

Supplementary Materials: Primary Power Analysis of a Global Electrification Scenario

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1. Primary Energy

Primary energy is the energy that has not been submitted to any conversion process. There are four main methods to quantify primary energy:

- **Direct Equivalent Method:** The primary energy of non-combustible energy sources is equal to the energy contained in the electricity [1]. The limitation of this approach is an underestimation of the primary energy required to produce electricity. The UN and IPCC use this approach [1].
- **Incident Energy Method:** This approach accounts for the primary energy of non-combustible sources, which means the energy before the conversion to electricity [1]. Examples are the incident solar radiation over a solar panel or the kinetic energy in the water conduct for a hydropower plant. The limitation is that most power plants do not report the incident energy, which limits the available data.
- **Partial Substitution Method:** The primary energy equivalent of non-combustible energy sources is represented by the amount of energy required to produce the same amount of electricity in a thermal power plant [1,2]. The conversion factor is based on the average generation efficiency of thermal power plants. The main challenge is to define an adequate factor for this energy substitution [2]. However, this approach violates the first law of thermodynamics by creating primary energy out of nothing. BP, EIA, International Institute for Applied Systems Analysis (IIASA), and the World Energy Council (WEC) use this approach [1].
- **Physical Energy Content Method:** The primary energy for non-combustible sources is the amount of electricity produced (*e.g.*, by hydro, solar or wind). In the case of sources with heat as an intermediate conversion step (*e.g.*, geothermal or nuclear), the amount of heat is accounted for [2]. EUROSTAT, IEA, and the OECD use this approach [1].

For reference, [Table S1](#) shows the conversion efficiencies for different approaches reported by various institutions. Usually, equivalent primary energy is estimated by applying a conversion efficiency factor to an amount of electricity produced.

Table S1. Conversion efficiency by different approaches. Adapted from Kraan *et al.* [1].

Method	Institution	Geothermal	Hydro	Nuclear	Solar CSP	Solar PV	Wind
DEM ¹	UN	100	100	100	100	100	100
IEM ²	—	16	90	33	21	12	26
PSM ³	EIA	35	35	33	35	35	35
PECM ⁴	IEA	10	100	33	33	100	100

¹ Direct Equivalent Method

² Incident Energy Method

³ Partial Substitution Method

⁴ Physical Energy Content Method

2. Potential Resources for Power Generation

This section provides a background on potential energy resources for power generation. It is mainly a cross-check with some forecasts that have been proposed. In the following subsections, we evaluate processes that seem to be en-route or feasible by 2050.

2.1. Biomass

EIA [3] points out that the electric sector mainly uses wood and biomass-derived “waste¹” to produce electricity. An important observation is that biomass “waste” includes energy crops, which are tree plantations, not waste [5]. Figure S1 shows the forecasts from different agencies, a logistic fit, and our projection that assumes that the equivalent of 20 % of the industrial forest is destined to be fuel-wood. Forecasts from IRENA [6] envision 384 GW, IEA [7] 732 GW, while our projection estimates 250 GW of capacity installed.

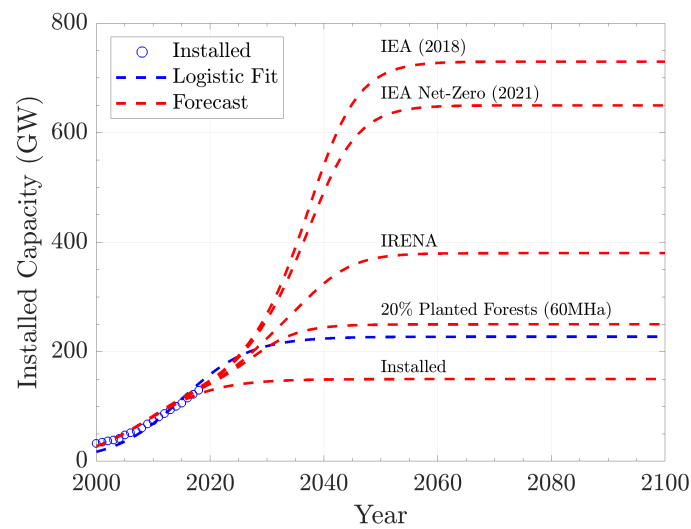


Figure S1. Biomass. The logistic fit is based on the current installed capacity. The red dashed lines show the nominal capacity installed, projections by IRENA [6], IEA [7], and our projection where 20 % of the industrial forests are destined to be fuel-wood.

Our estimate uses as reference the energy information in Table S2. Figure S2a shows the equivalent forested area that was consumed in that year if all the energy coming from biofuels was from fuel-wood. Figure S2b shows the required area that must be cultivated to feed a specific nominal power capacity. The current area dedicated to industrial forest is 293 Mha [8]. Using the equivalent of 20 % of these forests to generate power it could supply a nominal capacity of 250 GW.

¹ Waste is a human concept, because nature knows of no waste [4].

