100% renewable energy supply and the role of PV

The energy system is transitioning continuously. Drivers for changes are new technologies, societal preferences, policy measures, relative costs of options and environmental constraints. The Paris Agreement and the United Nations Sustainable Development Goals direct the energy system towards more sustainable solutions aiming for rebalancing the needs of mankind with the limits of our planet. As a consequence, emission standards for various pollutants have been further tightened with new awareness on energy supply security. The European Green Deal and REPowerEU are central elements. Technologies supporting high levels of sustainability are in the rise, while technologies with sustainability issues are in decline. On the supply side one can observe substantial growth for solar photovoltaics (PV) and wind power, supplemented by additional transmission capacities and storage solutions, in particular batteries, and an overall acceleration of electrification across the entire energy system, in particular for transport and heat sectors (e.g. road vehicles and heat pumps for thermal needs). Electricity-based e-fuels and e-chemicals are introduced to the markets and require electrolysers and CO_2 direct air capture.

Avoiding fossil and nuclear energy solutions prone to major sustainability issues and lack in energy sovereignty automatically leads to a 100% renewable energy (RE) system. Sustainability constraints further limit large-scale hydropower and energy crops as food supply deserves priority. Most of the hundreds of studies which investigated 100% RE systems conclude that 100% renewables is feasible worldwide at low cost. In most transition pathways, PV and wind power increasingly emerge as the central pillars of a sustainable energy system combined with energy efficiency measures. Cost-optimisation modeling and greater resource availability tend to lead to higher PV shares, while emphasis on energy supply diversification tends to point to higher wind power contributions. Recent research has focused on the challenges and opportunities regarding grid congestion, energy storage, sector coupling, electrification of transport and industry implying power-to-X and hydrogen-to-X.

The energy system transition options for Europe are sketched in Figures 1-4, following three scenario options modeled in hourly resolution for entire Europe structured in 20 regions. The central scenario is called Moderate (Mod) reaching 100% RE by 2050, complemented by the more ambitious Leadership (Lead) aiming for 100% RE by 2040 and the Laggard (Lag) that fails zero CO_2 emissions by 2050. The primary energy demand declines (Figure 1) as a consequence of electrification and respective energy efficiency gains as less efficient combustion processes are largely substituted, while an increase in energy service demand is enabled. Electricity emerges as the dominating source of primary energy driven by low-cost electricity and high efficiency of electricity-based solutions.

The applied scenarios rate the European energy sovereignty very high, investigating a case without energy imports. In combination with a comprehensive energy system electrification a fourfold higher electricity supply is required (Figure 2), thereof slightly more than 60% can be provided by PV, utilising rooftops for prosumers and larger ground-mounted power plants of various sizes and applications. PV is the major source of electricity supply across entire Europe, while wind power is especially prominent along the coastlines and other windy regions supplemented by hydropower along rivers and in mountainous regions. The resource complementarity reduces the storage demand. High efficiency and cost decline of RE technologies stabilise the levelised cost of energy (Figure 3), defined as annualised system cost divided by final energy supply, to pre-pandemic levels, while the levelised cost of electricity benefits from a decline in cost needed for affordable e-fuels where direct electrification is not possible such as for long-distance aviation and marine shipping, and for some seasonal balancing.

The characteristic element of the arising energy system is electricity, used directly to substitute fossil fuels for power generation, heating and transportation, and indirect electrification in power-to-hydrogen-to-X routes for e-fuels and e-chemicals. Hydrogen is very important for indirect electrification while it is not itself characteristic for the arising energy system. Electricity will dominate as the primary energy and in various power-to-X processes, so that the term Power-to-X Economy describes best the energy system (Figure 4). The Power-to-X Economy delivers sustainability, affordability, energy sovereignty and biodiversity. Dedicated measures are required to reach a 100% RE system through clear societal discourses, policy targets, effective execution, circular economy regulation and technology and manufacturing sovereignty.

