top ten most sold vehicles in 2018 [80]. The estimation of energy efficiency was a weighted mean based on the number of vehicles sold and the average fuel consumption of the respective model [81,82]. For EVs, the six most popular 2020 models were considered [83]. Energy efficiency of the transportation sector was a weighted mean based on the number of vehicles sold [82,84]. For H_2 vehicles, 3 models were considered. The energy efficiency was based on the arithmetic mean [82,85].

From the weighted mean, a correction on energy consumption was applied to EV and H_2. The typical range for charging efficiency in electric vehicles (EVs) is between 80% to 95% [86–88], with our study assuming a conservative estimate of 90%, which means the previous average was divided by this factor. For H_2, we assumed a high 70% efficiency of the electrolysis process [89,90]. The energy consumption considered in this study was 842 Wh/km for ICE, 180 Wh/km for EV, and 448 Wh/km for H_2. Supplementary Information Table S3 shows the reference data for the passenger vehicles we have considered.

2.2.3. Commerce and Residential Sector

The commerce and residential sectors have similar energy consumption profiles. The current energy consumption was gathered from IEA [91,92,93], IEA and UNEP [94], EIA [95]. We considered cooking, space, and water heating. We evaluated various technologies and their efficiencies (see Supplementary Information Section S3).

- **Cooking:** The technologies/fuels considered and their average performance for stove cooking were electric (55%), induction (77%), LPG (44%), wood (29%) and pellets (33%) [96–101]. Approximately 2.5 billion people rely on biomass fuels (charcoal, wood, agricultural residuals, and animal manure) for cooking [102]. The three-stone stove is the prevailing technology [103], and is wood powered, and it has a very low thermal efficiency ∼10% [104].
- **Water Heating:** The fuels/technologies considered and their average performance were natural gas (66%), electric (90%), solar (60%), and heat pumps (400%, COP equal 4) [105–115]. Heat pumps for water heating can have different performances and specifications depending on the country [107]. A study of the coefficient of performance (COP) under different weather conditions could vary from 3.3 to 4.7 [105]. A complete review gathered a range of COP data for the different heat pump arrangements (ground source, air source, solar-assisted, abd gas engine driven), where the COP can vary from 1.8 to 6 [116]. For typical working conditions, the seasonal COP can vary from 2.6 to 5.6 [106]. Dependence on water flow can reduce the COP to 2.7–4.3 [108]. For multi-functional applications, COP can vary from 2 to 4 [117]. In general, electric heaters have a better performance than gas heaters [115]. For systems with tank storage, the energy factor can describe their performance more accurately [109,110].
- **Space Heating:** The main technologies for space heating are pellets (71%), natural gas (87%), diesel (82%), electricity (98%), and heat pumps (290%, COP equal 2.9) [118–122]. The efficiency of each technology varies significantly due to the operational principles involved [119–123].

The information on the precise mix of technologies in place is lacking. Thus, the current performance is calculated from fuel consumption to estimate the energy savings, assuming an average energy efficiency conversion. The replacement scenario relies on a combination of fuel/technology information to assess performance. The savings are proportional to the gain in efficiency from the current to the electrified scenario.

For cooking, the current scenario based on the WHO [124] data can be approximated to 50% LPG, 45% wood, and 5% electric. The proposed electrified scenario considers 50% electric and 50% induction stoves.

For heating, the actual energy consumption worldwide is 42% natural gas, 15% oil, 6% coal, 11% district heating, 11% renewables, and 15% electricity [93]. However, these data include all heating activities. A better breakdown is available for the US, where the housing sector was surveyed in detail. In the US case, the main energy sources are natural gas and electricity [125].

In the case of space heating, adjusting energy consumption to mapped technologies, we assumed that the current scenario was composed of 15% oil, 20% electricity, 55% natural gas, and 15% pellets. The electrified scenario assumes 50% electric heaters and 50% heat pumps; the efficiency gain is not applied to direct heat inputs (e.g., district heating). For water heating, the current scenario assumes 30% of electricity and 70% of natural gas; this assumption strongly reflects the US usage; see EIA [125]. The electrified scenario consists of 50% electric, 30% heat pumps, and 20% solar devices.

3. Results and Discussion

We present an initial analysis of the system in place, followed by the scenarios of the electrification of the sectors we considered. The results and analysis are presented in a manner that provides an easy understanding of the impacts or biases that are inserted when different primary or final power sources are considered.

3.1. Systems in Place

The initial step is to obtain a clear understanding of the global power consumption. Figure 1 shows the primary power balance of current systems in place. This balance indicates that the actual resources that are exploited to run our economy are 600 EJ/yr, of which 25% is lost in the initial conversion/processing and 5% is consumed during these steps.