Table S2. Exergy output. Units are GJ/ha/yr. Data from Patzek and Pimentel [4].

	Acacia	Eucalyptus	Sugarcane ^a
Primary Energy	434	108.52	143.6 ^b
Electricity ^c	109.38	27.35	3.3
Ethanol	36.16 ^d	9.04 ^d	130.4

^a Calculation considers as output ethanol and excess electricity

^b The net exergy available from dry bagasse and attached trash is 143.6 GJ/ha/yr. This energy is consumed to produce ethanol (130.2 GJ/ha/yr) and the excess provides electricity.

^c Electricity conversion efficiency of 25 %.

^d Ethanol equivalent, instead of producing electricity.

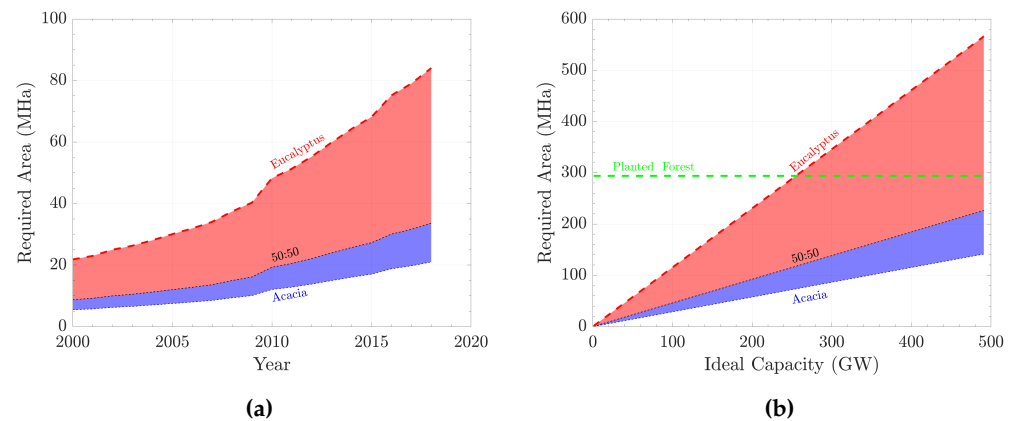


Figure S2. Forest biomass. (a) Equivalent required area if the energy consumed as biofuels was composed only by wood biomass. (b) Area required to run a nominal power capacity continuously.

2.2. Geothermal

Figure S3 shows current installed capacity and forecasts for electrical power from geothermal wells. Currently, there are approximately 12 GW of installed capacity [9,10]. World Bank [11] estimates a potential of 80 GW. Through adoption of more advanced techniques, such as enhanced geothermal systems, the installed capacity can reach up to 256 GW [12]. A current market outlook by the IEA shows that major expansion of geothermal power has been occurring in some key countries (Indonesia, Kenya, and Turkey) [13]. From the plans and projections by the leading countries, *i.e.*, Indonesia, Kenya, Mexico, New Zealand, Philippines, Turkey, and the USA, we could expect a doubling in the nominal capacity installed in the next 10 years [14–20]. 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 [21]. Due to lack of reliable information and long-term projections, our perspective is that an expansion trend will continue through 2050 and a nominal capacity of 50 GW might be installed.

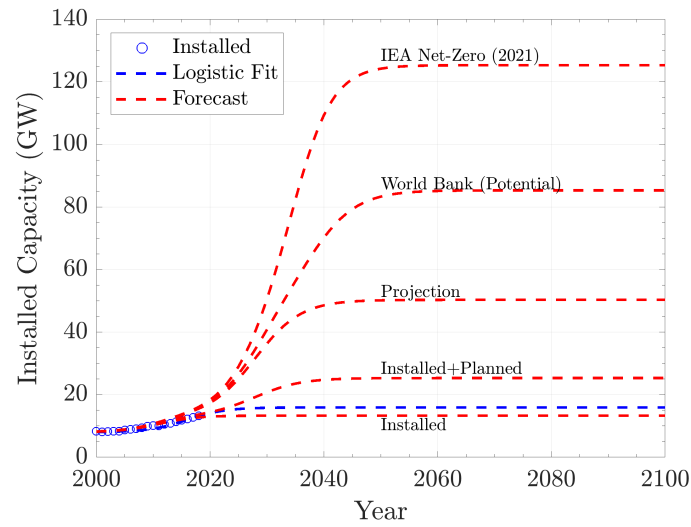


Figure S3. Geothermal. The logistic fit is based on the current installed capacity. The red dashed lines show the nominal capacity installed, planned, our projection based on the current expansion, and the total potential estimated by World Bank [11].

2.3. Hydro

Figure S4 shows the under-construction, planned, and forecasted capacity for hydropower. The under-construction and planned capacity is currently 688 GW[22]. Recent data show that the under-construction capacity is 233 GW, and the planned capacity is 491 GW [23]. It is important to mention that the 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 [24,25]. Mini-hydropower plants (up to 1 MW) and micro-hydropower plants (up to 100 kW), usually contribute to the regional or national grids [26]. Hydropower plants below 1 MW are not commonly reported, which makes it hard to make a good estimation of the power capacity of this category [22]. Overall, it is estimated that the technically feasible hydropower capacity to be installed could in the range of 4000 GW[27].

