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Building Blocks for an Energy Transition

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Abstract

The present need for an energy transition in the wake of a global climate catastrophe led to the "EU green deal" which requires a transition of the energy system in all countries. This study aimis survey aims to identify strategies within such an energy transition based on global trend analyses and reports on available technologies for implementation. Based on a literature analysis of over 300 pieces (of feasibility studies and technology implementation reports with a focus on Central Europe) and a statistical analysis of the levels of "energy intensity" (E/GDP) covering three decades and all countries worldwide, the diagnosis is made that steady improvements in several dedicated technological focus areas can be made and were made and could still be increased in the future, as required by climate targets. Across several distinct fields of energy economy, the concrete options for such improvements are portrayed: Energy infrastructure, Smart grids, Transmission grid management, Electricity storage, Heat storage, and Industrial waste heat; and linked with the diagnosed long-term trends emerging from the "Global Change Data Base" GCDB, allowing for a sectorial analysis of the so-called energy intensity, which was not yet delivered until now as time series in the literature. The main findings show which economic sectors and clusters of technologies can be most appropriate to achieve climate targets while safeguarding social aspects of sustainability.

Keywords
Potentials; energy costs; transiting; decentralised energy infrastructure; Europe; green deal; global change data base; GCDB

1. Introduction: The Policy Context

In energy policy, time is already pressing [1-14], and the paradigm of a required “energy transition” [15] is widely accepted [16-21].

The research objective consists in analyzing both (microeconomic) technological trends and (macroeconomic) trends in the energy economy and combining them into recommendations, which economic sectors provide high potential for enhancing the ongoing energy transition.

According to the study “The Austrian Energy Customer 2020” [22], two-thirds of Austrians want to generate electricity themselves already in 2020 and want to be prosumers [23-29], thus already being ready to change their consumer preferences and behaviour [30-36]. Hence, implementation of climate targets is urgently needed at the household, commercial, and industry levels, which consists of the topic's relevance.

The novelty of the results provided by this article consists of linking (i) the diagnosis based on country-wise correlations of statistical data on techno-socio-economic trends and (ii) detailed technological information about readily available technologies. Under the existing frameworks, this set of options will be fed into ongoing policy consultancy.

While these results apply to any country of the world at present, the limitations of the study include the status of novelty at the time of data retrieval, which has to be amended in a subsequent study.

The structure of the article starts with current narratives: three myths are discussed in the remaining Chapter 1, the introduction to the statistical method in Chapter 2, detailed technological availability assessments in Chapter 3, a synopsis of statistical and technological information in Chapter 4, resulting in strategic foci and operational opportunities, results in Chapter 5 and conclusions in Chapter 6.

1.1 Analysing the Frame of Existing Narratives: Three Myths

Within this frame, several myths [37] impede the energy transition, such as: "the energy transition poses insurmountable problems for the infrastructure"; but these myths can be invalidated by naming facts as follows.

Myth 1 "The power grids only have to be expanded at great expense because of renewables."
The facts: The main drivers for expanding the electricity grid are the liberalization of the electricity market and the European internal market. In addition, our networks are getting old and need to be renewed. Renewable energies are added, but conventional power plants require new networks [37-40].

Myth 2 "There is a risk of a blackout because the network expansion is progressing too slowly."
The facts: Grid expansion is vital for supply security and the transport of renewable energies. But the situation remains manageable, even if he were to come slower. The

grid could then not absorb all renewable electricity at certain times, and feed-in peaks would have to be curtailed. Reserve power plants must run more often [37, 38, 41-43].

Myth 3 "The energy transition jeopardizes the security of supply because too few power plants are being built." The facts: The liberalized market does not provide sufficient impetus to build enough new power plants. In the medium term, a new market design is needed that rewards electricity production and the capacities provided. This is the case with or without renewable energies [37, 40, 44-46].

1.2 A Meta-Study on Sector Coupling

Which overall strategy to choose now? Will our world be “all electric in a few decades and no trace of gas anymore?” According to a recent meta-study [47] on sector coupling, gas, gas infrastructure, and power-to-gas technology could play a vital role in the energy system of the future, based on the evaluation of a total of ten studies (including Fraunhofer, Dena, BDI, ewi ER&S, Öko-Institut), which have also dealt with scenarios for achieving climate policy goals.

The analysis shows those authors that there is a consensus that gas infrastructure can contribute to the energy transition. In most studies, a relevant gas consumption of more than 600 TWh remains in 2050, even with far-reaching decarbonization (for comparison: 2017 consumption at 985 TWh) [47].

In addition, the study reveals that in the German scenario, with a reduction in CO_2 emissions by more than 90% by 2050 compared to 1990, no consensus on suitable technologies and strategies can be derived in many sectors. In addition, the evaluated studies do not clearly depict the necessary measures and incentive structures to achieve the ambitious climate protection goals [48, 49].

Against the many uncertain assumptions, a strategy of openness to technology and innovation should, therefore, be continued [50-52]. Technology-open scenarios seem more cost-effective, especially in direct comparison with pure electrification scenarios [53].

1.3 The Double Approach of This Article: Technology Options Answer to Long-Term Trends

In the light of the above, the present article chooses the following approach:

1. Technology-oriented options are retrieved from a vast literature study (Chapter 3).
2. Their insertion into present-day energy economics and practice is deduced from an analysis of long-term trends (Chapter 2).

It is hoped that merging these analytic approaches facilitate implementation in practice.

2. Materials and Methods: An Evaluation of Long-Term Trends and Literature Review

The literature search undertaken [54] proceeds step-by-step and firstly undertook internet research and, secondly, a search in the Scopus and WoS (World of Science) databases regarding the following keywords [55]: Energy infrastructure costs, Electricity storage, Heat storage, Low-temperature district heating, Industrial waste heat, large heat accumulators, Island networks, Technology uncertainty, energy transition, infrastructure, Grid uncertainty, energy transition, infrastructure, energy storage technology, Energy transition infrastructure, Distribution network costs, Costs of decentralized energy networks, Cost of low-temperature storage, Costs of low-temperature district heating, Energy network dismantling costs, Prosumer households feeds, and Decentralized energy costs.

These search results were analysed [56-61], presented, and discussed among experts in the Austrian national environmental agency [62]. The model GCDB provides time series correlations, which was explained several times in the literature in detail [60, 63].

