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RESEARCH ARTICLE

Technology Transitions Towards a Green and Low-Carbon Economy

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Abstract: The present research analyzes over 300 pieces of literature and specifies the opportunities how a "EU Green Deal" on energy systems can be practically implemented in a country such as Austria, Germany, or any other state. In order to facilitate a real-world structural transition of the energy system towards non-carbon sustainability, both (i) technologies and (ii) underlying long-term trends are evaluated. (i) Results show present levels of feasibility for smart metering, micro-PV systems, electricity storage, heat storage, diverse industrial applications, smart cities, sector coupling, bridging time through energy storage, using the existing gas infrastructure, decentralized energy conversion, low-temperature district heating, heat management, large heat accumulators, the Big Solar project in Graz, Austria, industrial waste heat, island networks, and an equally needed "heat transition", while adopting a system dynamics viewpoint. (ii) Inspired by long-term trends as rendered visible through the "Global Change Data Base", especially that end-user-friendly energy carriers increase their market shares. Thus, a conclusion, a structural societal transition is an indispensable component of the "energy transition" worldwide, mainly based on solar and wind energy. The structure of an energy economy mirrors the views that a society has of itself: flexible, sustainable, and self-responsible.

Keywords: potentials, systemically transiting, energy transition, renewables, smart grid, decentralized energy infrastructure, heat transition

Based on the widely accepted **European Green Deal**[1], as a long-term strategy for accelerating a sustainable transition, concrete measures and viable technologies are needed to implement such a **techno-socio-economic evolutionary revolution** [1–4]. Within the Green Deal (and climate protection as such), the domain of energy strategies is certainly the deciding theme.

The present analysis builds on a detailed literature analysis [5] and continues an earlier analysis by the same author on "Potentials and costs for the transition of decentralized energy infrastructure in Europe". **Systems dynamics** as a guiding idea was introduced there and yields the following main key cornerstones:

1) Bridging *time* through energy storage (e.g., within a day, or from summer to winter)
2) Bridging *space* through coupling between energy carriers (e.g., electricity to gas)
3) Including waste energy (e.g., waste heat from industry)
4) Integrating different temperature levels in a system dynamics view (e.g., for heat)
5) Building self-sufficient local and regional cells of energy supply
6) Smart networks: lowering prices through decentralization
7) Energy transition is a systemic, non-linear topic, requiring a systems dynamics view.

Taking the energy structure of central European countries (such as Germany and Austria) as a starting point, several concrete and technologically mature energy strategies are proposed which can support the real-world transition of a national energy system, and within this text especially of the heat system's "heat transition" [6–11], where often municipalities are a driving force [12–15].

Within the Green Deal (and climate protection as such), the domain of energy strategies is certainly the deciding theme [16], as corroborated by scenarios comparing CO_2 emissions from energy and biosphere. A plethora of energy modeling exercises has been performed so far, and the present literature study dwells on several of them [17–19].

1. Introduction

1.1. Setting the frame

In order to facilitate an energy transition in a given country, fundamental information on the structure of the existing system, including its costs, became necessary, such as:

1) What does (de-)central power and energy infrastructure cost now?
2) What will (de-)central power and energy infrastructure cost in the future?

On a general level, the conclusion was made in an earlier article that infrastructure costs approximately 1–2 M€/km for energy lines of electricity, gas, oil, and heat [5, 20].

The scope of this present literature analysis includes the following themes: Heat storage; Low-temperature district heating; Industrial waste heat; Large heat storage; Isolated networks, Technological uncertainty, energy transition, infrastructure; Grid uncertainty;

[1]The European Green Deal. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.

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Energy transition; Energy storage technologies; Energy transition infrastructure; Distribution network costs; Costs of decentralized energy networks; Cost of low-temperature storage; Cost of low-temperature district heating; Energy network dismantling costs; Prosumer household feeds; and Decentralized energy costs [21].

1.2. Thinking in terms of transitions

The general thinking followed in this analysis follows the concept of evolutionary transitions [22].

This is underlined by a report by The World in 2050 [23] as presented to the UN in New York, setting out six key transformations that will enable the world to meet the UN Sustainable Development Goals (SDGs), exploring "six transformations and pathways that take a comprehensive approach to attaining the 17 SDGs, with a view to ensuring a prosperous and healthy future for all on a resilient and healthy planet. The emphasis is on synergies and multiple benefits that render the SDGs achievable", as emphasized by IIASA Deputy Director General and long-standing energy expert Nebojša Nakićenović. The challenge ahead consists of non-linear interactions in current societal dynamics [23].

1.3. The conceptual starting point: thinking openly about the future

In a frame of contemplating suitable paths towards climate protection [24–26], this article presents most succinctly some key findings of an earlier literature analysis on energy transition pathways [27]. One challenge for a worldwide energy transition lies in the fact that its goals are largely set out today but technology choices turn out their usefulness only tomorrow [28]. Among other aspects, it seems also clear that sector coupling plays a decisive role within energy-related measures [29].

However, it is unclear today what the ideal energy system will look like in 30 years: It is neither foreseeable today which future technology mix will prevail economically in view of consumer preferences and cost trends, nor what the transformation path will actually look like and when which decisions will be made by the actors [30] and above all politicians [31]. The relationships between energy consumption patterns, transport and storage infrastructure, and energy supply are also extremely complex and dynamic [29, 32].

One strategy to assess long-term structural energy is the "**Global Change Data Base**" (GCDB) which is explained thoroughly in References [33–36]. The GCDB exhibits evolutionary patterns for all countries in the world during the past decades for energy-related variables, namely as a function of the economic level (measured as GDP/capita); thus, re-normalizing all countries of the world into **one single graphic pattern**. As a first example, Figure 1 plots the "energy intensity", i.e., the efficacy of energy use in a given economic sector (here, the sector of agriculture) while using the quotient of "E/GDP" plotted against GDP/cap. (The word "total" in Figure 1 means that the total of all energy carriers is used here.) Each red line represents time-averaged data from one country during three decades [33]. Figures 1 and 2 [34] show clearly that during the last decades, the agricultural sector became ever more energy-efficient – both in countries with lower or higher GDP/cap. Therefore, Figures 1 and 2 [34] can be considered a portrait of the worldwide structural shift towards more economic output per energy input, and hence a trend towards improved (thus, lowered) energy intensity, while similar trends were often corroborated by literature [37].

The following Figures 3 and 4 [34] show a more detailed portrait of the countries' **sectoral energy intensities** and its **dynamic development** by yielding the same images as above for various other economic sectors.

Overall, the first four figures illustrate that **any "energy (r) evolution" sits on a complex dynamic (dis)equilibrium of continuously ongoing structural changes** within global energy markets [38]. Hence, every climate protection measure is well advised to take into account such evolutionary "underwater

Figure 1
The energy intensity (=E/GDP) in the agricultural sector decreases visibly during three decades in all world countries along an evolutionary growth towards higher GDP/capital