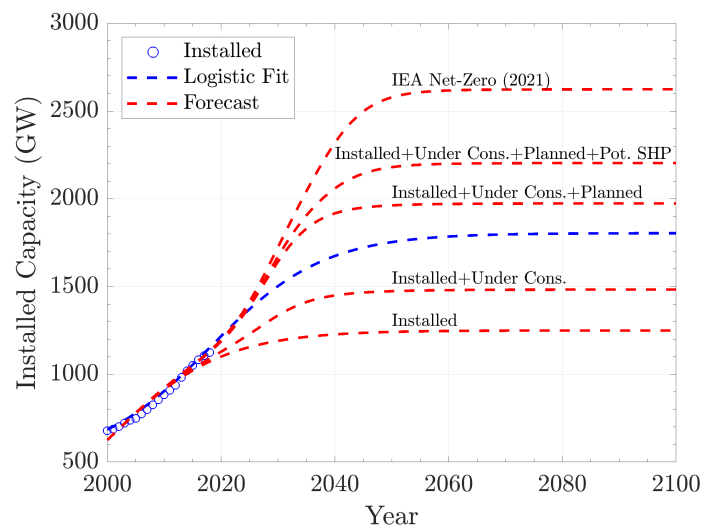


Figure S4. Hydropower. The logistic fit is based on the current installed capacity. The red dashed lines show the nominal capacity that is installed, under construction or planned. SHP is an acronym for small hydropower. Note that power plants with less than 1 MW are not considered.

Figure S5 shows the number of hydropower plants under construction or planned, categorized by nominal capacity. It follows a log-normal distribution. Also, it does not count power plants smaller than 1 MW.

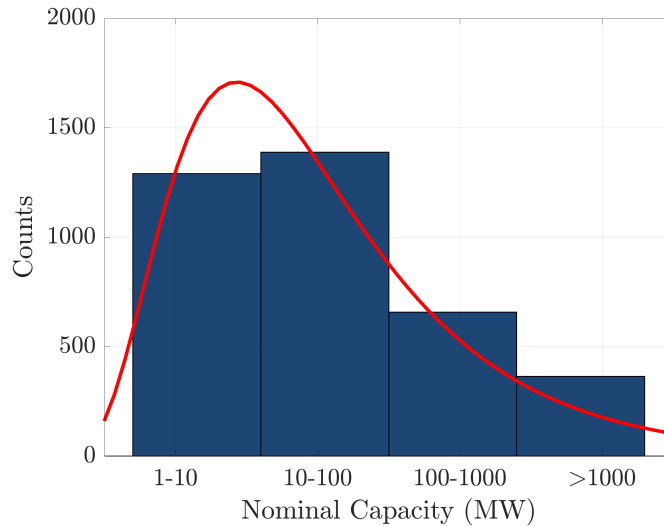


Figure S5. Hydropower plants under construction or planned. The count does not include power plants smaller than 1 MW. For each category, the lower bound is exclusive and the upper bound inclusive. Data from [23].

2.4. Nuclear

Figure S6 shows the installed, under-construction, planned, and forecasted capacity for nuclear power plants. The current nominal capacity under construction is 53 GW [28,29]. Planned capacity to be added is 104.6 GW. Furthermore, an additional 225.3 GW have been proposed [30]. It is important to emphasize the growing number of countries classified as “emerging countries” is interested in installing nuclear power. These countries are at an initial stage of studying feasibility and identifying partnerships to provide the technology (mainly with China and Russia) [31]. It will not be a surprise if installed capacity significantly exceeds the more optimistic forecast by 2050. Nuclear power represents a great alternative to supply the power needs of developing nations with the requirement of a carbon free economy.

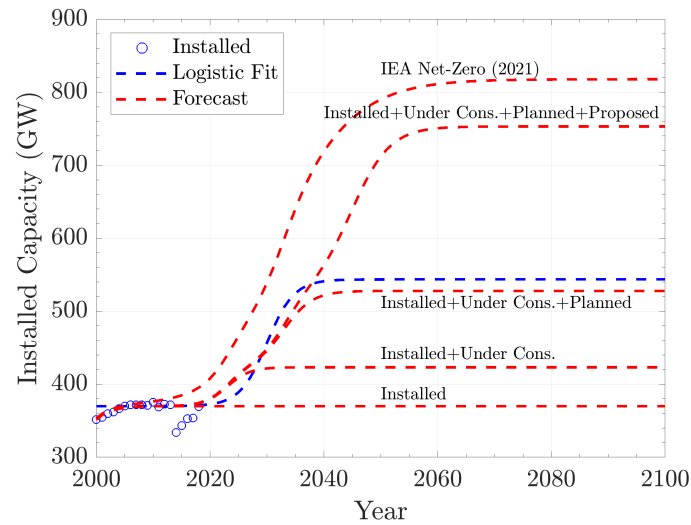


Figure S6. Nuclear. The logistic fit is based on the current installed capacity. The red dashed lines show the nominal capacity installed, under construction, planned and proposed.