The choice of this methodology is based on the understanding that complex evolutionary processes create a momentum that propagates itself into the future and that, therefore, a suitable trend projection can inspire forward-looking. However, not only should a parameter be projected, but its first and second derivatives should be especially projected because the latter represent the values of a society [64]. The appropriateness of this technique is explained and acknowledged by Manolov [65], Şen [66], Ahamer [67, 68], and Garcia [69]. Overall, the data is taken from the most trusted international sources, such as IEA [70] and UNSTAT [71], after harmonizing the economic sectors ([72]: 146, [68]: 56, [63]: 70, [56]: 19) to allow for the creation of sectoral quotients describing the structural dynamics within energy economics.

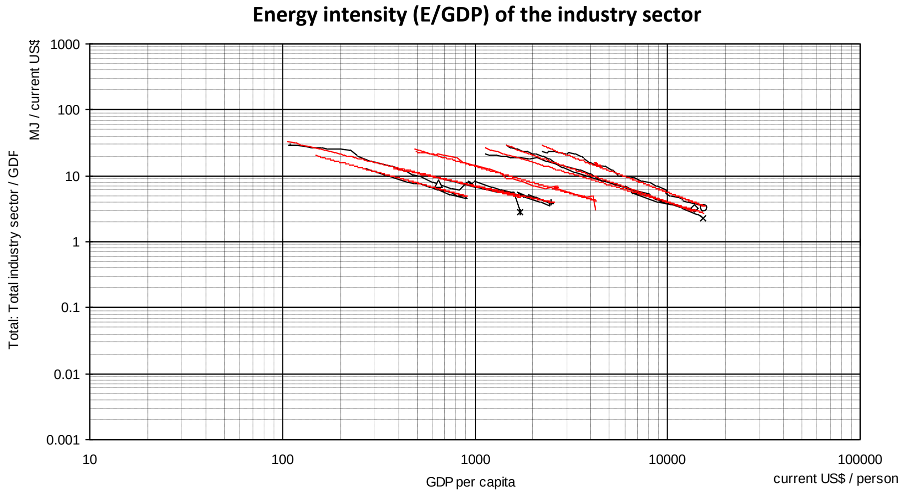
Data consists of a country-wise three-decade time series of over a dozen economic sectors. The sectorial quotients of energy intensity (E_i/GDP_i, with i meaning economic sectors in the UN statistics system, see Formula 1) provide the necessary energy input per economic output, named “energy intensity” [73, 74] in energy economics - a current descriptor of economic efficacy of energy utilisation, as used in IPCC scenarios.

$$CO_2 = (CO_2/E_{prim}) \cdot (E_{prim}/E_{end}) \cdot (E_{end}/GNP) \cdot (GNP/QL) \cdot (QL/P) \cdot P$$

Formula 1 Situating the sectorial energy intensity E/GDP [measured in MJ/US$] in the context of Cesare Marchetti’s [75] chain formula from CO_2 emissions to population leading via primary energy, final energy, Gross National Product, quality of life, and population (as indicated by the abbreviations in the formula). Compare figure in Ahamer [76].

2.1 Which Megatrends Do We Perceive? Sectoral Energy Intensity Keeps Improving

The author’s “Global Change Data Base” GCDB ([63]: 62, [60, 77]) allows for the detection and quantification of techno-socio-economic long-term trends. One interesting structural variable is the sectoral energy intensity (Figure 1, for the industry total, Figure 2, for single industrial sectors, and their change rates in Figure 3). The following figures provide average trends for each continent (discernible by their GDP/cap.) on sectoral energy intensities, which describe increasing or decreasing foci during the complex procedures governing the energy systems.



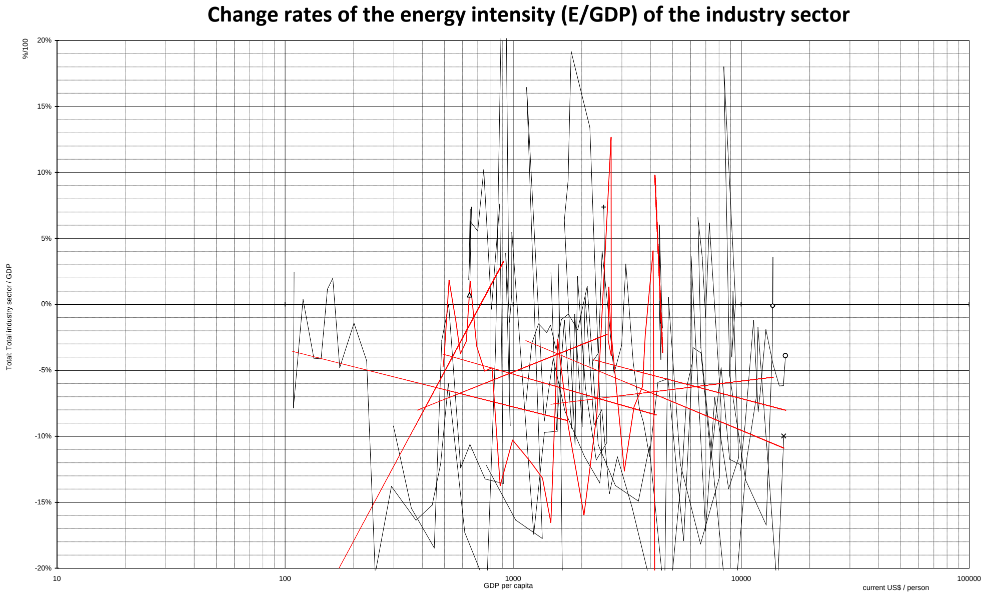


Figure 1 Above: energy intensity (E/GDP in MJ/US$) of the industry sector for eleven model regions; as a black time series and red exponential regression line. Below the change rate of the above values. Source: GCDB, IEA, UN. GDP/cap ranges horizontally from 10 to 100,000 $/cap (compare [63]: 78ff).