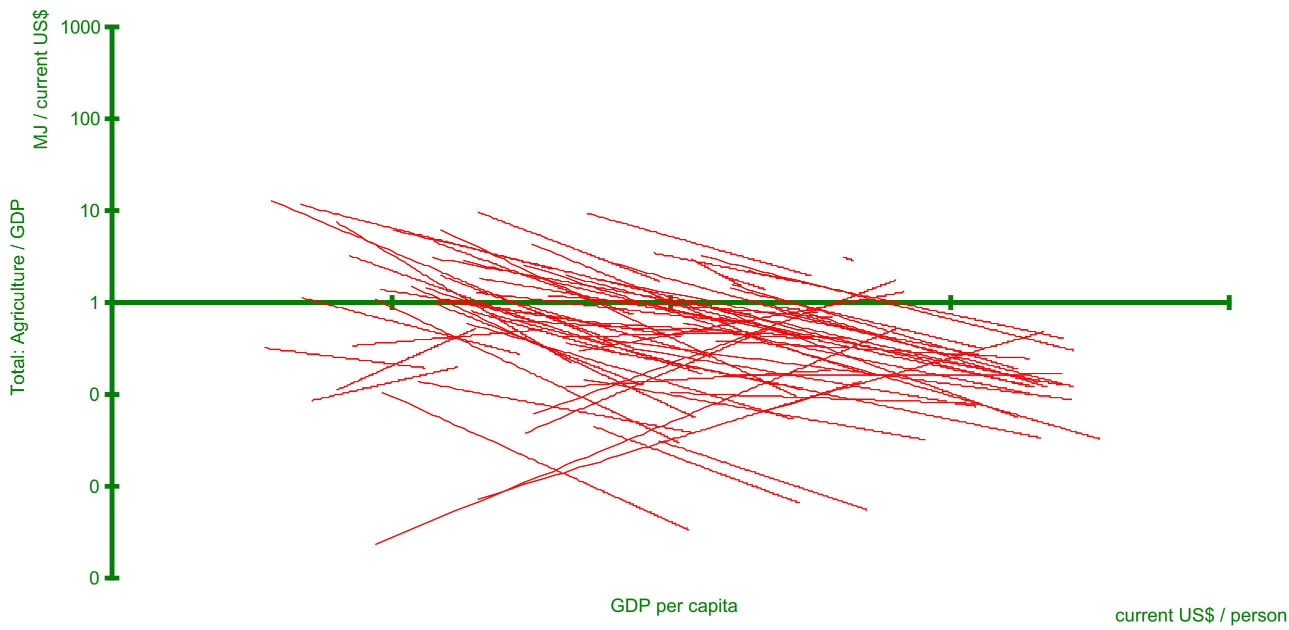
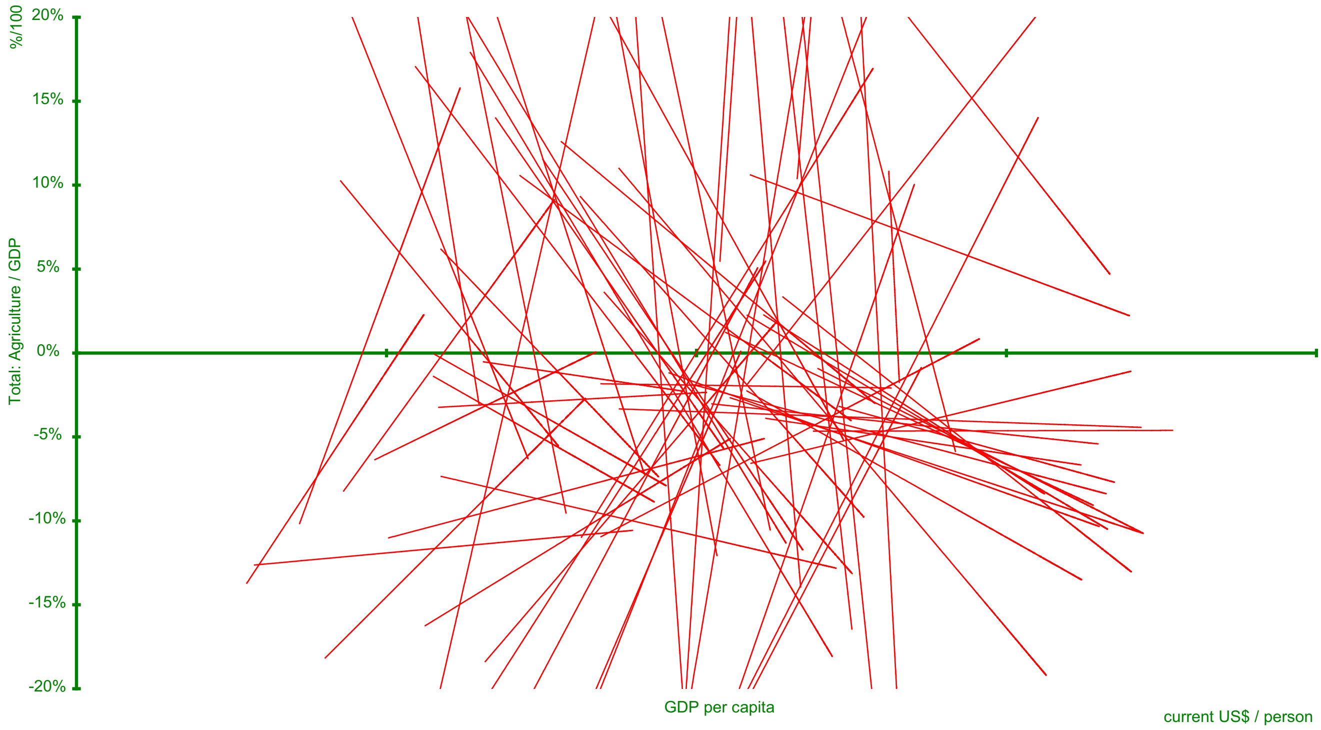


Figure 2
The rates of change on a linear scale from –20% to +20%



Note: When moving towards higher GDP/capita, the change rates for the energy intensity of the agricultural sector remain largely negative (around –5%/year) in the world's richest countries (represented by a GDP/cap above 10,000$/cap) but overall show a more irregular behavior.

currents" in the sense as Kon-Tiki was able to cross the Pacific Ocean [39].

2. Materials and Methods: An Evaluation of a Literature Survey

The present literature analysis proceeds step-by-step and firstly undertakes internet research and secondly a search in the Scopus (https://www.scopus.com/) and World of Science (https://www.webofscience.com/) databases, regarding the following keywords:

1) Energy infrastructure costs
2) Electricity storage
3) Heat storage
4) Low-temperature district heating
5) Industrial waste heat
6) Large heat accumulators
7) Island networks
8) Technology uncertainty, energy transition
9) Grid uncertainty, energy transition, infrastructure
10) Energy storage technology
11) Energy transition infrastructure
12) Distribution network costs
13) Costs of decentralized energy networks
14) Cost of low-temperature storage
15) Costs of low-temperature district heating
16) Energy network dismantling costs
17) Prosumer household feeds
18) Decentralized energy costs.

The search results were analyzed, presented, and subsequently discussed among experts in the national environmental agency.

2.1. Electricity

When using an electricity storage facility, during a sunny day, the electrical energy generated by photovoltaics is stored and used again when required (e.g., in the evening). Such a process can be conceptually compared with the new generation of the amount of the calculated kWh and also added to its generation costs in order to obtain a comparison of the cost efficiency of electricity storage systems in the overall energy management system [36, 40].