2.5. Solar

Figure S7 shows the installed, under construction, and forecasted solar power. Solar photovoltaic power generation is growing fast and seems to be aligned with the sustainable development goals [32]. The nominal capacity installed has been expanding at a rate close to 100 GW/yr [33]. Major projects currently under construction have a nominal capacity of 160 GW [34]. As solar photovoltaic expansion is still at an early stage, the data can fit any model from the most conservative to an overly ambitious forecast. We observe that in the 2018 forecast IEA [35], 5000 GW was foreseen by 2050; however, in 2021, the IEA [36] predicted 15 000 GW by 2050. The latter estimate is three times the previous estimate. This difference is not associated with significant changes in array deployment or manufacturing capacity, but is a reaction to the pressing need for a power transition to avoid a climate collapse. However, a forecast unbounded by reality can do more harm than benefit, because it is selling a solution that likely will not be achievable and prevents the implementation of more effective measures. From our perspective, we envision 3000 GW of solar photovoltaics by 2050, keeping the current trends in deployment and avoiding overly ambitious estimates.

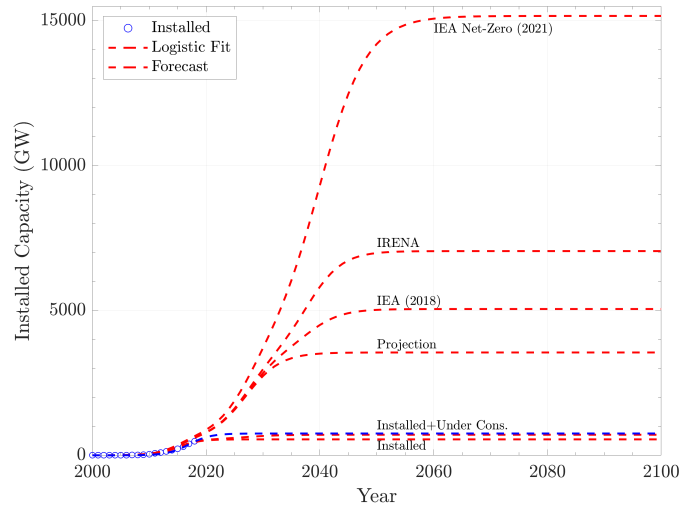


Figure S7. Solar. The logistic fit is based on the current installed capacity. The red dashed lines show the nominal capacity, under construction, projections by IRENA [6], IEA [7,36], and our projection based on the current deployment.

2.6. Wind

Figure S8 shows the installed, under construction, planned, and forecast capacity for wind power. According to IEA [37,38], 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 [39]. Major projects under construction and planned have a nominal capacity of 350 GW [40]. Similarly to solar photovoltaics, the urgent need for a power transition is reflected in these forecasts. In 2018, [41] foresaw 3000 GW by 2050; in the most recent [36], 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 our perspective, we expect an additional 2000 GW of wind power in 2050, which can be considered an ambitious target based on the current trends.