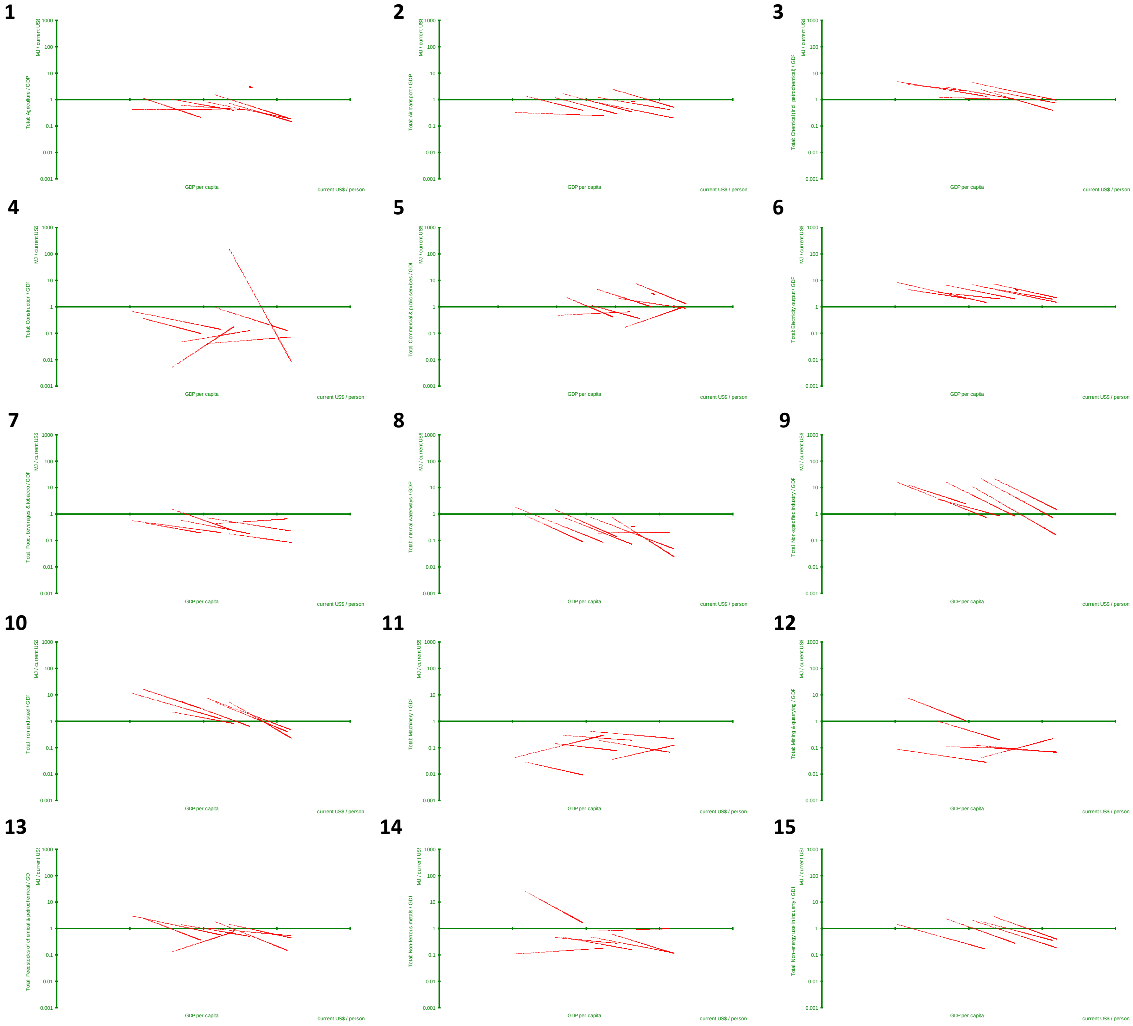


Figure 2 The same as in Figure 1 above, only for single industrial sectors (cf. [63]). From above left towards below right: 1. Agriculture, 2. Air Transport, 3. Chemical (incl. petrochem.) industry, 4. Construction, 5. Commercial & public services, 6. Electricity output, 7. Food, beverages, and tobacco, 8. Internal waterways, 9. Non-specified industry, 10. Iron and steel, 11. Machinery, 12. Mining & quarrying, 13. Feedstocks of chemical & petrochemical, 14. Non-ferrous metals, 15. Non-energy use in industry. Regarding units of this and subsequent figures, see the caption of Figure 1.