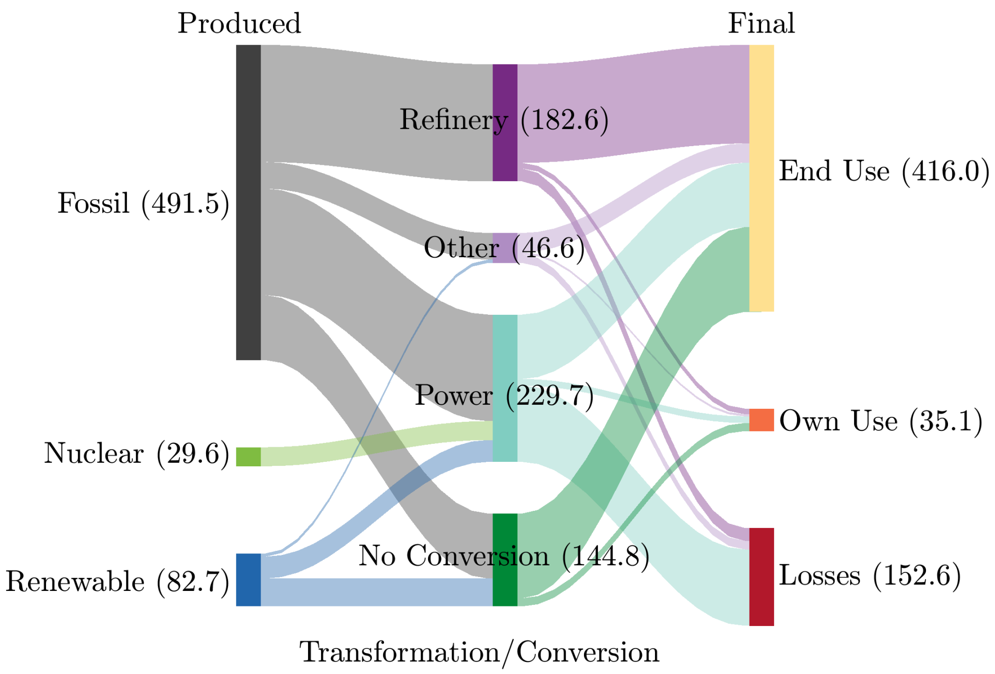


Figure 1. Global primary power. The right side of the figure lists the primary power sources, while the middle column specifies the transformations/conversions that the fuels undergo before reaching their final use. Primary power balance accounts for the losses from conversions before final uses. The units are EJ/yr. The data from IEA [92] are plotted using a modified version of [32].

The second step is to understand the final uses of primary power. Figure 2 illustrates the primary sources powering our needs. The final use of primary power ignores the losses from conversion, refining, and processing that are included in the power balance. Fossil fuels represent 67% of our final power use and oil products alone correspond to 40%. Currently, only 20% of our final power consumption is in the form of electricity; thus, in theory, there is room for improvement. Figure 2 disguises the power sector. We only show the primary power contained in electricity. From a primary power perspective, the power sector is three times bigger than electricity (see Figure 3).

Understanding these power flows is a fundamental step before proposing any power transition scenario. We could interpret the IEA definitions in a more intuitive way as framed by Gates [126], who refers to the industry sector as “how we make things” and the transport sector as “how we move things”. The “others” sector can be interpreted as miscellaneous, while non-energy is the use of energy commodities as raw materials.

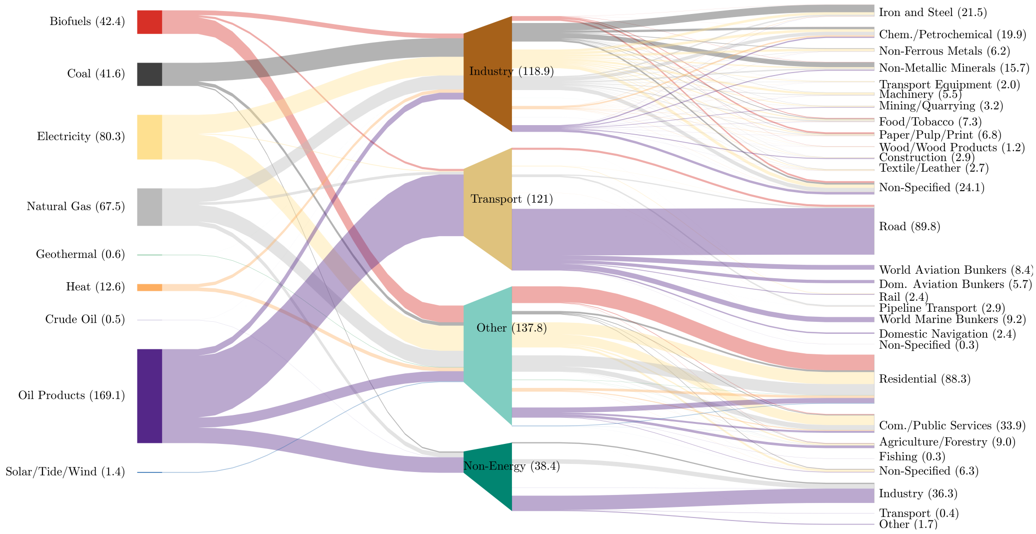


Figure 2. Final uses of net primary power. This Sankey diagram shows the net flows of energy from primary sources to final uses in society, neglecting the losses from primary conversion/transformation. The flows are a detailed version of the 416 EJ of *End Use* reported in Figure 1. The units are EJ/yr, and the reference year is 2018. Data from IEA [92] are plotted with a modified version of [32].