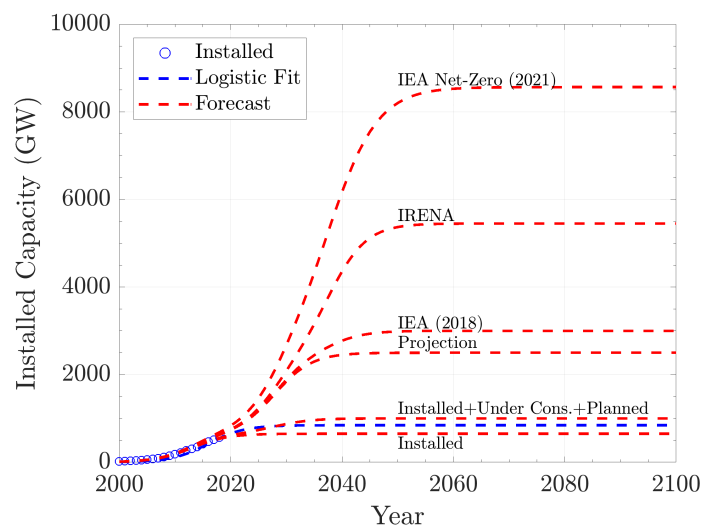


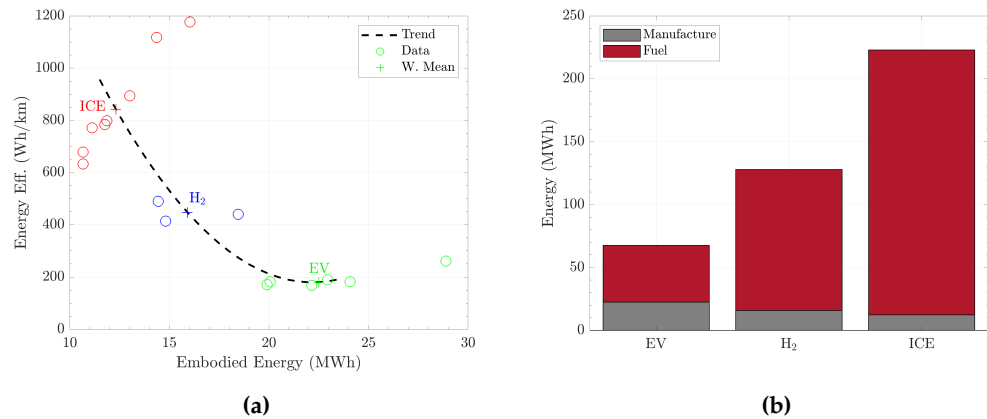
Figure S8. Wind. The logistic fit is based on the current installed capacity. The red dashed lines show the nominal capacity, under construction, planned, projections by IRENA [6], IEA [7,36], and our projection based on the current deployment.

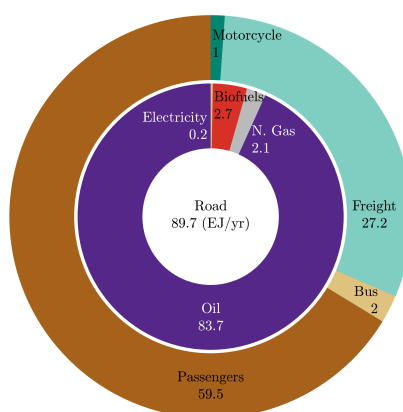
3. Electrification Details

In the following subsections, we provide the detailed results of the proposed electrification, including the current status, energy savings and technology replacement considered in each case.

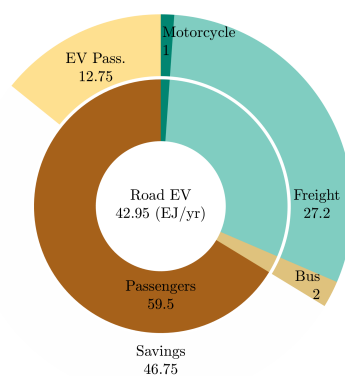
3.1. Transport

The electrification of transport is based on current trends and models available. [Figure S9](#) shows the technology replacement considered for passenger vehicles. [Figure S9a](#) shows the distribution of the vehicles with respect to energy efficiency and embodied energy. This distribution shows a negative correlation between energy efficiency and the embodied energy. From a life-cycle perspective, [Figure S9b](#) shows the total energy consumption assuming that the vehicle will drive 250×10^3 km during its lifetime. EVs consume less energy during their life cycle than other vehicles, while ICE has the highest energy consumption. As a reference, for the vehicles to break-even and compensate for the energy spent on manufacturing, an ICE needs to drive 12.4×10^3 km to break even with an EV; an H_2 needs to drive 14.7×10^3 km. For an ICE to break even with an H_2 , it needs to drive 4.4×10^3 km. It is important to mention that these calculations are based on net electricity consumption, and ignore losses due to thermal power conversion, transmission and charging.

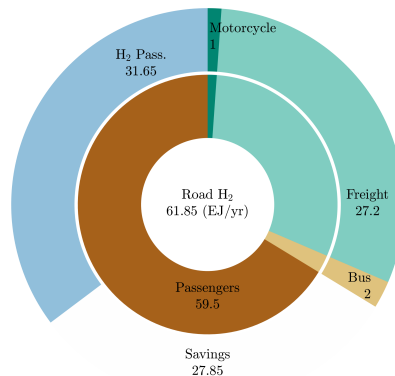




(a)



(b)



(c)

Figure S10. Primary energy consumption in the road sector towards technology transition. (a) Current status; Data from [45]. (b) Replacing internal combustion engine (ICE) by electric vehicles (EV). (c) Replacing ICE by fuel cells vehicles (H₂).

Table S3 shows the details and models considered for the transport electrification scenario.

Table S3. Reference data for passenger vehicles. Data from [42–44,46,47].

Category	Model	Efficiency (Wh/km)	Embodied Energy (MWh)	Share
H ₂	Honda Clarity	308	18.45	0.33
	Toyota Mirai	290	14.82	0.33
	Hyundai Nexo	343	14.45	0.33
EV	Tesla Model 3	152	22.15	0.54
	Tesla Model Y	171	22.95	0.12
	Hyundai Kona	154	19.90	0.10
	Volkswagen ID.4	164	24.07	0.09
	Nissan Leaf	164	20.06	0.08
	Audi e-tron	235	28.89	0.07
ICE	Toyota Corolla	633	10.67	0.20
	Ford 150	1118	14.37	0.15
	Toyota RAV4	798	11.86	0.13
	Honda CRV	785	11.76	0.11
	Honda Civic	679	10.67	0.11
	Volkswagen Tiguan	894	13.02	0.10
	Ram 1500	1177	16.03	0.10
	Nissan Sentra	771	11.12	0.10

3.2. Industry

Due to the nearly infinite number of complex industrial processes, we abstain from proposing electrification of this sector. However, we present a brief discussion on the topic and analyze the intense heat processes.