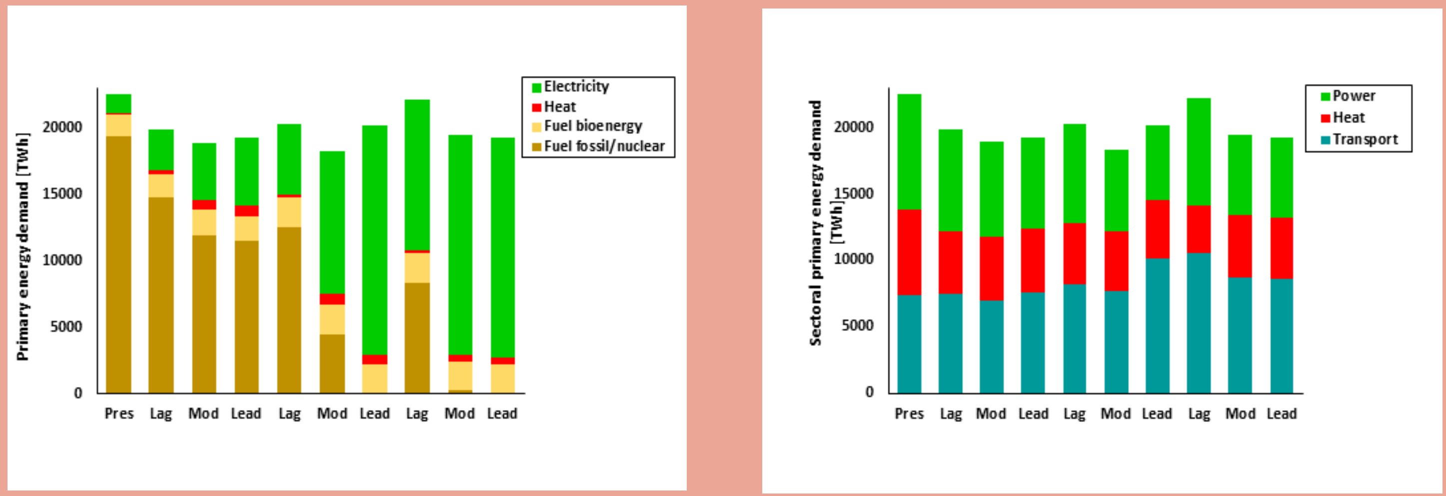

Figure 1.
European primary energy demand according to energy carriers (left) and according to different sectors (right) across the three scenarios from 2020 to 2050.