Figure 2 identifies the big consumers. The road and residential sectors are the biggest power consumers, at 40% of the total power consumption. Thus, widespread improvements in these sectors can have a huge impact. The industry sector has three main power consumers—iron and steel, chemicals and petrochemicals, and non-metallic minerals that account for approximately half of the power consumed by all industries.

Figure 3 shows the 2018 status of the power sector. Fossil fuels represent 72% of the power generation, with 45% coming from coal. We observe that of the primary power consumed, only 42% is converted into electricity. The associated losses are caused by the thermodynamic thermal efficiency of power conversion technologies. The losses are mainly heat, of which a fraction could be reused.

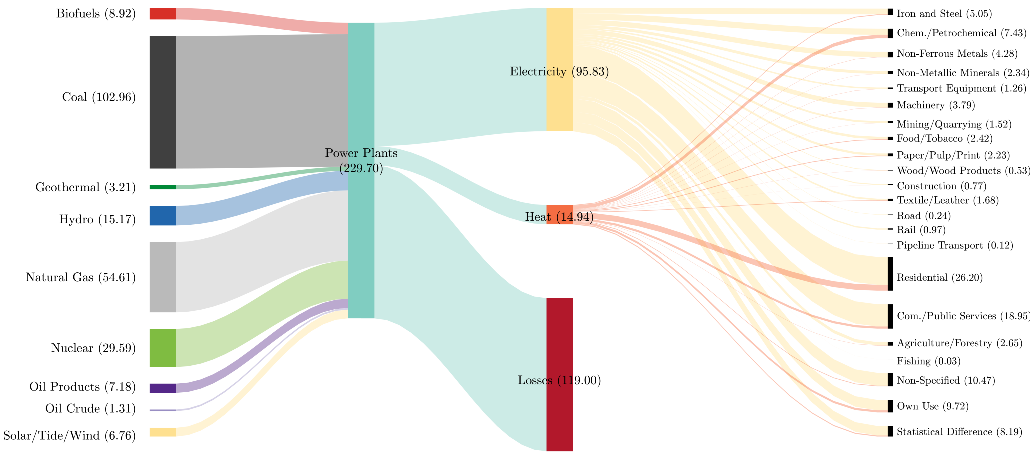
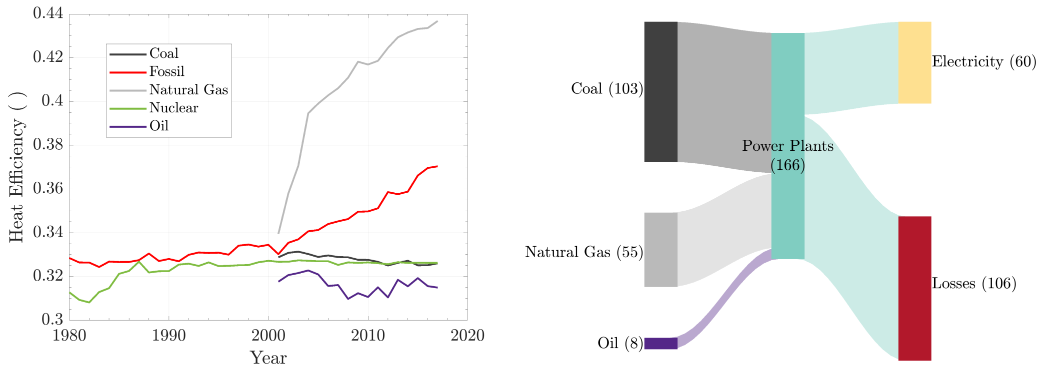


Figure 3. Power flows in electricity generation. This Sankey diagram is a detailed and expanded version of the *Power* transformation reported in Figure 1. The units are EJ/yr, and the reference year is 2018. The data from IEA [92] are plotted using a modified version of [32].

Primary power and electricity are linked through the heat efficiencies of the sources that drive thermal power conversion processes. Figure 4a shows the heat efficiencies of different sources in the US. The sharp increase over time in heat efficiency of natural gas is due to the widespread adoption of combined cycle power plants, which have a higher efficiency [127,128]. Conversely, there is a downward trend for coal, which in part is due to strict regulations of emissions to improve air quality [129,130]. Overall, we observe an improvement in heat efficiency of fossil fuels, mainly due to the adoption of combined cycle power plants. It is important to mention that overall the US has a better average power generation efficiency than the rest of the world—the global efficiency for power plants is 34% for coal-powered, and 39% for natural gas [131].

Figure 4b illustrates the effect of heat efficiency, and shows the amount of primary power from fossil fuels converted into electricity and the share lost as heat. We can observe that the heat efficiency of electricity generation from fossil power is 37% in the US (Figure 4a) and 36% worldwide, as shown in Figure 4b, confirming that these heat efficiencies are good reference values.