3.2.1. Iron and Steel

The energy demand to produce iron and steel is 19.8 GJ t^{-1} to 41.6 GJ t^{-1} , using a primary route (iron ore), *e.g.*, blast furnaces (basic oxygen furnace and open-hearth furnace), direct reduction and electric arc furnaces. In the case of using a secondary route (scrap steel) based on electric arc furnaces, the energy demand is 9.1 GJ t^{-1} to 12.5 GJ t^{-1} [48]. Promising technologies such as direct reduction with hydrogen and electrowinning (iron ore electrolysis) are more energy efficient, with energy demands of 13.1 GJ t^{-1} (including energy demand for H₂ electrolysis) and 9.3 GJ t^{-1} , respectively [49]. According to Lechtenböhmer *et al.* [50], only 30 % of global steel was produced from scrap metal in 2010. From these data, we could average the current cost of steel making to 18 GJ t^{-1} . For the potential technologies, the average energy cost could be reduced to 11.2 GJ t^{-1} , which could save up to 40 % of energy.

3.2.2. Chemicals and Petrochemicals

The chemical and petrochemical sectors are energy-intensive. This sector produces a wide range of chemical products via multiple processes [51]. Ammonia, ethylene, propylene, and methanol represent a significant share, and could be considered the most important building blocks of the chemical sector products [52,53]. The current standard processes are heat-intensive and involve high temperatures, *e.g.*, ammonia via Haber-Bosch process 300 °C to 600 °C; ethylene via steam cracking 700 °C to 900 °C; and methanol via gas synthesis 250 °C. Electrification of these sectors is complex and case-dependent. Different routes could be taken:

1. Process modification: *e.g.*, replacing thermochemical processes with electrochemical processes [54–57].
2. Hybrid systems: *e.g.*, some of the required heat is supplied by a more efficient source (*e.g.*, heat-pumps).
3. Technology improvement: *e.g.*, replacing old devices with more up-to-date ones. This action could reduce global power consumption by 15 % [58].

Direct or indirect electrification of chemical processes faces challenges. A case study of methanol production, made by Chen *et al.* [59] pointed out that in a case of direct electrification, only 8 % of the process was electrified. However, when an indirect electrification process was adopted, the total energy consumption increased by a factor of 42 due to hydrogen synthesis. The use of heat pumps can help with power savings. A hybrid process for methanol distillation using a heat pump can save energy in the range of 20 % to 50 % [60]. A heat pump-assisted distillation for ethylene-ethane can save 57 % of energy [61]. Technology replacement does not necessarily mean electrification of the system, and could be achieved by the adoption of more efficient practices or devices. For example, combined heat and power generation can increase energy efficiency; recycling can also reduce the use of feedstock and save energy [58].

3.2.3. Non-metallic minerals

The non-metallic minerals include cement, sand, and glass. These materials compose the bulk of construction materials. Currently, we are consuming 3.5 Gt of cement per year [62]. However, consumption of non-metallic minerals could be underestimated by up to a factor of four [63]. Usually, this sector is classified as hard to decarbonize. We illustrate the challenges faced by this group of materials by analyzing cement. Several studies have reported in detail the steps and energy consumption involved in producing cement [64–66]. The critical step occurs in the kiln. From a CO₂ emissions perspective, 46 % of emissions come from chemical reactions ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$) and 37 % usually comes from fuels [64]. From an energy perspective that discerns thermal and electrical consumption, thermal energy is consumed at the clinker burning step (corresponding to 90 % of total energy consumption). At the same time, electricity consumption is evenly distributed through the different steps [66]. A recent study by Fennell *et al.* [62] mentions that the most impactful solution for cement is clinker substitution, where the leading solutions are a combination of low-carbon cement and recycling.

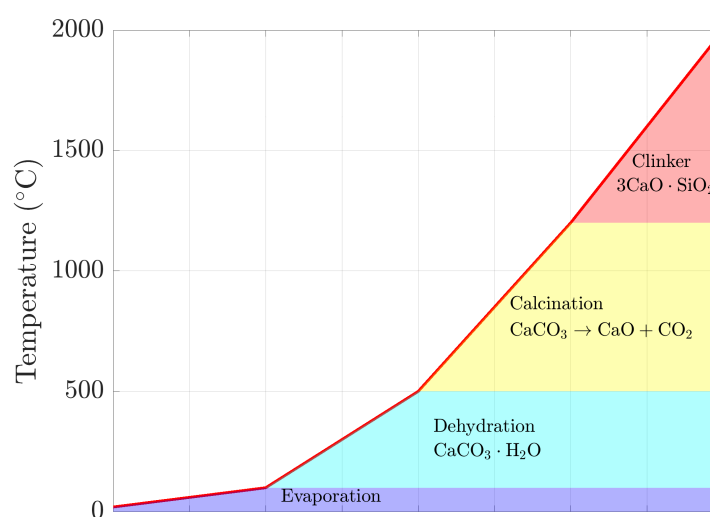


Figure S11. Temperatures required for cement production. The temperature references are from [62,64].