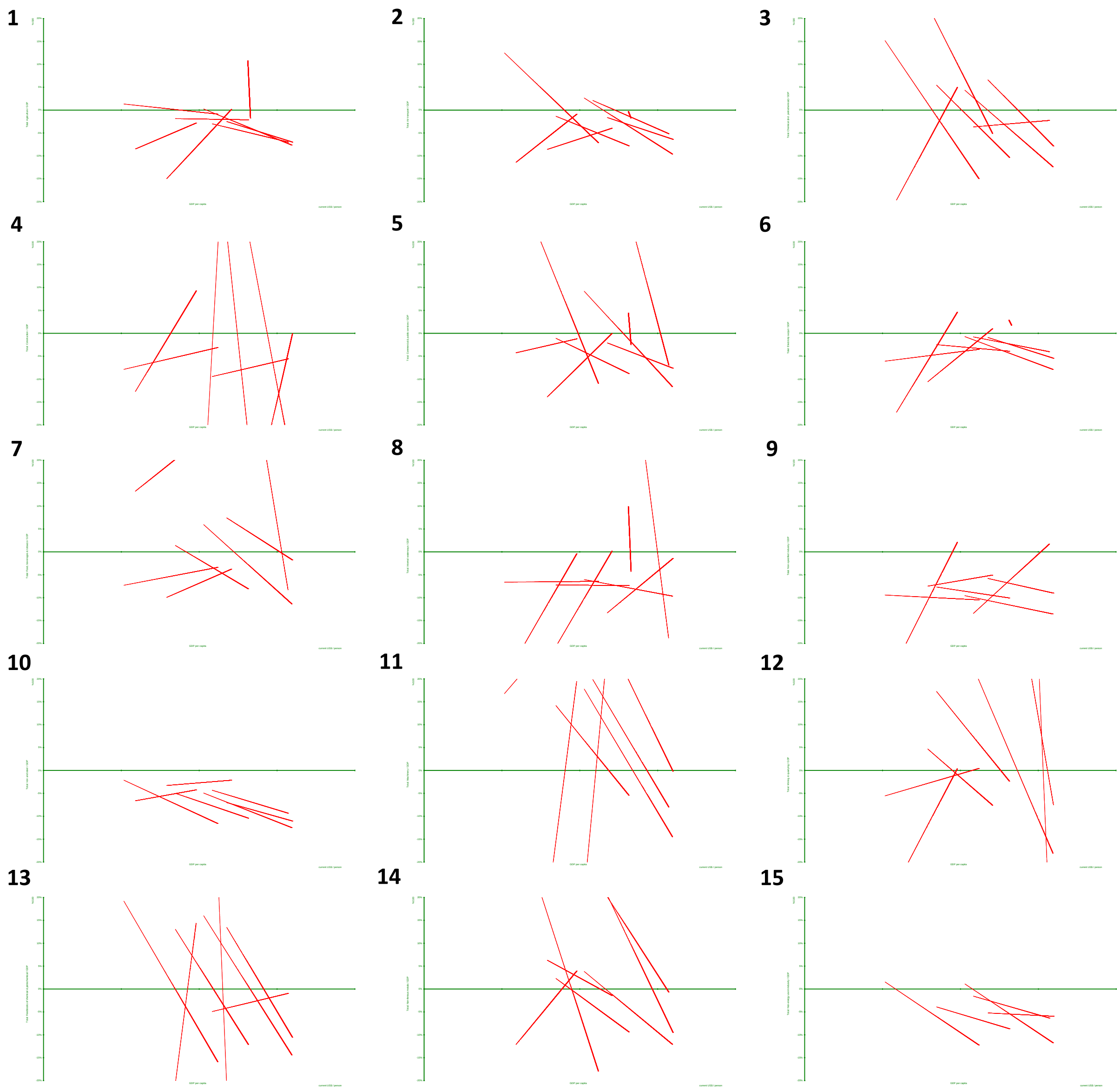


Figure 3 The same as in Figure 2, but it only shows the annual change rates. From above left towards below right: 1. Agriculture, 2. Air Transport, 3. Chemical (incl. petrochem.) industry, 4. Construction, 5. Commercial & public services, 6. Electricity output, 7. Food, beverages, and tobacco, 8. Internal waterways, 9. Non-specified industry, 10. Iron and steel, 11. Machinery, 12. Mining & quarrying, 13. Feedstocks of chemical & petrochemical, 14. Non-ferrous metals, 15. Non-energy use in industry.

From Figure 1, it can be seen that energy intensity is improving (i.e., lowering) in all regions across the world - while their change rates are diverse (Figure 2): especially regions with higher GDP/cap exhibit more consistently decreasing, i.e., improving, rates of change. This fact (graphically shown by the relatively lower lines on the right-hand sides within the images of Figure 3) encourages the search for improvement strategies in the latter countries.

Figure 2 informs about energy intensity in single economic sectors (as in principle needed for socio-economically informed energy modelling, e.g.: [78-80]), and all of them show the same principal behaviour, while Figure 3 adds more detail by showing their change rates.

The sectorial images in Figure 2 portray the energy intensity levels, and in Figure 3, the speed of energy intensity improvement: the lower an energy intensity is, the better the economic efficacity of energy use in that sector. Figure 2 shows the following sectors to work with relatively better energy intensity: 1. Agriculture, 7. Food, beverages, and tobacco, 8. Internal waterways, 11. Machinery, 12. Mining & quarrying, 14. Non-ferrous metals, while the following sectors work with relatively suboptimal energy intensity: 3. Chemical (incl. Petrochem.) industry, 6. Electricity output (cf. [81]), 9. Non-specified sector, 10. Iron and steel. From Figure 3 it can be seen that the following sectors exhibit a relatively fast speed of improving their energy intensity: 2. Air Transport, 3. Chemical (incl. Petrochem.) industry, 4. Construction (improving quickly, cf. [82, 83]), 6. Electricity output, 8. Internal waterways, 9. Non-specified industry, 10. Iron and steel, 15. Non-energy use in industry.

This diagnosis (1) can mean, on the one hand, that it remains possible to learn from well-advancing sectors by which concrete mechanisms of realistic progress were already possible and which socio-political frames might have favored them - to apply such auxiliary factors also to other sectors. (2) On the other hand, it may mean that the technological solutions offered in the following section may be even more promising when applied to not-yet improving sectors because they could still better develop their potential for improvement - as may be analysed in more detail in a later study.

2.2 Electricity Generation as a First Case Study

In the view of photovoltaics [32, 84], for a decade one key theme is the appropriate storage of electricity on a day-to-day basis for households [85-87], which would augment the solar harvest factor from 50% to 75%. As an overall assessment, during a sunny day, the electrical energy generated by PV is stored in the memory and removed again when required (e.g. in the evening [31]). Such an injection and withdrawal process can be conceptually compared with the new generation of this calculated kWh or added to its generation costs ([57]: Table 1) to compare the cost efficiency of electricity storage systems in the overall energy management system. Figure 2.6 and Figure 3.6 underline the high potential for an increasing and even accelerating potential (see Figure 3.6) for higher efficacity here.

3. Methods and Analysis: From Successful Cases to Structural Planning

3.1 Key Statements from Research Results on the Practical Status of Sector Coupling

The most important messages of the excerpts collected in this article are:

The energy transition is a systemic topic and does not open up to linear thinking.

In particular, couplings are required between

* Energy sources (e.g. electricity & gas: e.g. for long-term storage)
* End-consumption sectors (e.g. electricity & traffic: e-mobile buffer batteries and electricity & gas: space heating).

A core topic is the management of the time balance between the intermittent generation of renewables (solar & wind) and the (possibly shiftable, within certain limits) consumption. Previous "smart metering" does not yet provide this management. It only generates information (for load management).

Plug-in, grid-connected micro-PV systems can cover 50-70% of the electricity requirements of a 1-4-person household. The (modest) costs are € 450-600, and the payback time is around 11 years [88].

Regarding decentralized energy generation, a study by IHS & KPC gives the infrastructure costs per charging point for e-cars at 3080€; that is around € 0.2 to 1.2 billion annually in Austria, depending on the expansion scenario. The annual expansion costs range from 500 to 1200 €/MWh for biomass, PV, and wind. a with an expansion of 2-8 million MWh by 2030.

According to a market study by the German journal Wirtschaftswoche [85] for lithium or lead batteries, prices for electricity storage amount to more than 500 euros per kilowatt hour of capacity plus inverter and installation. Prices are currently falling by 18% per year.

Large heat storage systems are already being built, costs are not yet available, and only a few cost data are available for low-temperature district heating.

Industrial waste heat and process heat use: the amortization times are 0.3 to 7 years with very different technologies. The Austrian supplier Kelag invested around 6.5 million euros in constructing an 8.2 km long district heating line from Donawitz to Trofaiach, transporting 32 million kilowatt hours of heat annually for 6500 apartments from 2014 onwards.