(**a**) (**b**)

Figure 4. Heat efficiency of electricity generation from fossil fuels. (**a**) Heat efficiency for different sources in the United States. (**b**) World's fossil power Sankey's diagram. Fossil fuels power the flow, units are in EJ/yr. Losses include heat that could be recovered through cogeneration or other approaches. The data are from EIA [38], IEA [92]. (**b**) was plotted using a modified version of [32].

3.2. Electrification of the Power Sector

Table 1 summarizes the current status and our proposed power generation mix, aligned with a power transition aiming to decarbonize the power sector. The detailed, extensive analysis of current trends and projections for the main power sources that support the chosen scenario is available in Supplementary Information Section S2. This scenario relies on the political willingness already expressed by several countries, biophysical limits, and deployment of production capacity. It seems that we might not have a complete decarbonization of our power system by 2050. Furthermore, the excess expansion of power demand will probably be absorbed by fossil sources, delaying complete decarbonization.

Table 1. Proposed Generation Mix. Capacity factor (CF) values based on data reported in Bolson et al. [5].

	Nominal Power (GW)				New Mix Energy (EJ)	
Source	**Installed**	**Added**	**New Mix**	**CF**	**Primary**	**Electricity**
Coal	2081	-	-	0.53	-	-
Biomass	130	120	250	0.55	17.46	4.25
Geothermal	13	37	50	0.74	8.53	1.38
Hydro	1125	1075	2200	0.43	29.75	29.75
Natural Gas	1757	-	732	0.38	20.11	8.78
Nuclear	369	381	750	0.79	58.65	19.15
Oil	374	-	-	0.28	-	-
Solar	488	3000	3488	0.11	12.50	12.50
Wind	563	2000	2563	0.22	18.54	18.54
Total	5143	6613	10,033	-	165.54	94.35

Figure 5 illustrates the proposed power generation mix. It seems that even with very ambitious targets, fossil fuels will still deliver a significant share of power generation. In the best case, we assume that the fossil fuel share will be powered by natural gas. In the worst case, it will be coal. From a primary power perspective, when compared with the 2018 power mix (see Figure 3), the power consumption will decrease by 30%, mainly as a reduction of thermal losses due to the more significant shares of hydro, solar, and wind. It is common to hear a claim that electrification could reduce primary power consumption by two thirds. These claims only hold if the system in place is replaced by primary sources that produce electricity directly without an intermediate conversion step, i.e., hydro, solar and wind, and there is a sufficient electricity storage capacity [5].

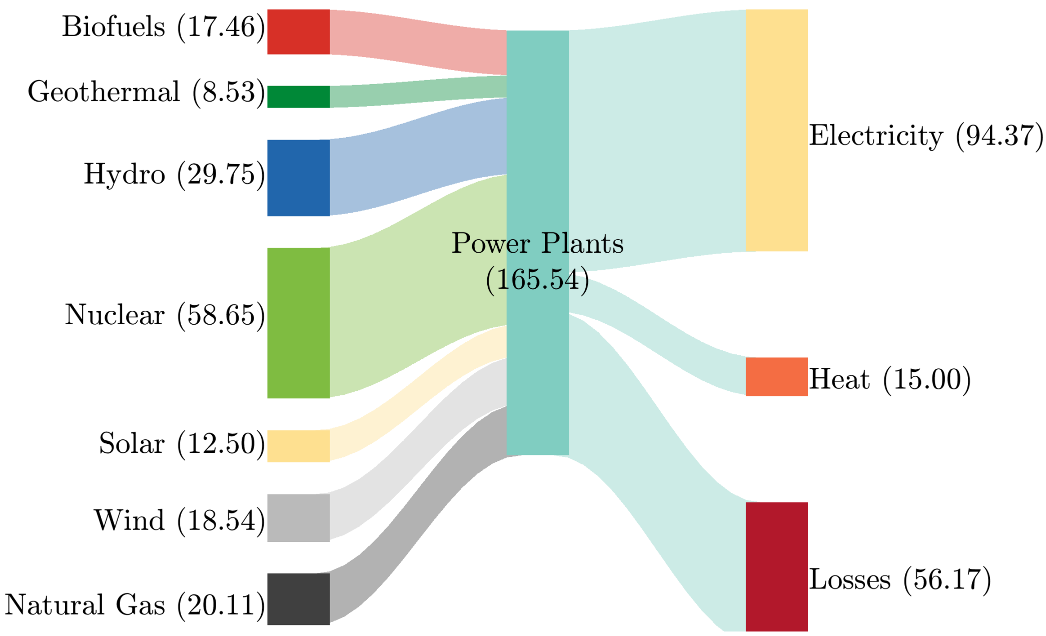


Figure 5. New power generation mix. The proposed power replacement scenario leads towards decarbonization by 2050 and replacement of fossil fuel sources. This projection is based on current trends and political will. Losses include heat that could be recovered through cogeneration or used directly. The units are EJ/yr. Plotted using a modified version of [32].