3.3. Residential and Commerce

The residential and commerce sectors share similarities in power consumption and end-use. Figure S12 shows the current status and electrification savings from the proposed scenario. The left column of Figure S12 (Figure S12a and S12c) shows the current status. It is important to mention that space and water heating represent major shares of primary power consumption in both sectors, and the commerce sector is already more electrified.

Figure S12b and S12d shows the power savings due to electrification. A significant part of power savings is due to the adoption of heat pumps (see Figure S14 and S15). In the proposed technology replacement scenario, the residential sector reduces its primary power consumption from 88.3 EJ/yr to 52.8 EJ/yr. For the commerce sector, primary power consumption falls from 33.8 EJ/yr to 23.7 EJ/yr. These sectors achieve savings of 40 % and 30 %, respectively. The most important aspect is that the electrification does not affect the end-users. In practice, they will have access to the same heat comfort as before the transition.

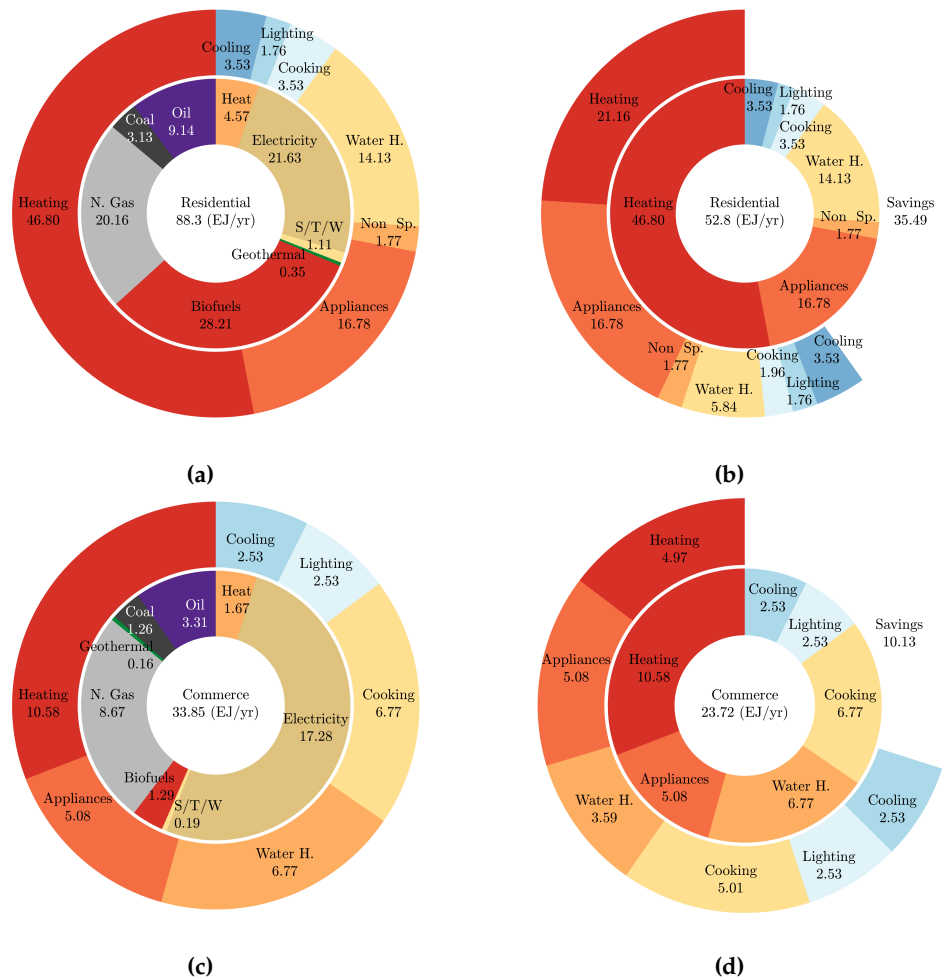


Figure S12. Primary power consumption by the residential and commerce sectors. Current status (left column) and the proposed electrification scenario (right column). (a) Current status of the residential sector. (b) Power savings from the proposed electrification of the residential sector. (c) Current status of the commerce sector. (d) Power savings from the proposed electrification scenario of the commerce sector. Data from [67–70]

3.3.1. Technology Replacement

The residential and commerce sector have similar profiles. Here, we considered only cooking, space, and water heating. A range of technologies and their efficiencies were evaluated:

- **Cooking:** The data for the stove's efficiency are from [71–76]. Approximately 2.5 billion people rely on biomass fuels (charcoal, wood, agricultural residuals, animal manure) for cooking [77]. The three-stone stove is the prevailing technology [78], which is wood powered, and it has very low thermal efficiency $\sim 10\%$ [79].