Large heat accumulators bring costs (outdated by 2 decades) with 200-400 €/m³ storage volume, i.e. construction costs of 1 M € with 12000 m³ storage volume, for example, in Friedrichshafen-Wiggenhausen, Germany. A recent study indicates 50-150 €/m³ for such large storage tanks up to 450 €/m³ for smaller heat storage tanks. At 120-200 €/MWh, consumer costs are still slightly above biomass boilers as a technology comparison. According to Dr. Miedaner at Solites, large-scale solar thermal systems have system costs of 300-600 €/m² flat-plate collector or 50-130 €/MWh, in each case without funding. The Berlin AEE (=Agency for Renewable Energies) states that energy storage systems have been high on the political and scientific agenda since the beginning of the energy transition, even if the focus has so far been on the storage of electricity (from renewable energies). Up to now, district heat storage has been the wallflower of energy research. A German research company [89] was building a test facility for a new concept of a heat storage system based on molten salt.

Island grids can simulate control issues with a very high proportion of PV (including its only intermittent availability and, therefore necessary compensation), as was successfully tested using the example of a local distribution grid in Wildpoldsried in the German Allgäu region.

Other search keywords (technology uncertainty, energy transition infrastructure) turned out to be the starting point for a lot of further knowledge. For example, Roland Berger Consulting [11] provides the "24 most important questions of the energy transition" from an expert survey - trends and core uncertainties from the areas of political, economic, social, ecological; including “19 Development of Intelligent Power Grids” and “20 Advances in Energy Storage Technologies”. This "360° stakeholder feedback" results in four scenarios with the two main dimensions "technological integration" hi/lo and "market" versus "state".

Further, the exciting study “The value of gas infrastructure for the energy transition in Germany” [16] argues that strategically including gas infrastructure lowers decarbonization costs and increases supply acceptance and security for the energy transition. This first study shows that a *systemic* overview is necessary and that the mere addition of the sub-systems or sub-measures costs is insufficient. This second literature analysis calculates lower costs of € 13 billion per year when using gas infrastructure in Germany and further advantages in terms of network flexibility and security of supply. In addition to PtG (gas power), conversion back into power is considered possible but is currently still too expensive. The costs for an electrolyser were assumed to be in the lower range, but this is understandable because degression is expected.

The study: "Sector coupling - an integrated view" [16] suggests three criteria each for three stages of creating a value chain are assessed using their "energy policy target triangle", and some 24 scenarios are generated and discussed. While electrolysis investment costs today amount to 700-4000 €/kWh (electr.), estimates for 2050 are 200-700 €/kWh (el). Because it is not yet known which gases and technologies will prevail, technology-open regulations are constantly being introduced, quite reasonably. Three conclusions are drawn at the infrastructure level: 1. Understand parallel infrastructures as an option and as insurance, 2. Ensure openness in storage technologies; 3. Create a level playing field for flexibility. The core issue is to create acceptance in the population, especially regarding infrastructure facilities such as networks and generation plants. Today, it is unclear what the ideal energy system will look like in 30 to 40 years, and the path to its transformation is not yet known. The lack of knowledge of future developments - and thus also opportunities - also directly affects the topic of sector coupling and the energy transition in general. The relationships between energy consumption patterns, transport and storage infrastructure, and energy supply are also extremely complex and dynamic. The extensive lack of knowledge about the future must be taken into account in political decisions and framework conditions. Otherwise, politics will become volatile. However, today's predominant political approach is a philosophy of top-down control of the energy system: Based on the medium and long-term energy forecasts already mentioned, detailed energy management target systems are developed, which are then implemented with very concrete political interventions.

It is also possible that the "classic" technologies adapt to strict climate requirements, e.g., through "green fuels" (which should be produced sustainably [56]). To exclude this means to forego options. A policy that is open to the future accordingly also means deliberately not making certain decisions today, thus allowing open development. The infrastructure sector is characterized by long lead times and investment cycles. At the same time, the costs of maintaining partially competing infrastructures are very high. In the case of an overly restrictive policy and, for example, premature dismantling of specific infrastructures, the costs of an incorrect definition also increase immensely. If price signals adequately reflect scarcity, market players and not politicians should force the development of certain technologies. In summary, a definition is only required at the infrastructure level. Above all, this should represent a decision for a new infrastructure rather than a decision against an existing one.

A study commissioned by the City of Vienna: "Alternative financing models with a special focus on (energy) infrastructure projects" [18], concludes There are changed framework conditions on the financial markets, as well as the growing financing pressure in the municipalities and the increasing willingness of citizens to get involved in real (energy) projects invest that make many financing models feasible; these were discussed in a workshop.

According to the study "The Austrian Energy Customer 2020" [22], two-thirds of Austrians want to generate electricity themselves by 2020 and want to become prosumers. They would prefer to heat with solar thermal energy or heat pumps and be on the move with alternative drives. The same applies to energy: "Together and sharing" are the new "having" (importance of the co-creative change in the concept of property).

The very informative study "Electricity Future Austria 2030" [86] by Vienna University of Technology is based on the Environment Agency Austria’s [90] study "Renewable Energy 2030 and 2050" (providing the Reference & RES scenarios which are similar to the WAM+ scenario, meaning “with additional measures”). The RES scenario reduces the average spot market prices of €3.35/MWh, and Austria becomes a net solid electricity exporter. The additional necessary pumped storage expansion is included in all scenarios - with and without the flexibility options electromobility and P2H (power to heat) - in the shallow range of 140-200 MW. The coupling of the electricity sector with the transport and heating sector leads to significant electricity peaks with maximum loading peaks at 5.9 GW. The greatest impact of the flexibility options examined is a stabilization of the PV market value by 10 percentage points. Electromobility plays the most crucial role here since P2H only has a low power consumption in times of high photovoltaic feed-in. Through the increased expansion of renewable energies, CO_2 savings of 13.5 Mt CO_2 can be achieved, i.e., even by +86% compared to the RES scenario - and this entails significant employment effects: 36,000 to 53,000 full-time equivalent jobs. To accomplish the RES targets, on the other hand, the total funding requirement ranges between around €250 million and €5271 million per year, depending on the funding policy, the development of electricity prices, and the market value of decentralized photovoltaics. In the author’s opinion, what is surprising in contrast to the German study is that the possibility of technology-specific funding for individual technologies would enable an ideal design of instruments for the respective technologies. This would result in a cost-effective path for each technology. On the other hand, a system change towards a technology-neutral quota obligation combined with tradable green electricity certificates astonishingly proved to be highly inefficient in terms of costs. The expansion potential for photovoltaics amounts to over 20 TWh in 2050, for wind power almost 30 TWh, around 3.7 TWh for small hydropower, and 7.6 TWh for large hydropower, and can only be realized with optimistic assumptions about social acceptance. Overall, the projected expansion potential for 2050 is over 50 TWh. Geothermal energy only 19 GWh. By means of building district heating storage tanks (e.g. in the third-largest Austrian city of Linz with a height of 65 m, 34,500 m^3 of water, 55° to a maximum of 97°C), the heat generated by a CHP (combined heat and power plant) can be temporarily stored, and thus the electricity and heat requirements can be decoupled which indeed solves a crucial problem. Furthermore, an electric car share of 31.7% for the year 2030 (value from the related WAMplus scenario) was assumed,and that all-electric cars can be charged at night at home with 3.52 kW. In this way, e-mobility generates an additional peak load of 3.2 GW (i.e. about as much as for district heating). With controlled charging, electric cars avoid charging exactly when the peak load occurs. Admittedly, such a comprehensive control system has first to be installed everywhere. Modelling of the supply side teaches that electromobility and exports most often utilize surplus generation. Pumped storage needs 30-40% electricity price differences to compensate for the pumping losses and is active less usually. Power to Gas (P2G) is not built in any scenario, representing a fundamental difference to scenarios computed for Germany.