Globally, there is a shared aspiration to decarbonize and achieve net-zero targets. However, different countries have varying timeframes for these goals [132]. The literature outlines several pathways to decarbonization [45,74]; however, the results presented here are the outcomes of current commitments and trends. This study includes only a replacement scenario that neglects the unavoidable expansion of power demand—most projections expect an annual growth of nearly 3% [133,134]. The sustainable development goals boast affordable, clean energy [135], and that poses a challenge. We observe that currently, there is no capability to deploy enough clean energy to meet the global demand. The most expensive energy is the energy that we do not have. For a developed nation that is aiming to replace power sources, this cost will delay decarbonization. A glaring example is China that in 2022 was permitting roughly two new coal-fired power stations per week [136]. In a developing nation, limited access to clean sources could lead to the adoption of fossil fuels—mostly coal—to power the increasing demand, as is happening in India [137].

3.3. Electrification of Transport, Commerce, and Residential Sectors

The electrification of the transport sector seems to be of great interest [138–140]. The passenger vehicles are relatively easy to electrify in the road sector, and the current technology exists. However, electrification still faces the scaling up challenge. With a significant adoption of EV vehicles, primary power consumption by passengers could reduce from

59.5 EJ/yr to 12.75 EJ/yr, or to 31.65 EJ/yr in the case of H_2 powered vehicles. We limit our analysis to the final power consumption by the road sector. Supplementary Information Section S3 provides these results in detail, and the embodied energy and mileage required for these vehicles to break even with the ICE vehicles.

The residential and commerce sectors share similarities in energy consumption and end-uses. It is important to mention that space and water heating are the major shares of primary power consumption in both sectors. A significant part of power savings is from the adoption of heat pumps. The commerce sector is already more electrified. In the proposed technology replacement scenario, the primary power consumption of the residential sector reduces from 88.3 EJ/yr to 52.8 EJ/yr. For the commerce sector, this consumption reduces from 33.8 EJ/yr to 23.7 EJ/yr. Both sectors achieve savings of 40% and 30%, respectively. The most important aspect of this transition scenario is that electrification does not affect end-users. In practice, they will have access to the same heat comfort as before the transition. The war in Ukraine has already challenged this scenario in Europe.

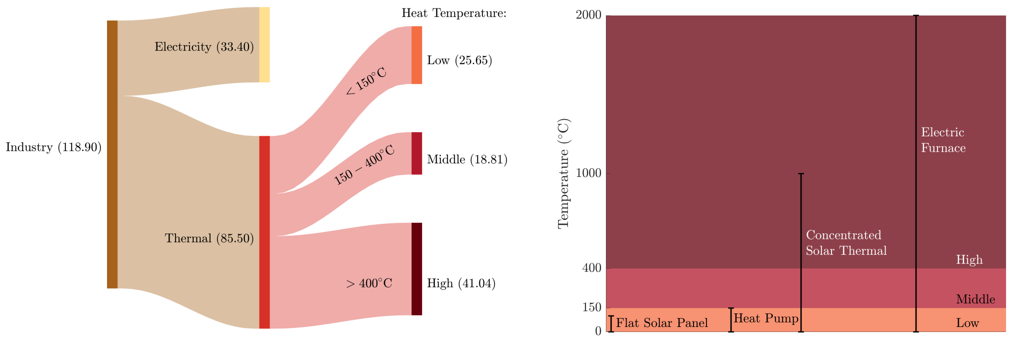
3.4. Electrification of Intense Heat Processes

Heat corresponds to approximately 70% of energy consumption by the industry, and it is generated mainly from coal. Due to complexity of the innumerable industrial processes, we refrain from proposing the electrification of this sector. However, Supplementary Information Section S3 briefly discusses this topic. From a broad perspective, the potential electrification of heat sources can be achieved:

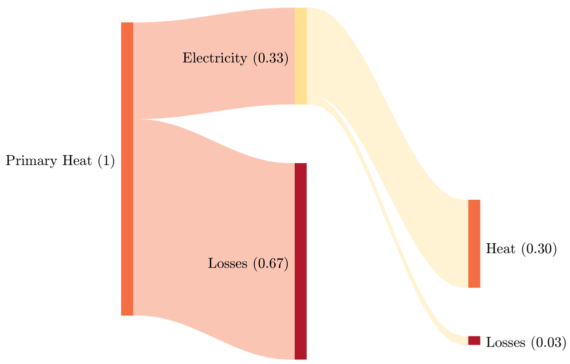
- **Heat pumps** could be a viable alternative for conventional heat generation. The current technology appears to be able to achieve temperatures of up to 160 °C, and has a COP from 2.2 to 6.5, depending on the temperature lift [141]. In a recent experiment, a heat pump-based system could generate steam at a temperature of up to 175 °C [142]. A range of applications can be unlocked with the potential of hybrid systems, indicating a promising future for the application of heat pumps [143]. The adoption of the best technology requires a trade-off between efficiency and volumetric rates, which is affected by the working fluid selected [144].
- **Electric furnaces** could be initially classified into three categories: electric arc, induction, and muffle. The current temperature limits for muffle and electric arc furnaces are close to 2000 °C, while induction furnaces can go above 3000 °C. Electric arc furnaces have already been implemented in steel making, where they play an important role in recycling scrap [145], and are still the subject of investigations to minimize energy losses [146]. Induction furnaces are still not widely adopted. This technology requires optimization and improvements to process practices [147,148], but appears promising, mainly for processes that require temperatures above 2000 °C.
- **Solar thermal** could play an important role by supplying a part of the heat demand. The simplest technology are flat-plate collectors that do not need to track the sun, require little maintenance, and can supply energy for processes that demand temperatures up to 100 °C [149]. To achieve higher temperatures, more complex systems such as concentrated solar thermal (CST) are required. CST has been studied for decades, and several commercial and pilot plants are currently in use [150]. Recent trends are towards adopting solid particle receivers that achieve higher temperatures compared with molten salt [151]. Hybrid systems may offer several benefits, such as increased reliability, improved energy efficiency, and cost reduction [152]. A recent highlight is Heliogen [153], a pilot plant that can generate temperatures above 1000 °C; this is a noteworthy achievement that unleashes a new range of applications.

Figure 6 summarizes the essential information that must be considered for the electrification of intense heat processes. Figure 6a shows the power consumption by the industrial sector, discerning the power that is consumed as heat and electricity. This figure also provides insights about the heat temperatures, of which approximately 48% is above 400 °C, 30% is below 150 °C, and 22% is between 150 °C to 400 °C. Figure 6b illustrates the technologies described above and the ranges of temperatures at which they work. In theory, the electrification of the majority of intense heat processes is possible; however, some processes have specific limitations that may require tailored solutions.

Figure 6c,d illustrates the bottleneck of the electrification of heat. Figure 6c shows that, from an energy perspective, it does not make sense to convert heat into electricity and back into heat. This series of energy conversions can easily result in 70% energy losses. Figure 6d provides the energy available as heat and electricity for selected sources. We observe that the electrification of intense heat processes makes sense when the electricity comes from hydro, solar photovoltaic or wind. In any other scenario, the gain in the efficiency of the electrified process should compensate for the losses in electricity production. For reference, assume that a thermal process has efficiency X, considering the direct use of heat with 80% efficiency. Suppose this process is electrified, considering that the primary source is now used to generate electricity with 33% efficiency. In that case, the efficiency of an electrified process must be $2.5X$ to achieve the same primary energy consumption. If the electrified process is less efficient, we become less sustainable.



(**a**) (**b**)



Source	Energy Content Heat	Energy Content Electricity
Biofuels	1	0.24
Coal	1	0.33
Geothermal	1	0.16
Hydro	1	1
Natural Gas	1	0.44
Nuclear	1	0.33
Oil	1	0.31
Solar PV	1	1
Solar Thermal	1	0.33
Wind	1	1

(**c**) (**d**)

Figure 6. Rates of heat and work generation. (**a**) Industry power flow with thermal power detailed, units are in EJ/yr. The data are from IEA [92], Solar Payback [154]. (**b**) Potential technologies and working temperatures. (**c**) Heat conversion flow and losses towards a process that converts heat into electricity and then converts it back into heat. (**d**) Energy content available as heat and electricity for selected fuels/technologies [38–40]. (**a**,**c**) plotted using a modified version of [32].

3.5. Electricity Demand: A New System

Implementing the proposed scenario of electrification will modify primary power flows. Figure 7 shows the power flows of the emerging system. Please remember that electricity is an energy carrier. Section 3.2 and Figure 8 clarify the primary power and power savings. The proposed electrification scenario will result in a reduction of 134 EJ/yr of the primary power from fossil and biofuels. From this reduction, 40 EJ/yr will be relocated as electricity demand, 2 EJ/yr as solar thermal, and 92 EJ/yr as potential primary power savings. Coincidentally, the proposed electrification provides support to the rule of thumb that two-thirds of power savings are due to the conversion of thermal/chemical energy into electricity.