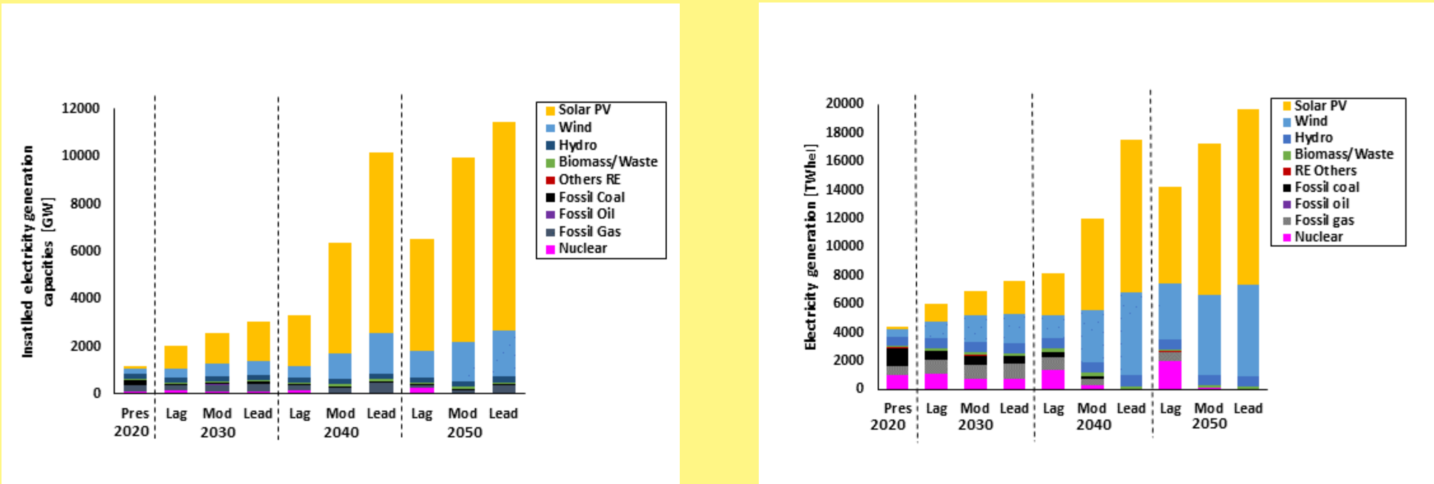

Figure 2.
European installed electricity generation capacities (left) and electricity generation (right) from various energy sources across the three scenarios from 2020 to 2050.

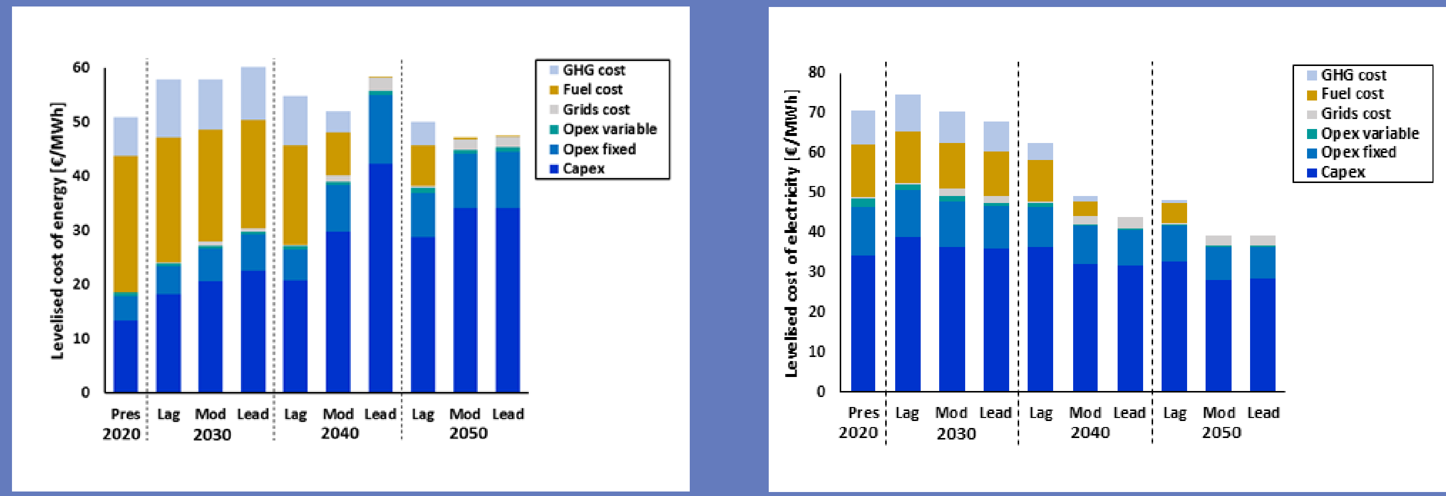

Figure 3.
Different aspects of the levelised cost of energy (left) and the levelised cost of electricity (right) across the three scenarios from 2020 to 2050 in Europe. Levelised cost of energy is defined by total annualised system cost divided by all final energy demand. Abbreviations: GHG, greenhouse gases; Opex, operational expenditures; Capex, capital expenditures.