On a more general and paradigmatic level, the critical point for a successful energy transition in the early stages are the associated new social patterns, virtual and actual communities, and online cooperation, i.e. social innovation in "co-creation". In the same vein, and based on Herman Daly’s [91] terminology of an empty world now becoming a whole world, the well-known German author von Weizsäcker states: "The ‘full world’ needs a new enlightenment".

3.2 Results for the Single Themes Within Energy Technology Development and Deployment

3.2.1 Renewable Energies Integration

The market integration of renewable energies in Germany [92] requires an economic and legal assessment of increased direct marketing, which can set a vital impulse for networking renewable energies. Higher transaction costs and overall economic loss would arise without a firmly steering state and more market freedom. The total benefit of mandatory direct marketing remains limited. The flexibility differences between the technologies (e.g., hydropower and wind power, including heat: [93]) should be observed in further developing the legal basis to carry out a more severe expansion control. It should be noted that the safe power supply is a very precious asset. A careless approximation of the power supply to the free market with the hope that it alone will produce security of supply can be a great danger [55, 92].

Overall, direct marketing is a positive instrument, especially since such a large task as the power supply conversion cannot be mastered with a single measure. Direct marketing is an essential component of the market integration of renewables [92].

3.2.2 Smart Cities: A Techno-Socio Compound

New science-oriented and knowledge-based districts emerge in the smart cities of Graz [57, 58, 94], in the model region "Graz-Reininghaus" [95-97] and Mannheim [98] to facilitate the energy transition. An almost entirely new district for 9,000 people is being built in Mannheim on 144 hectares. The latter area, named Franklin, comprises buildings of all kinds- from the family home to the shopping centre and the complete infrastructure. A network control station for the energy flows of the new district provides district heating from the Mannheim power plants. Power-to-heat should also contribute to heat supply. This only makes sense economically because Franklin's electricity in this research project will be used as a real laboratory within a research and demonstration project and is thus exempt from the otherwise due taxes. Smart meters make high-resolution real-time metering and energy management possible, allowing for informed decisions in energy providers [99] and integrating the supply from the on-site PV systems [98].

The focus is not on the highest technological standards but on other aspects. What data does one need to optimize the energy supply? What is economically feasible? How can the user behaviour be influenced in such a way that it contributes to network stability? These questions are asked to a user group that does not strive for the highest ecological standards. Most people will live in Franklin, who cannot afford zero and plus energy houses. Instead of a concept that dispenses with individual mobility, Franklin combines the variety of existing demands [98].

3.2.3 Transmission Grid Management: Testing Small Regions

What does a percentage of over 50 percent renewables mean for the transmission network? The growing number of PV in the transmission network challenges the system management engineers [100] and calls for removing the growing number of network bottlenecks. In a first step, this can happen through network-related measures [101], namely, controlling the load flows so that top loads are avoided. If this is not enough, power plants are called to adapt their production. Without these interventions in the load flows and the production, the stability of the power supply system could not always be guaranteed. With the quick expansion of renewable energies, these interventions are increasing steadily. Currently, the network expansion is not keeping up with the rapid expansion of renewable energies [100].

Large projects in a small village can serve as a network laboratory: In Sonderbuch, a town in the Swabian Alb region with around 190 inhabitants and 70 PV installations in South-Western Germany [102], the fed-in PV input exceeds the maximum electricity load six times at peak times. Due to this high penetration of photovoltaics, Sonderbuch (Figure 4) represents a suitable experimental sample to research concepts and equipment to reduce or move network expansion in the future. This tiny village has thus become a central network laboratory for low voltage. The public utility, i.e., the networks company, tested here in a realistically functioning electricity supply network environment in a long-term experiment, namely with real customers and ongoing network operation, innovative technologies and processes for integrating photovoltaic stream [102].

Figure 4 Sonderbuch in South-western Germany has 190 inhabitants and 70 photovoltaic installations and shows an integrated small-scale energy infrastructure [102].

Technically, the substantial expansion of decentralized production results in a regular reversal of the load flow, which might result in injuries to the permissible voltage band and an overload of electrical equipment. This risk requires massive investments to increase the connection capacity through larger cross-sections of the lines and increase the performance of the transformers [102].

In the Sonderbuch network laboratory, however, the public utility has relied on innovative technology since 2011: intelligent meters, continuous measurements at various strategic nodes, and the low-voltage exits of the three local network stations provide significant data on the current network state. One of the first adjustable local network transformers was installed based on the data obtained. This controllable transformer automatically reacts to changing network states and prevents voltage hikes. In addition, a lithium-ion battery memory was installed, which can switch between storage and feeding [102].

3.2.4 Smart Grids in Germany and Beyond

The German project ENERA shows that purely Smart Grid projects are no longer sufficient for a structural energy transition [103, 104] while using the three Northern German districts of Friesland, Wittmund, and Aurich, as well as the independent city of Emden serve as a coherent model region in northwestern Lower Saxony. With a renewable electricity share of 235%, significantly more regenerative energy is already generated here than consumed. In this case study, network, market, and data act on an equal footing, thus demonstrating the future energy system's continuous digitization and technical flexibility through a systemic approach. Network operators face new challenges because consumers are becoming more and more dynamic. Therefore, the standard load profile is outdated and should be reconsidered, including through innovations such as controllable local network transformers and improved consumption forecasts [103].