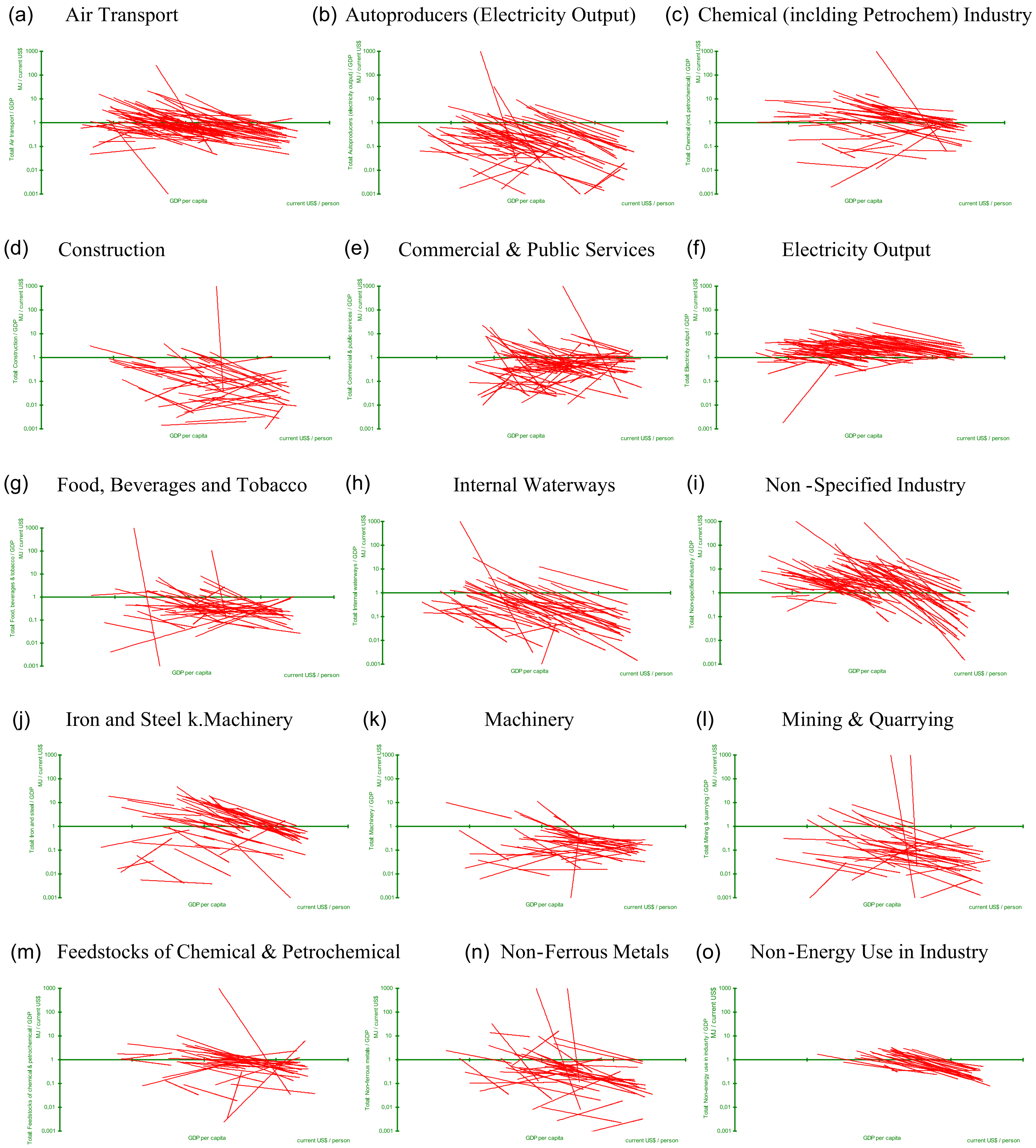
2.2. Heat

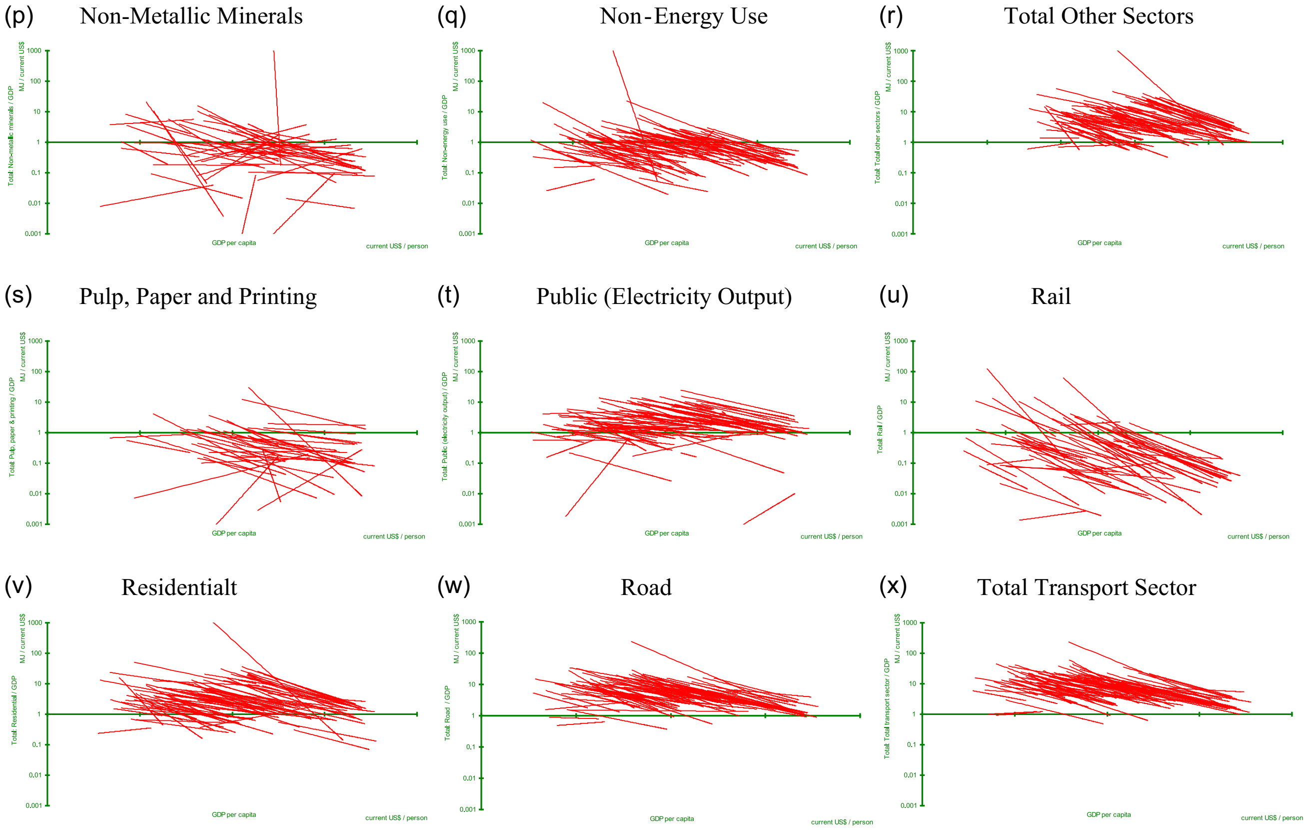
Two pioneering projects are Big Solar in Graz, Austria (300 k inhabitants [41]), which was re-dimensioned since then. Its (smaller) model and example is the project in Dronninglund, Denmark (22800 GW thermal, 3 billion m^3 underground storage tank) and those might deliver a coverage rate of over half of urban energy demand.

2.3. Sector coupling

The topic of sector coupling has become a much-cited catchphrase in the energy industry since half a decade (thus representing a prime example of transdisciplinary systems thinking which reaches beyond traditional contemplation of single energy strategies only [42]).

Figure 3
The evolutionary shifts within energy systems (measured as sectoral energy intensity)





Note: While moving rightwards towards higher GDP/capita (both axes have identical metrics as in Figure 1).

2.4. Low-temperature district heating

Especially, large solar heating installations such as the famous Austrian project "Big Solar"[2] in Graz[3] [41, 43–45] are advantageously combined with low-temperature district heating [46–58].

A brief technical explanation offers [59]: As different from common district heating systems, low flow and return temperatures are the most important "enablers" for the integration of alternative heat sources, which are mainly available at a low-temperature level or whose full potential can only be developed at low-temperature levels.

2.5. Heat management in smart cities

Especially, municipalities and "smart cities" can be prime actors within the heat transition [60–70]. Main focal points of a general roadmap are, including the "Smart City Graz":

1) Multi-temperature systems: Linking options for high-temperature/low-temperature networks, supply from the return, and systems with several feed points.
2) Building technology and automation: Use of buildings as storage, monitoring, low-temperature systems, and return reduction.

2.6. Large heat accumulators

Is large-scale heat storage [71–83] possible and practical for entire cities? Holter[4] proposes a very interesting concept, in cooperation with the Graz Energy Agency. Seasonal storage or seasonal heat storage or season storage is a long-term storage of thermal energy of a seasonal heat storage heating, often for a solar system (comparable installations see in Figure 5 [59]). Different storage types are:

1) Tank heat storage
2) Earth basin heat storage, for example as gravel/water heat storage
3) Geothermal heat storage, up to 100 meters deep
4) Aquifer heat storage.

2.7. Integration of large-scale solar thermal systems

In the northern Danish town of Dronninglund (3350 inhabitants, 1400 houses, of which 1350 are connected to the district heating system), there are 37573 m^2 of solar collectors, which correspond to a square area of 193 m side length [44, 84–86] (https://www.solarwaerme.at/solare-fernwaerme). The 61,700 m^3 underground heat storage tank would correspond to a 2 m deep, square bathing pond with a side length of 175 m^2. This means that it is much smaller than common natural lakes in Austria and can fit into realistic land-use planning of a village as Figure 6 [87] shows. Smaller areas for solar thermal strategies are strikingly visible, which adds to the principally weak argument of carbon neutrality for biomass [40, 44, 88, 89].