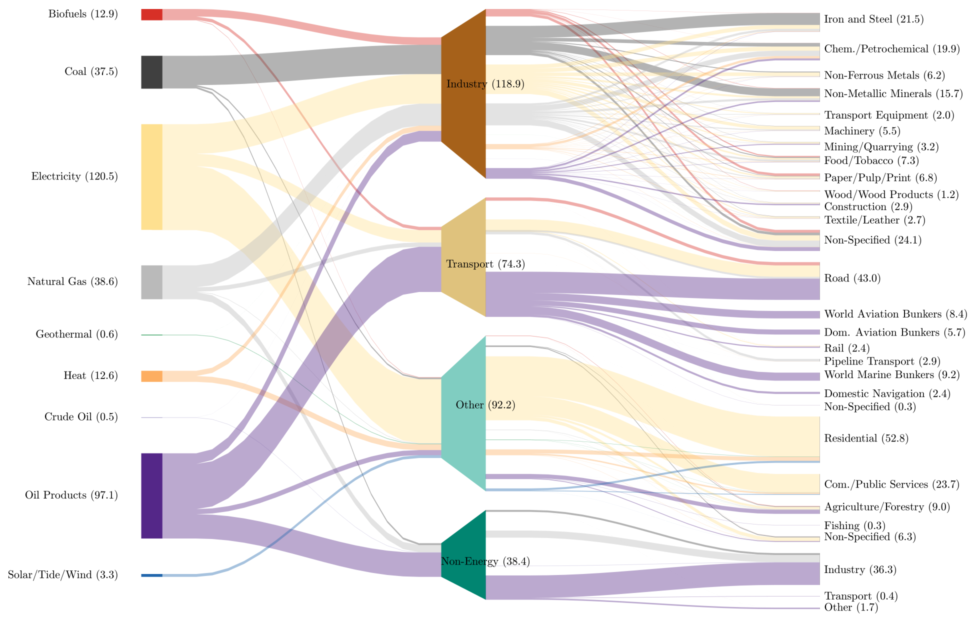
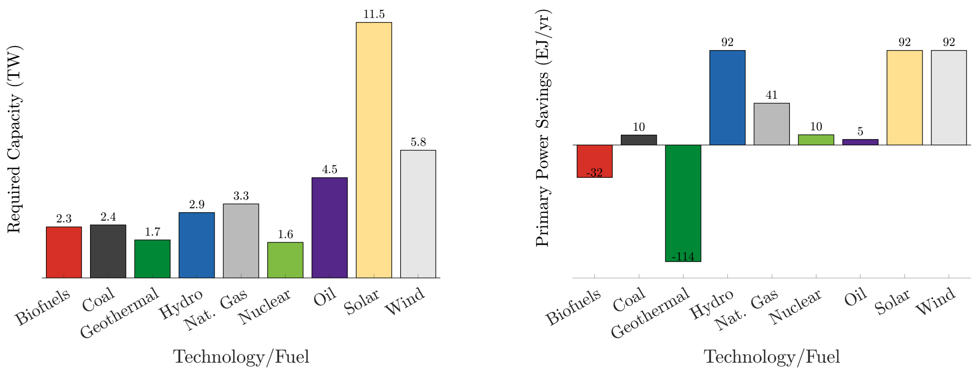


Figure 7. Final use of primary power for the proposed electrification scenario. This Sankey diagram is the decarbonized version of Figure 2. The scenario accounts for the proposed decarbonization/electrification of power, transportation, commerce, and residential sectors. It incorporates power savings due to gains in efficiency in these sectors. The final use of power neglects losses from primary conversion/transformation. The units are EJ/yr. Plotted using a modified version of [32].

This Sankey diagram shows the final use of primary power in a proposed electrification scenario. The scenario accounts for strong decarbonization and electrification of the power, transportation, commercial, and residential sectors. It also incorporates power savings due to gains in efficiency in these sectors. Figure 8 provides a more detailed analysis of the consequences of the proposed electrification scenario. Figure 8a shows the required capacity to be installed. In this case, we consider that each listed fuel alone supplies the new electricity demand. We are aware that, in reality, a mix of sources will be required. However, this analysis highlights the challenges ahead. Figure 5 shows that for the current demand, it appears that a complete decarbonization will not occur. It is not a misguided claim to expect that fossil fuels will probably supply this extra demand from natural gas in the best scenario, and from coal in the worst scenario. We expect this extra electricity demand to slow down the shutdown of fossil power plants, and the phaseout of coal and natural gas power plants will probably be delayed.

Figure 8b shows the amount of primary power that could be saved from the deployment of a specific technology to generate electricity. Hydropower, solar PV, and wind provide the maximum savings, because they generate electricity directly. The savings from other sources depend on their heat efficiencies. Interestingly, even if powered with fossil fuels, electrification results in power savings. However, when electrification is powered by geothermal or biofuels, there are no savings in terms of primary power. The overall thermodynamic efficiency of using biofuels to generate electricity is also inherently low, and their global ecological impacts are high [15,16,43].



(**a**) (**b**)

Figure 8. Requirements and savings from electrification. (**a**) Required capacity to be installed to supply the new demand for electricity (considering that the individual source will supply the new electricity demand entirely—40 EJ/yr). (**b**) Primary power savings from the source used to supply the electricity.

However, the reality is far more complex. The combined studies of material demand, CO_2 emissions, embodied energy, and life cycle assessments could provide better support for decision making. Analyzing primary power is simplistic. Nevertheless, it provides a clear picture of the required resources. When faced with the data related to power savings from electrification, the most pertinent question to ask is: *where is electricity coming from?*

3.6. Limitations and Uncertainties

Emerging technologies not considered in this analysis could appear in aspects of technology replacements. The proposed scenario aims to explore the impact of electrification. Unforeseen circumstances can occur, hindering massive electrification. Alternatives, such as symbioses among different sectors, which could provide thermal energy (e.g., district heating), are not covered and could potentially reduce total power demand. Finally, the shares of electrified technologies could be adjusted.