Within the German ENERA project, around 30,000 intelligent measurement systems were installed, and a generic data ecosystem was established. The population of the model region was included, thus implementing the next big step of the energy transition, namely the support of the people who are not excluded from the transition process. The quite unconventional communication concepts include a road trip that reached over 50,000 people in one year and qualitative interviews on creating profiles and their further development to symbolic, representative personas in the region [103].

Reuter [105] and his team create the largest of these model regions, extending over the German federal states of Baden-Württemberg, Bavaria, and Hesse, entitled "C/Sells", a project with 56 partners from science, industry, and utilities with a view to successful dissemination in the mass market. The letter "C" stands for cells constituting the entire model region, while "Sells" refers to new business models that create new economic structures and opportunities with the digital energy transition. On the one hand, the energy industry must gradually adjust to new players and, on the other hand, keep the energy supply stable despite all changes, volatilities, and uncertainties.

Starting from over 30 demonstration cells, a variety of cellularly structured energy systems are shaped by the active participation of citizens and stakeholders involved. In addition to the demonstration cells that demonstrate technical solutions and market investments and the participation cells with special attention to communication, this project also invites cities to join Reuter’s [105] societal movement. A massive rethink in terms of habits in dealing with energy or energy services is necessary to keep frictional losses in transforming the energy system.

The Windnode area is one of five model regions in Germany, promoting a second phase of the energy transition" [106], representing one of the five "real laboratories" funded by the German Federal Ministry of Economic Affairs and Energy. The aim is to efficiently integrate large amounts of renewable electricity into the energy system while keeping the power grids stable. Windnode comprises all East German federal states, including Berlin. Faring populated areas with lush wind power capacities are connected to urban load centers and around 11 million power grid connections. Today, the local electricity mix is more than 50% renewable. And now, the focus lies on a cross-sectoral use of data. The preparation and visualization of large, complex data supports decision-makers and informs the interested public [106].

3.2.5 Synthesis with Economic Structural Change: Sectorial Needs Keep Evolving

Figure 5 shows ongoing shifts of energy demand within the economic structure of the eleven world regions, focussing on agriculture, industry, and the electricity generation sector, namely the averaged timelines of the shares of energy demand with the given sectors. Increasing red lines mean a growing percentage of energy demand within total energy demand.

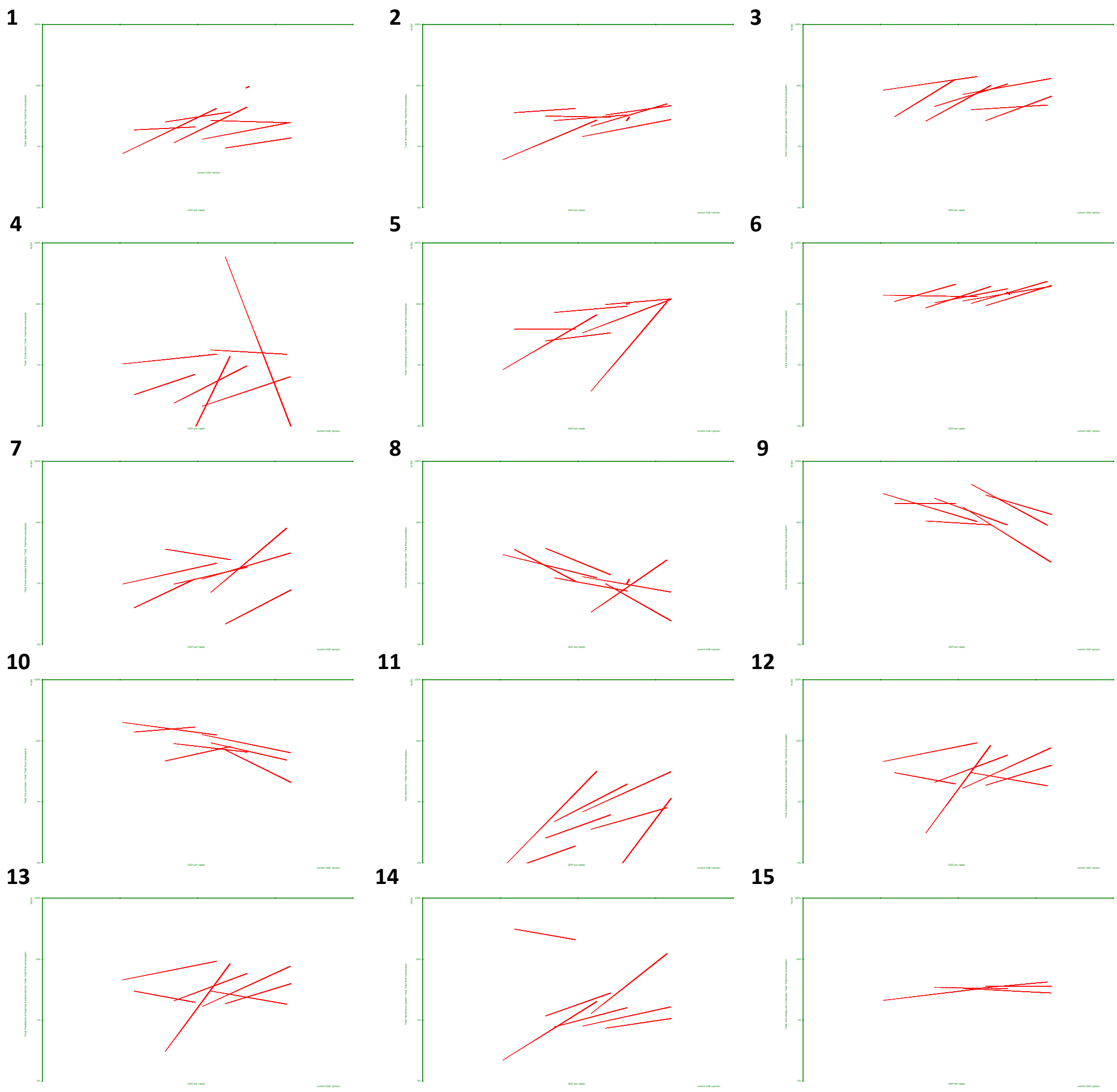


Figure 5 The shares of various economic sectors within the economies of eleven world regions. Starting from above left: 1. Agriculture, 2. Air Transport, 3. Chemical (incl. petrochem.) industry, 4. Construction, 5. Commercial & public services, 6. electricity output, 7. Food, beverages, and tobacco, 8. Internal waterways, 9. Non-specified industry, 10. Iron and steel, 11. Machinery, 12. Mining & quarrying, 13. Feedstocks of chemical & petrochemical, 14. Non-ferrous metals, 15. Non-energy use in industry. Data source: GCDB, IEA, and UN statistics ([63]: 78ff).