2.8. Industrial waste heat

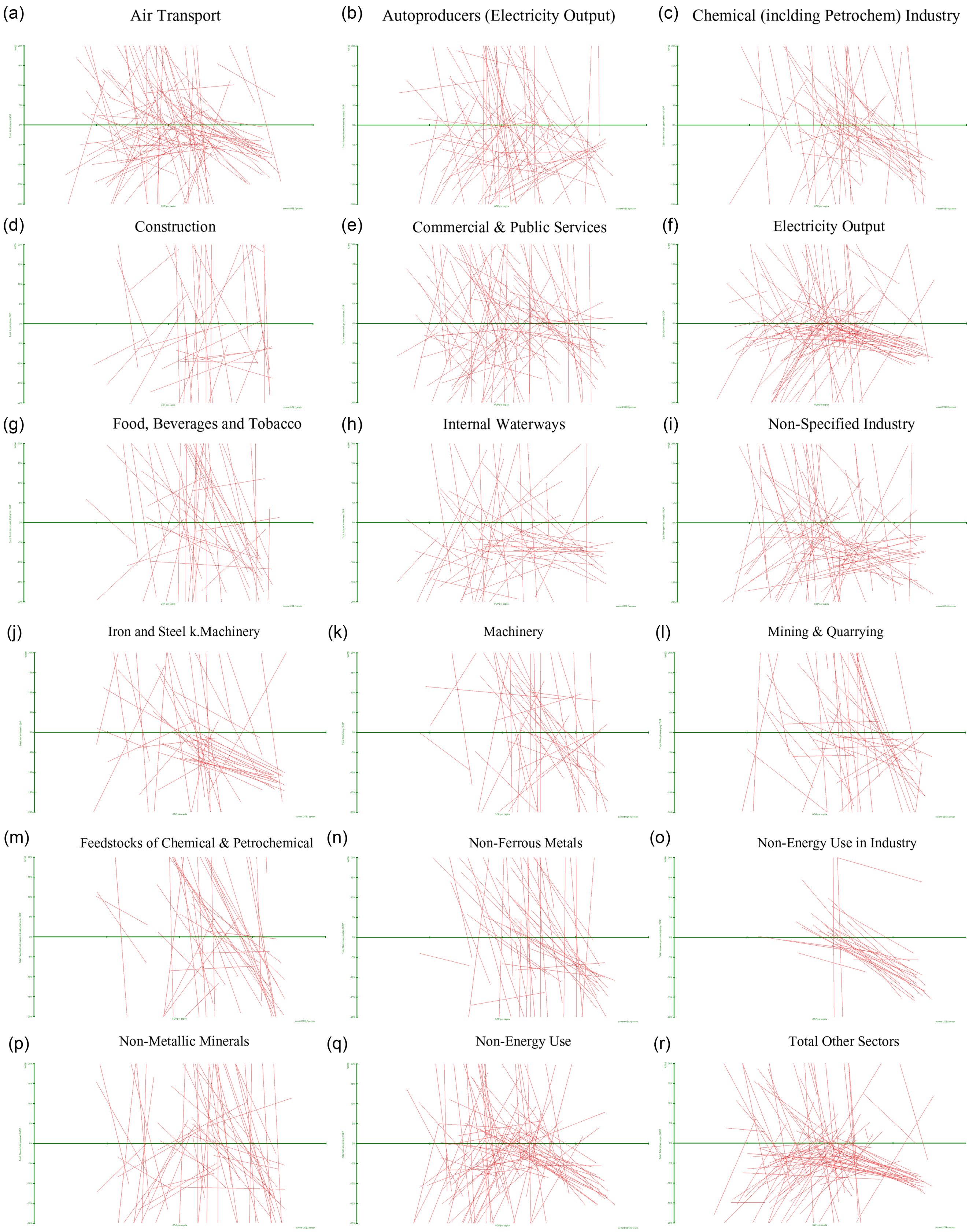
Scientific literature (as retrievable in the European portal Scopus, 2023) increase on "industrial waste heat" increased hundredfold in the last two decades [90–103] and has a

[2] BigSolar for the decarbonization of current district heating systems: Potentials & Challenges, https://www.irena.org/-/media/Files/IRENA/Agency/Events/2020/Apr/Technology-specific-focus-Challenges-Christian-Holter.pdf

[3] Austria: Decision on Operating Company for Big Solar Graz Expected Soon. Solarthermalwind.org, https://solarthermalworld.org/news/austria-decision-operating-company-big-solar-graz-expected-soon/

[4] Machbarkeitsstudie BIG SOLAR: 20% solarer Deckungsanteil eines Fernwärmenetzes - Beispiel Graz. https://www.aee.at/zeitschrift-erneuerbare-energie?id=908

Figure 4
In analogy to Figure 2 (for the sectors shown in), the rates of change characterize even better the ongoing evolutionary structural shifts (measured as change rates of energy intensities)



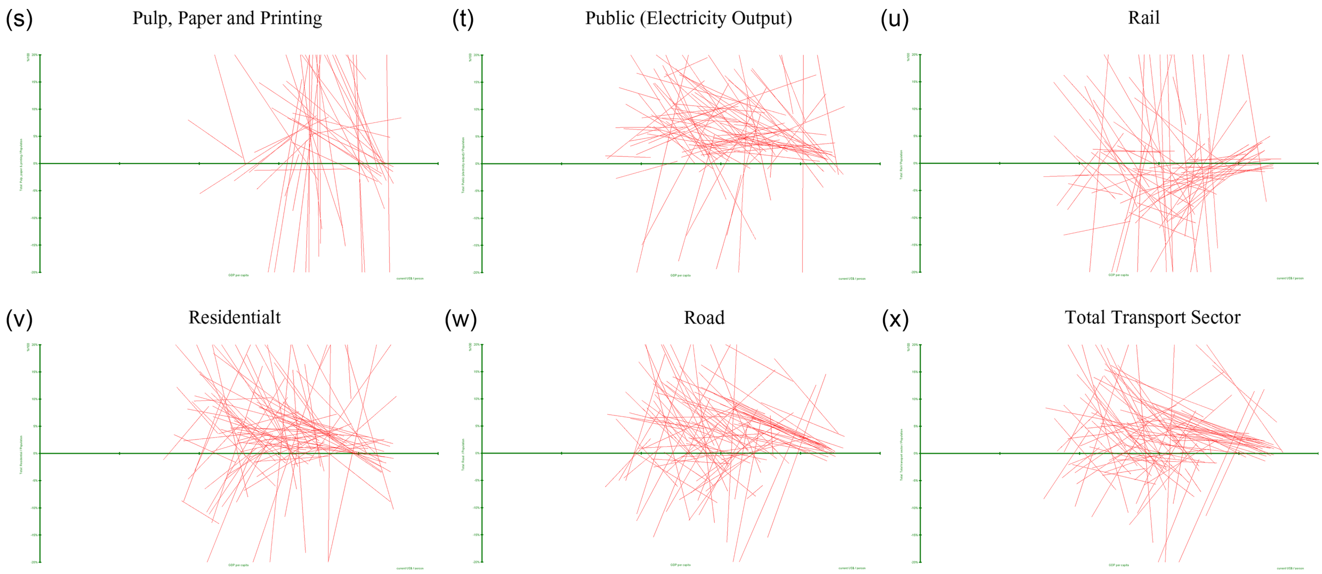
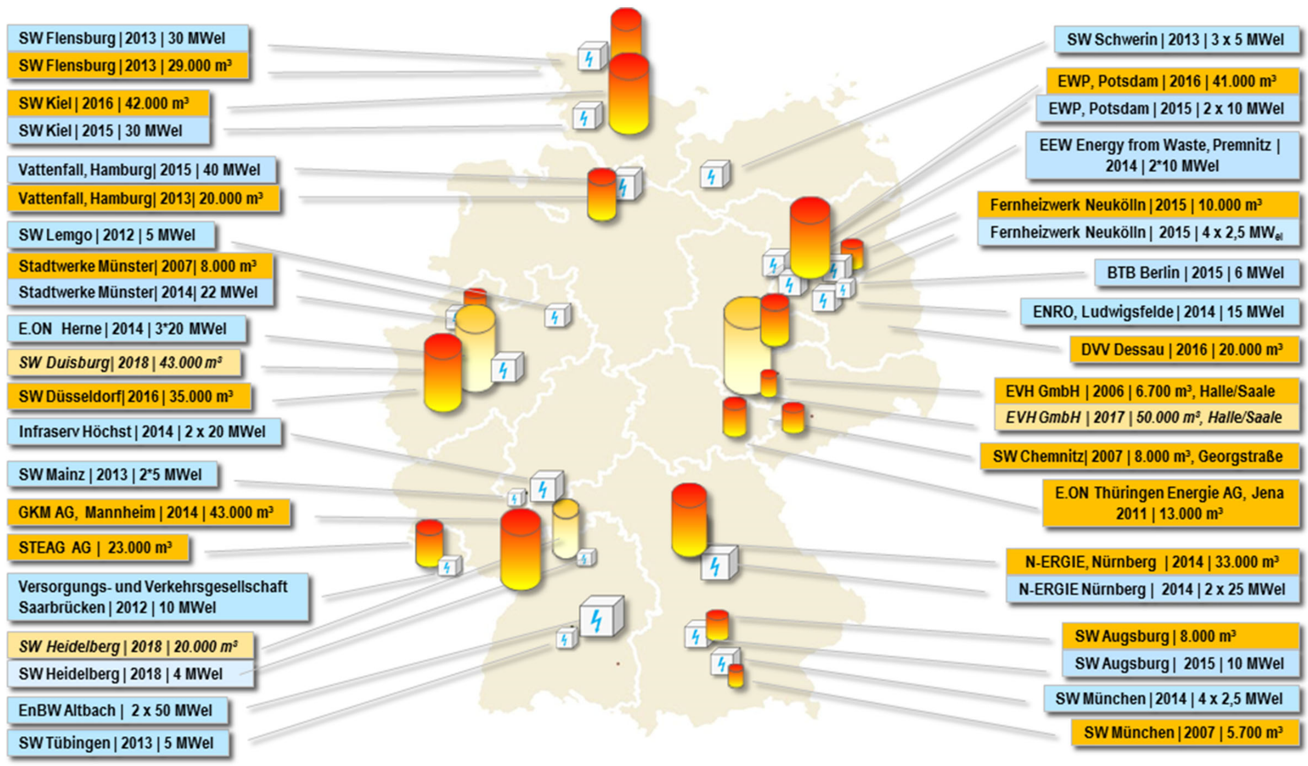