Questions regarding limitations of the proposed transition, such as raw material (un)availability [18], are not covered here. Strong electrification could build up competition for material resources, limiting the feasibility of proposed scenarios.

Global events (war in Ukraine; pandemics) can change government plans towards energy. The availability and costs of fossil energy on global markets are making governments rethink energy security and bring back the exploration of fossil resources. In addition, high energy prices have shifted the public opinion on nuclear energy. A great example of these points is the UK, which will return to exploit the hydrocarbon reserves in the North Sea, and is planning to increase the share of nuclear energy in the power mix [155]. This scenario was unimaginable a few years ago.

Another limitation of our analysis is the assumption that the proposed power capacity will be integrated directly into the grid. This powerful assumption is commonly omitted or implicit in most analyses. In reality, a massive backlog of new electricity generation facilities is in a "waiting phase". New energy developments can wait for up to 13 years to be integrated into the grid in the UK [156]. In the US, close to 1000 GW of renewable power is waiting to be connected to the grid [157]. This situation can delay the decarbonization of the global power system even further.

Beyond prevailing integration challenges, additional factors such as power quality and storage considerations can arise [158,159]. Addressing this issue at a global scale becomes complex due to its contextual dependence on regions/countries. Diverse technologies have different roles in energy storage: lithium-ion batteries demonstrate competitiveness in short-term storage, while pumped hydro, compressed air, and hydrogen have a greater suitability for the longer term [160]. Research indicates that achieving a system with over

80% renewable power implies the need for seasonal storage [159,161]. In practical terms, energy storage implementation demands an overestimation of current projections, as the generated power must account for storage losses.

Finally, there is an inherent uncertainty in the energy consumption data. Precise allocation and description of end-uses provide a more accurate analysis. However, relying on global databases and reports might not provide the most accurate picture. An underestimation of energy resources consumed in developing countries seems to be a fact [162]. This mismatch between accounted and actual energy consumption can result in a more significant challenge in the electrification or decarbonization of the global power system.

4. Conclusions

Primary power analysis offers valuable insights into the impact of electrification on natural resources. While electrification yields significant power savings in key areas, such as transportation, commerce, and residential sectors, it may not effectively address the issue of intense heat processes. Converting heat into electricity and then back into heat is a highly inefficient approach.

Based on current political will and ongoing planning and construction, the global economy is unlikely to achieve a complete decarbonization of the power sector by 2050. A further expansion of power consumption will likely be met by fossil fuels, thereby delaying deeper decarbonization. This finding has important implications for scenarios that rely on renewable energy surpluses to promote inefficient energy systems, such as hydrogen, which may not be feasible in the short- and medium-term.

The analysis in this paper underscores the need for more substantial efforts towards decarbonizing the current power system through clean electricity. However, a simultaneous replacement and expansion will be challenging. Potential alternatives to achieve this goal include (1) an increased contribution of nuclear power; (2) individual people and companies opting to electrify everything, including their power generation systems, with technologies such as photovoltaic panels; and (3) promoting ecology-aware and less energy-intensive lifestyles overall, but especially in developed countries, as the most critical step.

Global analyses can be limited in resolution and may not provide sufficient detail for specific sectors. Therefore, following this study, a risk analysis ought to be conducted to identify and address uncertainties associated with resource limitations, as well as the required infrastructure and socioeconomic factors within the proposed scenarios. Future work could be directed towards comprehending the resource requirements for the proposed electrification scenario. This extension requires an assessment of ecological implications of mineral extraction. From a socioeconomic perspective, we need to better understand supply chain frailties, emergence of dominant stakeholders within the new technological landscape, and shifts in current lifestyles. These new insights will help to inform decision making in other spheres of energy transitions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151914440/s1. Section S1 provides a review of primary energy and its accounts [163]. S1 includes: Table S1. Conversion efficiency by different approaches. Section S2 provides detailed information on the potential resources for power generation. S2 includes: Figure S1. Biomass. The logistic fit is based on the current installed capacity; Figure S2. Forest biomass; Figure S3. Geothermal. The logistic fit is based on the current installed capacity; Figure S4. Hydropower. The logistic fit is based on the current installed capacity; Figure S5. Hydropower plants under construction or planned; Figure S6. Nuclear. The logistic fit is based on the current installed capacity; Figure S7. Solar. The logistic fit is based on the current installed capacity; Figure S8. Wind. The logistic fit is based on the current installed capacity; Table S2. Exergy output. Section S3 provides details on the electrification of the different sectors. S3 includes: Figure S9. Vehicles life cycle assessment; Figure S10. Primary energy consumption in the road sector towards technology transition; Figure S11. Temperatures required for cement production; Figure S12. Primary power consumption by the residential and commerce sectors; Figure S13. Efficiency for cooking; Figure S14. Efficiency of water heating; Figure S15. Efficiency of space heating; Table S3. Reference data for passenger vehicles.

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