Linking together the data from Figure 2 and Figure 3 with the data from Figure 5 shows that the sectors with a (i) high and (ii) growing share within national economies especially show the effects of increasing efficacy. This message underlines the importance of actually taking the options described in the literature analysis of Chapter 3.

From Figure 5, the following diagnosis can be made: economic sectors with growing shares of energy demand are: 1. Agriculture, 2. Air Transport, 3. Chemical (incl. petrochem.) industry, 5. Commercial & public services, 6. electricity output (starting from an already very high level), 7. Food, beverages, and tobacco, 11. Machinery, 12. Mining & quarrying, 15. Non-energy use in industry. Economic sectors with decreasing shares of energy demand are 8. Internal waterways, 9. Non-specified sector (here, starting from an already very high level), 10. Iron and steel (more geographical data can be found in the book [63]).

4. Results: Integrating the Above Partial Findings

The findings in this article stem from both statistical analysis and literature analysis. With a focused view on the "energy transformation" [107-109], it is possible to combine these two approaches in a synthesis of policies [110-113] while obeying available technologies [114] as follows:

- Various sectors of industry are prone, ready, and inclined to apply (but should be motivated more by tools of economic policy) systemic improvements that will increase overall efficacity, such as exploiting waste heat on several temperature levels ([54, 57]: 189, [58]: 239), inputting their waste heat into municipal heat grids at various temperature levels, and including heat pumps into their technological designs
- Households [115], commerce, and suitable industrial sectors should proceed using biomass energies as already familiar in Austria and Central Europe [54, 57, 116] at points in time when no (admittedly intermittent, but complementary) trustworthy non-carbon energy source is available, namely solar combined with wind.
- Transferring the traffic sector to electricity and gas is facilitated for corporate vehicle fleets.
- Apply diurnal and seasonal energy storage (esp. electricity and heat) in households, commerce and industry [117]
- Hydrogen as an intermediate energy carrier may, of course, only be included in strategies to the extent it is produced sustainably, without fossil input [118-120]
- The continued growth in the need for energy in agriculture (and food production) should be met by biofuels instead of fossil fuels, given the geographic and organizational proximity to waste biomass, thus also improving the level of carbon neutrality ([56]: 21-24).

Accompanying social policies should resolve potential inequalities of chances in order to also care for societal sustainability [121-123] while maintaining nature's vital functionalities [124].

5. Discussion: Lessons Learned for the Energy Transition

The above technological details and cost data (e.g., [125]) can serve to identify a path towards national energy transition.

The most important messages of the analysed articles are:

The energy transition is a systemic topic and does not open up to linear thinking.

In particular, couplings are required between

* Energy sources (e.g. electricity & gas: e.g. for long-term storage) and including biomass energy [126-131] or even waste [132]

* End-consumption sectors (e.g. electricity & traffic: e-mobile buffer batteries and electricity & gas: space heating).

The gas network may act as a source of flexibility when coping with a scientifically required CO_2 reduction target [133, 134]. In most of the studies considered, however, a relevant gas consumption of more than 600 TWh remains even in the year 2050 and with far-reaching climate protection goals. Some studies [47] emphasize the critical role of power-to-gas, especially for solid climate protection efforts.

In a scenario of minus 95 percent CO_2 emissions for Germany, synthetic gas would account for three-quarters of gas consumption, according to the meta-study. Power-to-gas thus might play an innovative role as "deep decarbonization" technology. Some studies see the need to build large-scale power-to-gas plants. The first small-scale pilot projects already exist. In that study's view [47], the role of the gas infrastructure as a source of flexibility is exciting in the case of "deep decarbonization". Surplus green electricity is converted into synthetic gas and, if necessary, converted back into electricity. Therefore, all the studies examined assume that gas pipelines and storage facilities will be retained. "This meta-study shows that the complexity of the sector coupling discussion is even higher. In this respect, drawing up an action program within the envisaged period harbors the risk of making hasty decisions." [47].

Moreover, the policy-relevant link between open, democratic societies and successful energy transition should be noted - Magazzino et al. [135] is one of the few articles including this aspect while focussing on a statistical analysis.

The most rigorous result from the analysed evolutionary paths of the GCDB is that the energy intensity is improving (i.e., decreasing) in all sectors but with a focus on industrial sectors (as of now), and is accelerating in these same sectors (see Figure 4 and Figure 5).

6. Conclusions

This article follows the world view of the former German chancellor Willy Brandt who said: "The best way to predict the future is to design it" [136, 137].

On a more general and paradigmatic level, the key points for a successful energy transition in the early stages are the associated new social patterns, virtual and real communities, online cooperation, i.e. social innovation in "co-creation". In the same vein, the well-known German author von Weizsäcker stated: "The 'full world' needs a new enlightenment". The task of a transdisciplinary and synoptic energy science is to bring the transformative power of this general enlightenment down to earth during the ongoing energy transition.

The conclusions from GCDB trends focus on the energy transition, technological details, and phasing. From Figure 5, the following diagnosis can be made: economic sectors with growing shares of energy demand are: 1. Agriculture, 2. Air Transport, 3. Chemical (incl. petrochem.) industry, 5. Commercial & public services, 6. electricity output (starting from an already very high level), 7. Food, beverages, and tobacco, 11. Machinery, 12. Mining & quarrying, 15. Non-energy use in industry. Economic sectors with decreasing shares of energy demand are 8. Internal waterways, 9. Non-specified sector (starting from an already very high level), 10. Iron and steel.

Policy implications mainly contain the necessity to foster the energy transition in all its phases, namely by state funding in the initial phases and by regulating prices in advanced stages while maintaining social equilibrium. The specific sectors to focus on are derived from the enumeration above. Further research may include validating the diagnosed trends during more recent decades, including the effects of the war of attack on Ukraine, including the resulting opportunity to leave a fossil fuel-centered path and thus regain energy-related sovereignty. Limitations of the study include statistical biases when transnationally comparing statistics on energy and economy and the need to delve into the feasibility of recommended technological change under market conditions and the global investment climate.

Abbreviations

GCDB	Global Change Data Base
IEA	International Energy Agency
UN	United Nations
GDP	Gross Domestic Product

Author Contributions

The author did all the research work of this study.

Competing Interests

The author has declared that no competing interests exist.

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