Figure 5
Overview of all heat storage projects in Germany with a volume of more than 5,000 m³ and selected power-to-heat (P2H) projects, as of 2017



strong focus in China of at least one-third. Within any urban concept – and also in the Graz concept – industrial waste heat plays a major role in filling the remaining heat demand.

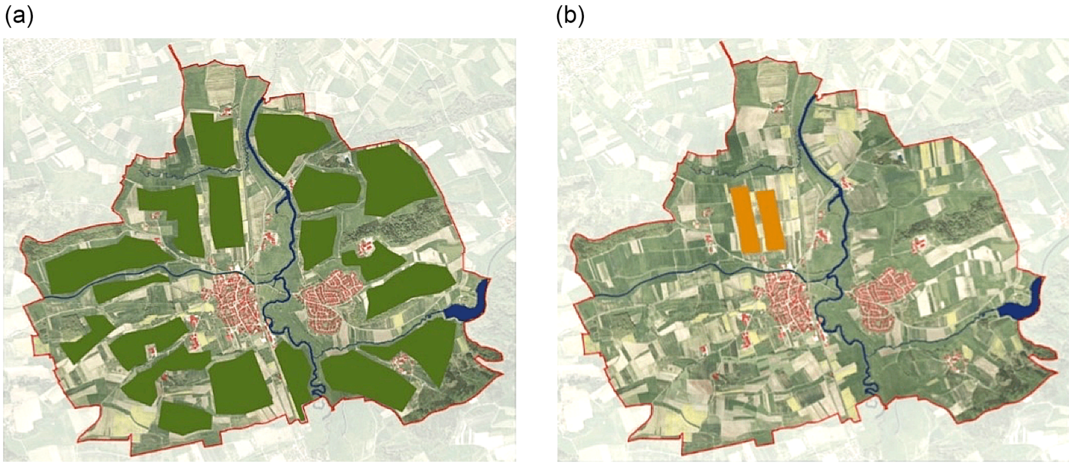
2.9. Island networks

Island grids [104–108] are also named island networks, stand-alone grids, isolated networks, isolated electrical grids, and separate networks; similar but connectable grids are microgrids.

2.10. Evolutionary improvement of energy intensity

Macroeconomic data analyses [34, 36, 40, 109] underline the diagnoses from the above subsections, as quantifiable through improving (i.e., lowering) **energy intensity** values in Figure 7.

Figure 6
Required areas for a small town for energy supply with biomass energy (at left) and solar energy (at right)



3. The Value of Gas Infrastructure for the Energy Transition

3.1. The potential role of gas infrastructure

A model-based analysis [110] asks the question: What lasting contribution can the gas infrastructure provide to the future energy system[5] [111–113] based on renewable energies?

The background is that sector coupling carries the energy transition into all consumption sectors, with new challenges for energy transport and storage [114] when analyzing the infrastructure as a prerequisite for the transformation of the energy system[6] [115, 116]. By the way, these latter authors created "windgas" as a nickname for power-to-gas.

The analysis of the impact of different energy transport scenarios on the entire value chain of the energy system allows for the assumption that in 2050, gas infrastructure will be used to transport and store green gas (especially "power-to-gas"), which is illustrated by scenarios comparing energy systems in 2050 with and without the use of gas infrastructure [117, 118].

The use of the gas grid reduces the expansion of the electricity grid in the transmission grid by 40% and in the distribution grid by 60% [110]. The scenarios portray the comparison of energy systems in 2050 with and without the use of gas (Figure 8 [110]):

1) "Electricity-only" – End users mainly use electrical end use applications such as heat pumps and electric cars ("direct electrification"), the connection between electricity generation and final energy use is made solely through electricity grids and storage (hence "Electricity-only"). In this scenario, the gas infrastructure (both storage and pipelines) will no longer be needed in the long term [119].
2) "Electricity and gas storage" – As in the "Electricity-only" scenario, end consumers mainly use electrical end applications. However, storage is not based solely on electricity storage: There is the option of temporarily storing electricity in gas form and converting it back into electricity in gas-fired power plants ("Power-to-Gas-to-Power, PtGtP). The energy transport in the area continues to take place based on electricity. Unlike gas storage, gas transport and distribution networks are no longer required in this scenario.
3) "Electricity and green gas" – In this scenario, part of the end use is based on green gas, which is generated in power-to-gas (PtG) plants in Germany based on renewable electricity [110].

The value of the gas infrastructure for the energy transition in Germany Lassak [110] includes the approach of "indirect electrification" meaning that the existing gas infrastructure for energy transport will continue to be used in parallel with the electricity grid [120]. In order to ensure complete comparability, it is assumed in all scenarios that the government's ambitious climate goals will be achieved with a reduction in greenhouse gas emissions of 95% compared to 1990, which ultimately requires almost complete decarbonization of the electricity, heating, and transport sectors. In addition, a uniform demand for useful energy (i.e., the energy ultimately consumed) is assumed in all scenarios.

Figure 9 [110] (at right) compares the annual savings within system costs in the scenario "electricity and gas" with the scenario "electricity and green gas" in the year 2050 and finds that the usage of gas infrastructure reduces the demand for building an additional electric grid, and consequently increases the acceptance for an energy transition.

Overall, the use of the gas grid reduces the expansion of the electricity grid in the transmission grid by 40% and in the distribution grid by 60% on the basis of the scenario comparison for the year 2050 in Germany [110]. It turns out that a pure "electricity-only" solution is prohibitively expensive due to the lack of seasonal storage.