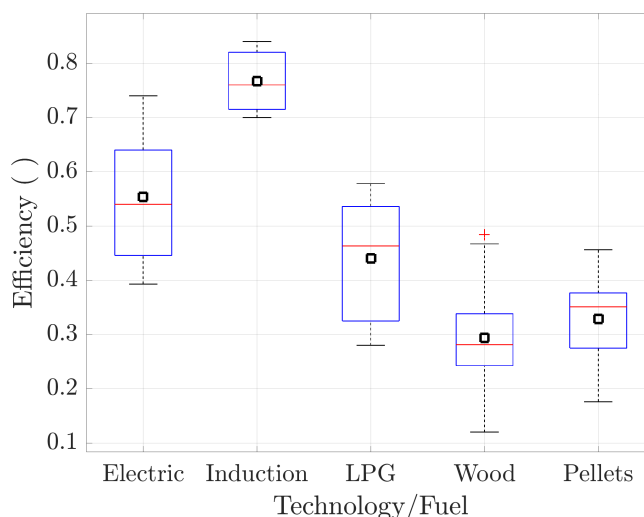


Figure S13. Efficiency for cooking. Energy efficiency comparison of different technologies/ fuels.

- **Water Heating:** Heat pumps for water heating can have different performances and specifications depending on the country [80]. A study of the coefficient of performance (COP) under different weather conditions could vary from 3.3 to 4.7 [81]. A complete review gathered a range of COP data for the different heat pump arrangements (ground source, air source, solar-assisted, gas engine driven), where the COP can variate from 1.8 to 6 [82]. From typical working conditions, the seasonal COP variation can be from 2.6 to 5.6 [83]. Influence on the water flow can interfere in the COP with variations from 2.7 to 4.3 [84]. For multi-functional applications, it can vary from 2 to 4 [85]. Performance of electric heaters is usually better than that of gas heaters [86]. For systems with tank storage, the energy factor can describe their performance better [87,88].

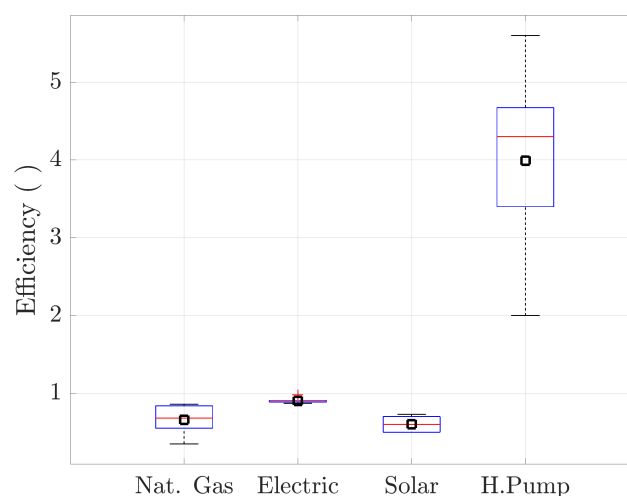


Figure S14. Efficiency of water heating. Comparison of different technologies. Heat pump efficiency is its coefficient of performance.

- **Space Heating:** The leading technologies for space heating are powered by pellets, natural gas, diesel, and electricity [89]. They have a significant variation on the efficiency due to operational principles involved in the technology [90–94].

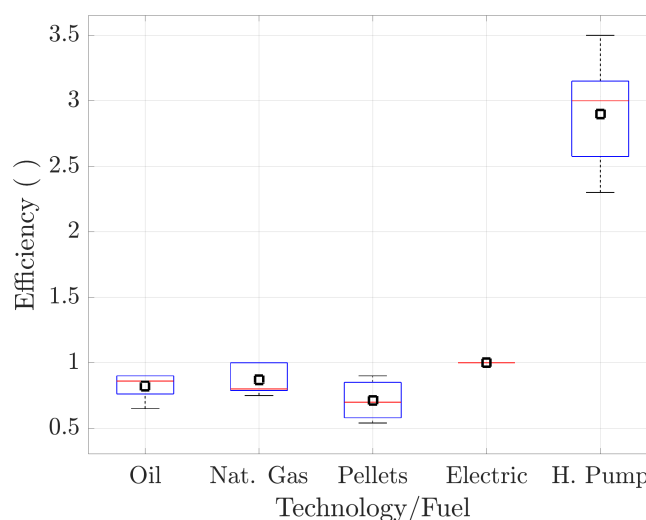


Figure S15. Efficiency of space heating. Comparison of the main technologies. Heat pumps are characterized by coefficient of performance.

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