Further reading:

- Reflecting the energy transition from a European perspective and in the global context – Relevance of solar photovoltaics benchmarking two ambitious scenarios, Progress in Photovoltaics 2022:1-27; DOI: https://doi.org/10.1002/PIP.3659
- On the history and future of 100% renewable energy systems research, IEEE Access 2022:10;78176-78218; DOI: https://doi.org/10.1109/ACCESS.2022.3193402

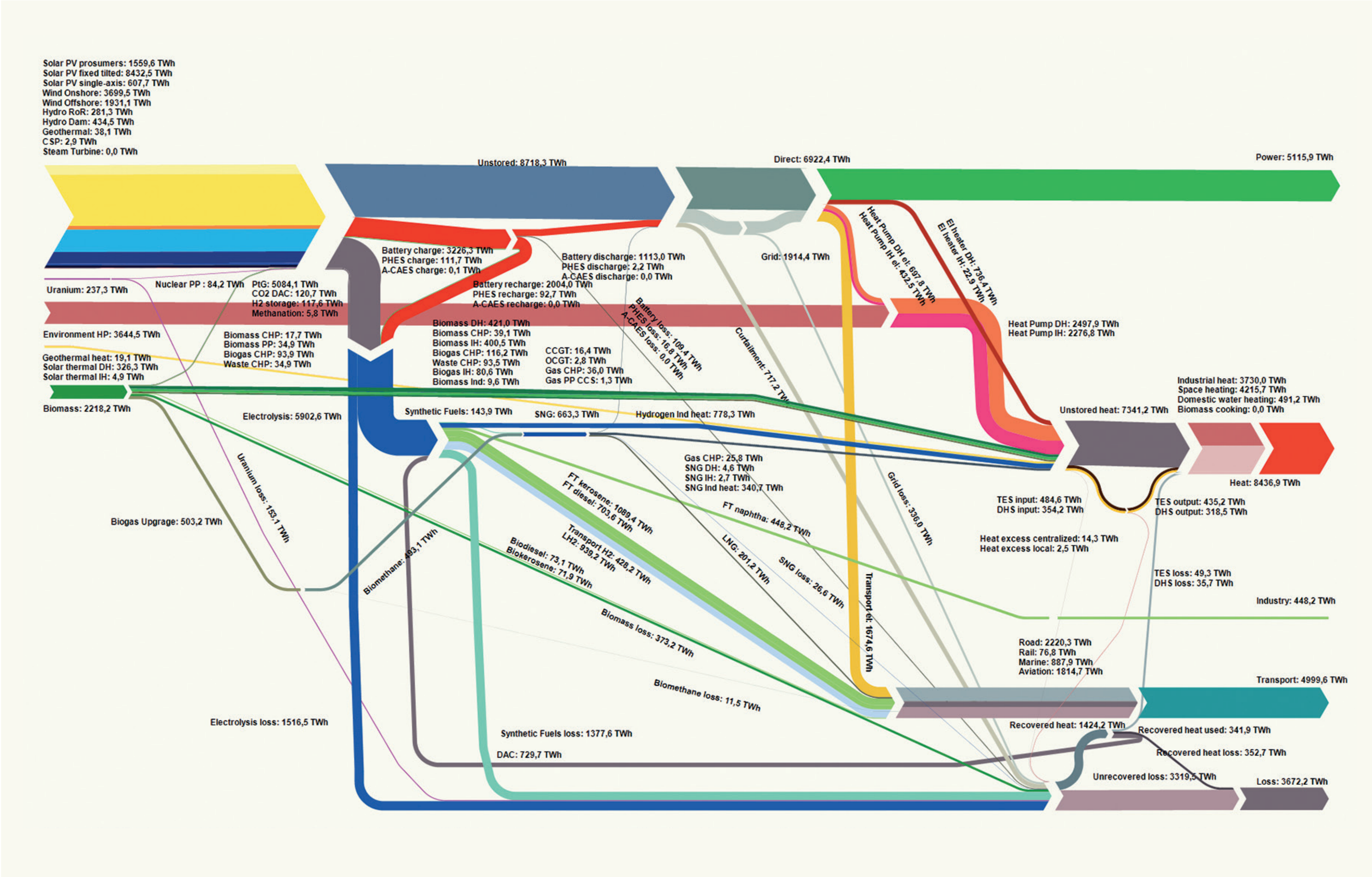

Figure 4.
Energy flows for the European energy system in the Moderate scenario in 2050.

Funded by the European Union, under the Horizon Europe programme, Grant agreement number 101075398. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.