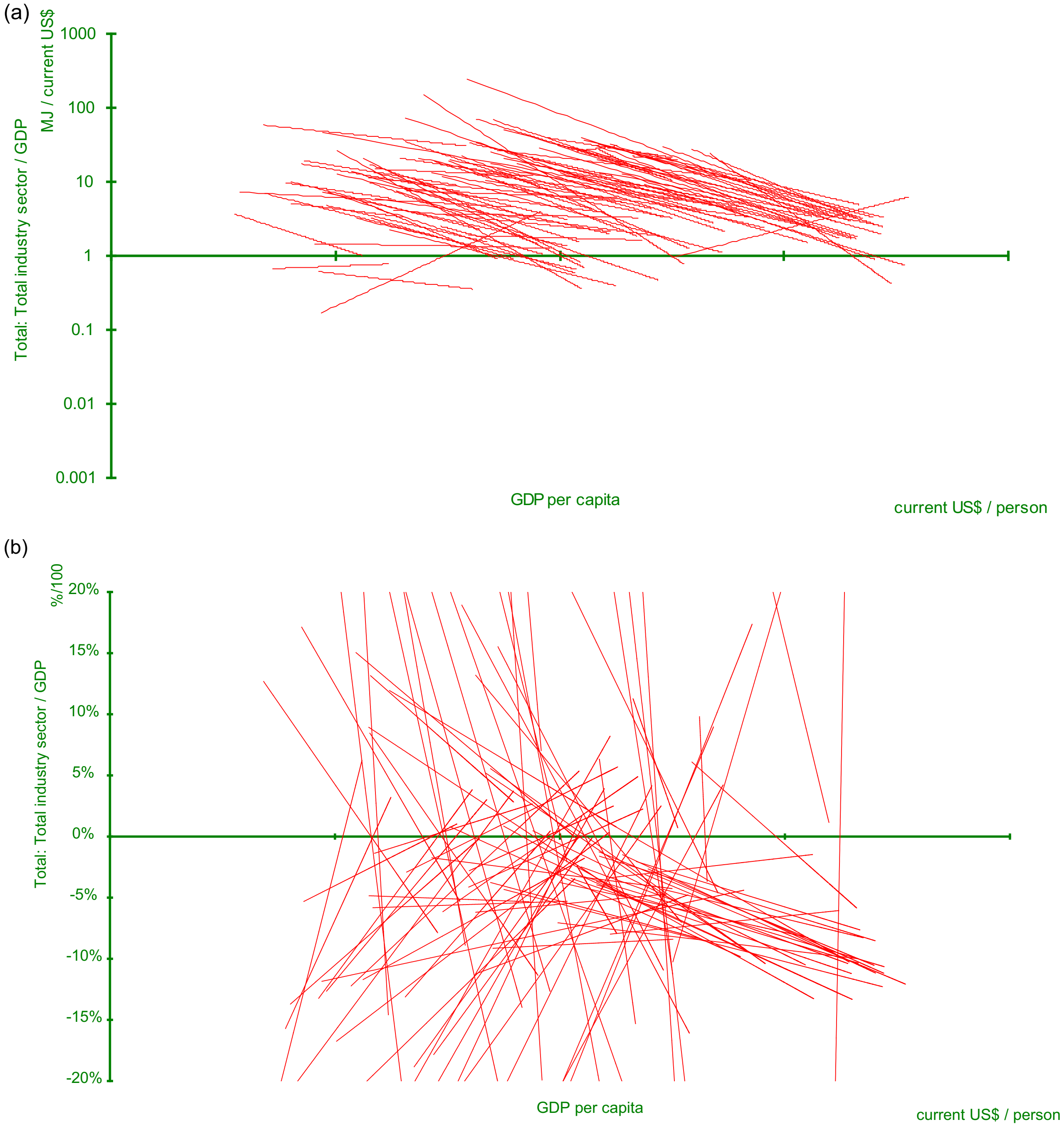
When looking into details, the seasonality in the electricity and heating sectors is a key challenge for the system [110]. According to current knowledge, there is no viable technology for seasonal intermediate storage in an almost completely decarbonized electricity sector, an energy system that is to manage without chemical storage (in gas form) and (at least in Germany) without nuclear power and CCS requires the development of high overcapacities of renewable capacities and power grids. Such a scenario leads to enormously high system costs, as simple analyses quickly show [110].

3.2. Transformation paths to the energy transition and sector coupling

According to Ausfelder et al. [29], it is needed to identify the key drivers of future development at the individual stages of

[5]Energiewirtschaft 2030 und 2050. Infrastruktur als das vernachlässigte Fundament für den Umbau des Energiesystems. In Workshop des Öko-Instituts „Infrastruktur der Energiewende", Berliner Energietage 2009 „Energieeffizienz in Deutschland. https://www.oeko.de/oekodoc/881/2009-005-de.pdf
[6]Energiewende als Chance Investitionen. https://www.klimaschutz-niedersachsen.de/_downloads/FaktenpapiereLeitfaeden/2018-06-13_Energiewende-als-Chance_Investitionen.pdf

Figure 7
The energy intensity changes of the total industry sector in all countries of the world



Note: Energy intensity continuously in all countries of the world (Figure 7(a), descending lines), while the energy intensity's growth rate even improves in wealthy countries see Figure 7(b), roughly parallel data line bundle at right), as based on trend data derived from the GCDB (Legend per in Figures 1 and 2).

the value chain, i.e., at the end applications, at the infrastructure level, and at the energy level and to outline possible transformation paths in which the previously identified core drivers take on different characteristics, namely in the field of end uses, at the infrastructure level, and in energy production. Based on these transformation paths, one can derive core theses about the relevance of various drivers with regard to the success of the energy transition. These are the basis of the political recommendations for action in Ausfelder et al. [29].

Transformation paths in the area of end applications in this view [29, 121] include the following:

1) Reference path makes sense if all conditions are met: If the above-mentioned necessary developments in terms of technical progress, consumer acceptance, and international harmonization actually occur, the transformation path announced by the Government is able to change the climate targets at reasonable costs [122, 123] and thereby guarantee a secure energy supply.

Figure 8
Schematic representation of the three scenarios "electricity-only", "electricity and gas", and "electricity and green gas" for Germany

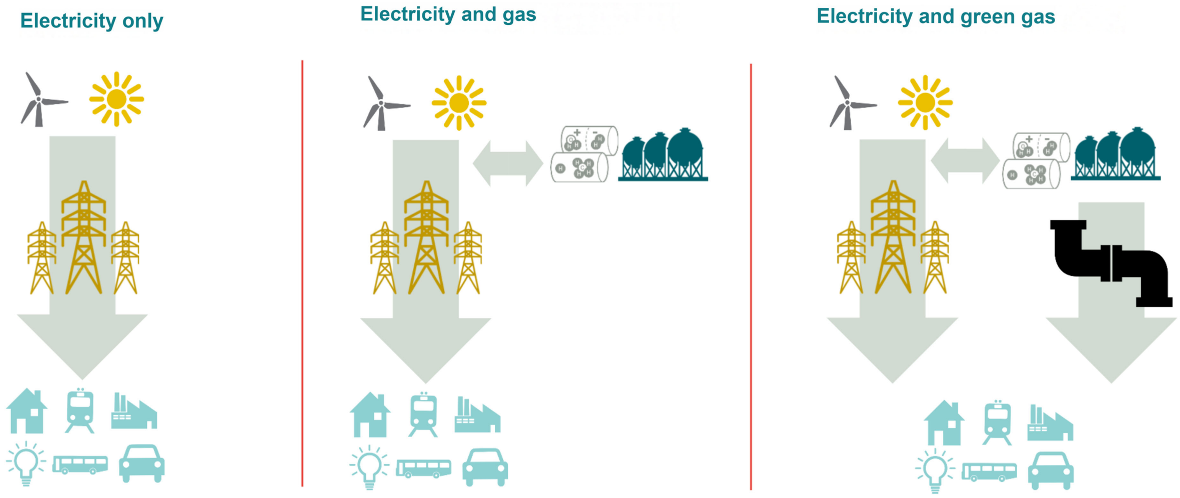
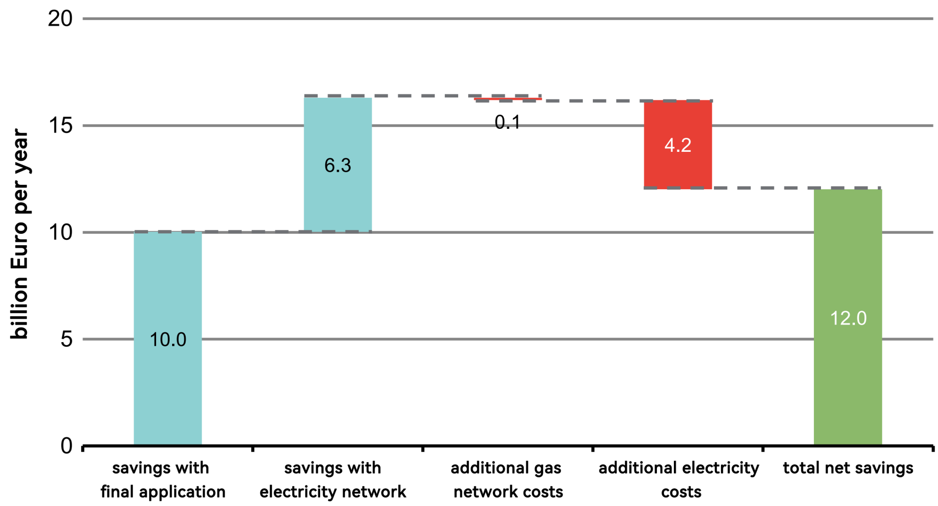


Figure 9
Schematic representation of the annual savings within system costs in the scenario "electricity and gas" with the scenario "electricity and green gas" in the year 2050 in Germany



2) Alternative path a: A lack of international harmonization could jeopardize climate goals and lead to additional costs – It is possible that significant technical progress will be made in the end applications envisaged by the Government (e.g., e-vehicles) and their acceptance by end users will also increase significantly, but other countries will make other target decisions on decarbonization.
   - The most vivid example of this would be if Germany relied on overhead line trucks to decarbonize road freight transport and installed a corresponding infrastructure, but Germany's neighboring countries based their climate strategy on other technologies such as railways or battery or fuel cell-based trucks.
   - The same applies to motorized individual transport, where a charging infrastructure in Germany alone is not sufficient to be able to effectively switch to electromobility on a large scale. In the future too, drivers will hardly want to be restricted by a lack of fueling infrastructure abroad, e.g., in their choice of vacation.
   - Inadequate international harmonization of climate strategies, especially in transport, can therefore jeopardize the goals intended in Germany and lead to additional costs.
3) Alternative path b: Energy efficiency can be increased in various ways, see substitution effects.

3.3. Options for foresight and energy innovations

The extensive lack of knowledge about the future must be taken into account in political decisions and framework conditions. Otherwise, politics will be erratic; and opportunities, e.g., from innovations, will be missed, industry and other consumers will be burdened with unnecessary "compulsory costs" and the *acceptance of the energy transition* will be jeopardized overall [29].

However, the basis of today's prevailing political approach is a philosophy of top-down control of the energy system: on the basis of the medium- and long-term energy forecasts already mentioned, detailed energy management target systems are developed, which are then to be aimed at very concrete political interventions.

In the view of Ausfelder et al. [29], it is also possible that the "classic" technologies could adapt to strict climate requirements, e.g., via "green fuels". To exclude this means to forego options. Accordingly, a policy that is open to the future also means deliberately not making certain decisions today and thus allowing an open development.

In addition to these fundamental considerations on the advantages of definitions and openness to technology, the maturity of technologies or fields of action determines whether and when political decisions need to be made at an early stage. The term depends, for example, on approval periods, depreciation, and maintenance cycles.

This consideration can be repeated for each stage of the value chain [29]:

1) Demand/end use – At the level of demand or end use, an early political commitment to a specific technology, e.g., through the e-car quota currently being discussed, does not make sense. The cost of applications is typically less capital intensive than other tiers, so there is less risk of sunk investments. If end consumers make their decisions on the basis of efficient price signals, the risk of a consumption decision that is not beneficial to the system decreases at the same time.
2) Infrastructure – As described above, 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 [124]. In the case of an overly restrictive policy and, for example, the premature dismantling of certain infrastructures, the costs of an incorrect determination also increase extremely.

Against this background and taking into account the importance of the infrastructure for the upstream and downstream stages of the value chain, the widest possible range of technologies should be taken into account overall [29].

However, it may be that the benefits of the infrastructure only come into play in connection with the corresponding end applications. Political intervention may be necessary to internalize these network effects. The "chicken-and-egg problem" of electric mobility can be cited as a prominent example here: Without a sufficiently dense network of charging stations, drivers will hardly buy e-cars, and without penetration of e-cars, private actors may have no incentive to use the charging infrastructure to invest.

1) Energy supply – At the level of energy supply, the situation is basically the same as for end applications: if price signals adequately reflect scarcity, market players and not politicians should push the development of certain technologies. Politicians provide research funding to provide an impetus to enable the development of new technologies. The more diverse this is, the higher the costs, but the probability of having bet on the "wrong horse" decreases [125].

In summary, it can be said that a specification is only required at the infrastructure level. Above all, this should represent a decision for new rather than a decision against existing infrastructure. By maintaining existing infrastructure, existing options can be kept open (e.g., supplying buildings with climate-neutral gas) and, under certain circumstances, new technologies at other stages of the value chain (e.g., supplying H_2 filling stations for traffic) can also be made possible. In any case, a differentiated view is required [29].

3.4. Remove barriers to sector coupling and enable innovation

The legislature should therefore develop a target system in which it defines overarching targets, e.g., with regard to climate protection (as there is) – this provides orientation for all actors – but not commit to individual technologies at an early stage or reject other technologies at an early stage [29].

However, this does not mean that politics cannot do anything: there is a particular need for action in the design of framework conditions that ensure a "level playing field" between a wide variety of technologies and energy sources. The decision about the "right" technological solutions should be left to the market players (is also an ideologically co-determined determination), which enables productive competition and promotes innovations in terms of consumer preferences. As a result, preliminary administrative decisions are not very effective, even if they may appear plausible in the short term [29, 126].

Politicians are well advised to protect themselves here. One option here would be the preservation or long-term use of the existing gas network infrastructure. It is technologically possible to transform electricity from renewable energies in northern Germany into synthetic gases, transport them to southern Germany via the existing gas network, and use them in end applications (heat, transport) or convert them back into electricity [127]. This is another example of how redundancies in infrastructure can serve as "insurance" against unexpected future developments and create options.

3.5. Alternative financing models

Alternative financing models [128] with a special focus on (energy) infrastructure projects in the City of Vienna are presented in a very interesting report commissioned by the municipal department for energy planning[7] This report begins with a presentation of selected alternative financing models for energy (infrastructure) projects. In this context, "alternative" means that the financing models have special features in their design.

Financing models for energy (infrastructure) projects are mostly project financing. Project financing is the financing of an economically and mostly legally definable, self-refinancing business entity with a limited lifespan. The following features are typical of project financing: Cash-flow-oriented lending (cash-flow-related lending), explicit risk sharing (risk sharing), and off-balance sheet financing [129].

3.6. The importance of synergies across energy carriers

The German study [130] highlights the **importance of the three pillars of efficiency, renewables, and infrastructure for the energy transition** and provides the following suggestions:

1) *Relieve the power grid with power-to-gas*: The surplus electricity generated from renewable sources can be converted into gas, fed into the gas grid, and then stored if required [130].
2) *Organic photovoltaics* – a technology with potential: The new technology promises cheaper and more flexible products for generating electricity from sunlight [130].

[7]Alternative Finanzierungsmodelle mit besonderem Fokus auf (Energie-) Infrastrukturprojekte der Stadt Wien. https://www.oegut.at/downloads/pdf/nf_finanzierungsmodelle-e-infrastruktur.pdf

An energy transition including gas would be faster and cheaper to implement climate protection: this is an (interest-led) recommendation by the Association of German Gas Companies[8]:

1) The use of the gas infrastructure [20] is a particularly cost-efficient option for sector coupling and increases acceptance of the energy transition in the population.
2) In the electricity sector, gas-fired power plants have the best prerequisites for providing secure, flexible, and low-CO_2 output.
3) A successful heat transition should rely on cost-efficient and technology-neutral subsidy programs and investment security for heating networks.

It can be noted that such a loud "gas voice" is institutionally largely missing in some other countries, such as Austria. A quick first answer to this dilemma could be: Austrian geography offers much-pumped storage options by its mountainous terrain, while Germany does not have this attractive option and therefore is forced to rather choose power-to-gas. Other (and even contradictory) opinions were voiced by the electricity industry [44]: "In order to achieve the climate targets, the share of renewable energy sources must increase. This means that more solar systems and wind turbines will generate electricity in the future. If, depending on the weather, a lot of electricity is produced with low demand at the same time".

To date, pumped storage is the only truly efficient storage technology [131], at least in Austria. This technology is well available in Austria and will play an important role in a sustainable energy supply based on renewable energies. Due to the difference in altitude, mountainous Austria has good conditions for pumped storage, which can cover electricity storage in this country, with an efficiency of 85 percent. While batteries are mentioned as short-term storage, power-to-gas is added as long-term strategy and Ahamer [44] boasts of a 96% efficiency – especially Green Hydrogen strategies are frequently discussed [112].

3.7. The changing mindset actually steers changing energy patterns

On a fundamental and general level, Schwan et al. [132] also argue in favor of sector coupling, while stating that coupling between the sectors of electricity, heat, traffic, and gas is much more common in Germany as compared to other countries, such as Austria, given that it represents one of the three pillars of German climate policy. From an ecological point of view, **the use of Power-to-X is only justified if the electricity comes from renewable energies** [132]. The earlier report[9] and Westphal [133] are very extensive but contain no cost data.

United Nations places the German "Energiewende" in the context of the SDG Goal 7(https://sdgs.un.org/goals/goal7), namely to ensure access to affordable, reliable, sustainable, and modern energy for all.

Bach [134] highlights that in Germany, approximately 50% of the 35,000 newly installed PV systems are equipped with storage systems, and approx. 33 MW were installed in the USA in 2015, while some 500–700 systems were in operation in Austria, and in 2016 around 147 GW of storage capacity is installed worldwide, of which 145 GW (about 98%) of the installed storage capacity are pumped storage systems [135, 136]. The key point for a successful energy transition in the early stages is **associated with new social patterns**, virtual and real communities [137–139], online cooperation, i.e., social innovation in "co-creation" [140, 141].

Democratization of a society is mirrored by democratization of the energy system

4. Conclusions: Key Paradigms Derived from Research Results

4.1. The paradigm of coupling

The most important messages of the case studies 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 (as described in Section 2.3) between

1) Energy sources (e.g., electricity & gas: including for long-term storage)
2) End-consumption sectors (e.g., electricity & traffic, such as e-mobile buffer batteries, or electricity & gas, for space heating)
3) The concept of "energy transition" as an evolutionary achievement is applicable to every single world region, including South Asia and Southeast Asia
4) State policies should enhance the framework being suitable to allow for self-optimizing energy system transition towards a fossil-free energy system that sustains itself by true energy prices
5) Openness for technologies can be achieved by state regulations which address only targets but not necessarily the means for reaching these targets.

4.2. The paradigm of bridging time through energy storage

A core topic is the management of the time balance between the intermittent generation of renewables (solar & wind) and the (possibly shiftable) consumption. As previously mentioned, "smart metering", however, 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.

4.3. The paradigm of lowering prices through decentralization

Regarding decentralized energy generation, a study by IHS & KPC[10] 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. For biomass, PV, and wind, the annual specific expansion costs range from 500 to 1200 €/MWh.a with an expansion of 2–8 million MWh by 2030.

Prices for electricity storage according to a market study by the German journal Wirtschaftswoche [36] for lithium or lead batteries amount to more than 500 euros per kilowatt hour of capacity plus inverter and installation. Prices are currently falling by 18% per year.

[8]Commit to Connect 2050 Zielbild Energieinfrastrukturen für Ostdeutschland: https://www.ontras.com/sites/default/files/2021-11/2020_04_21_CTC2050_Abschlussbericht.pdf

[9]Progress Report 6a - Assessment of existing funding schemes and official policy strategies, assessment of innovative concepts, and general policy recommendations. http://www.umweltbuero-klagenfurt.at/feasiblefutures/wp-content/uploads/Assessment_Policies_and_Funding_WP7_24072013_final.pdf

[10]Zukünftiger dezentraler Infrastrukturbedarf in Österreich: Ökonomische Effekte von Investitionen in den Bereichen Elektromobilität, Energie und Wasser/Abwasser. https://www.ihs.ac.at/de/forschung/forschungsprojekte/project-details/zukuenftiger-dezentraler-infrastrukturbedarf-in-oesterreich-oekonomische-effekte-von-investitionen-in-den-bereichen-elektromobilitaet-energie-und-wasser-abwasser-1/

Large heat storage systems (Section 2.6) are already being built, costs are not yet available, and only few cost data are available for low-temperature district heating.

4.4. The paradigm of a system dynamics view

Sections 2 and 3 started out to provide single technologies and systemic energy strategies which allow us to put into practice what was announced as "paradigm of coupling" in Section 4.1. Additional publications by this author will provide more detail.

4.5. The final results for cost of decentralized energy conversion

Based on the above quantitative analyses, the synopsis of costs is provided as the final result in another article.

On a more general and paradigmatic level, the key point for a successful energy transition in the early stages is associated with 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 states: "**The 'full world' needs a new enlightenment**".

4.6. Conclusions on the gas infrastructure

Based on the above-mentioned deliberations, evaluations, and scenarios (in Section 3), the author's final overview suggests the following practical and tactical conclusions:

1) Make use of energy-economy modeling to the extent appropriate, but keep in mind that interpretation of results should be founded on thorough practical knowledge of the matter
2) Make functional maps of the thematic relevance to allow for dynamic analyses
3) Flexibility is a new (systems-dynamics-related) dimension of this theme of energy transition
4) On the practical-political level, the success factors can be immediately drawn from the systems dynamics factors
5) For an analysis of the system relevance of individual sub-topics within the overall process, the relevance of decentralized storage to enable the flexibility requirements of the energy transition, as well as cost degressions, should be treated as a key element.
6) Thereby analyzing the overall system behavior, including autopoietic system locations, e.g., bitcoin-like money creation competence of the renewable energy carriers, as well as the system storage potentials such as large gas storage (e.g., as existing in Austria) and pumped hydroelectric storage (e.g., as existing in Austria) are essential. Which energy/economy system necessities are autopoietically driven? Which ones get stuck within the given structure of system dynamics?
7) The network flexibility (e.g., demand vs. supply) becomes a value in itself, which also costs or redeems a substantial value.

4.7. The larger context of the energy transition

The German consultant Roland Berger identified 24 factors determining the energy transition, entitled "Energy transition reloaded: rethinking the mega-project". Berger[11] defined 12 core uncertainties and 12 trends, attempting to think and act beyond mainstream. This study identifies the following trends, while "an abundance of decentralized micro power stations and so-called prosumers are turning the energy flow upside down":

1) Trend 1: New Energy transition
2) Trend 2: Market integration and globalization
3) Trend 3: Efficient use of resources
4) Trend 4: Regulation and deregulation
5) Trend 5: New technologies and digitalization.

On a strategic level, an analysis should develop an overall view of the energy transition from all factors critical to success. At present, the **energy transition** is the dominant economic topic in Europe – as it was two decades ago in Germany. In the current geopolitical context, its overall success will determine whether democratic countries can maintain their competitiveness as an industrial region. Also, *energy education* should take into account these findings in a self-responsible manner [39, 142]. At the same time, the energy transition offers the unique opportunity to become a pioneer in the conversion of the energy supply and to be able to sell new technologies and products worldwide.

4.8. Systemic conclusions

Based on the above analysis, the following conclusions can be drawn:

1) When it comes to defining feasible climate protection strategies, the conceptual starting point is to think openly about the future, namely to not narrow down too early on pre-conceived combinations of technologies. In concrete terms, this often can mean to either concentrate on an electricity-only future in a country or to rather promote power-to-gas strategies. Based on their geography, the countries of Austria and Germany might rely on the first and second alternatives, to a certain extent.
2) Moreover, the "**GCDB**" suggests a solid trend towards end-user-friendly energy carriers, among which electricity presently seems as most promising. Other framework conditions appear to be consumer preferences, technological development of power-to-x strategies (including heat), and the (quite shaky) public acceptance of required expansion of the electricity transmission grid as key infrastructure. Barriers to sector coupling should be removed, and alternative financing models should be identified and implemented as well as synergies across energy carriers should be enabled better.
3) While concrete modeling exercises have to be performed in every country, based on day-to-day availability of modeled energy sources, recent reporting requirements in the climate protection framework necessitate anyhow detailed scenarios on how national plans can be implemented and financed.
4) However, the present study sees the crucial deliberation in the following: The **mental and social status of a society is strongly mirrored by the energy system** – and therefore, democratization of a society is mirrored by **democratization of the energy system** in a co-evolutionary manner.
5) In this view, every single phase within the "energy transition" has its own requirements, needs, bottlenecks, and sensitive themes. At the time of writing (2023), the creation of an energy infrastructure on national and continental levels appears as the primordial task.

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[11] Energiewende Reloaded: Das Megaprojekt neu denken. 24 Faktoren entscheiden über die Energiewende. Roland Berger Strategy Consultants. https://www.erneuerbareenergien.de/energiemarkt/energierecht/studie-von-roland-berger-24-einfluesse-auf-die-energiewende

Conflicts of Interest

Gilbert Ahamer is an Editorial Board Member for *Green and Low-Carbon Economy*, and was not involved in the editorial review or the decision to publish this article. The author declares that he has no conflicts of interest to this work.

Data Availability Statement

Data are available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Gilbert Ahamer: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

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