E.ON Energy Research Center | RWTH AACHEN UNIVERSITY

E.ON ERC Contributions to Sustainable Energy Pathways

Thinking the Future
Zukunft denken

Contents

Chapter 1 Research, Innovation and Education at E.ON ERC

Take-away Messages (Rik De Doncker)

- E.ON ERC demonstrated excellent performance in terms of both research and education
- All RWTH directors of the Section JARA Energy so far have been E.ON ERC Professors
- E.ON ERC Professors representing Fac. ET&IT and MBA are members of the RWTH Research Area ECPE
- Over the past five years, annual R&D project funding was about €13.5 million
- About 130 scientists (post-docs and Ph.D. assistants) are currently conducting R&D projects at ERC
- 100 PhD theses have been published since the founding of E.ON ERC (62 over the past 5 years alone)
- The International Energy Cooperation Program (IECP)) (exchange of scientific staff and joint master's thesis projects) has been signed with more than 10 renowned international Research Centers / Universities worldwide
- In addition to regular lectures offered by the E.ON ERC professors, E.ON ERC offers various courses and seminars (e.g. LEONARDO Sustainability, Future Energy Systems, E.ON ERC Colloquia)

Prof. Rik De Doncker

June 23, 2016 marked the date on which the second phase of the public private partnership (PPP) cooperation between RWTH Aachen University and E.ON SE was signed. Different from the first phase, which lasted for 10 years, the five-year second phase cooperation agreement had a stronger emphasis on contract research and development projects, which were conducted in close cooperation with E.ON SE market units. This so-called second phase started July 1, 2016 and ended on June 30, 2021. It shaped the structure and the scope of the center further.

As can be seen in Figure 1.1, since middle of 2016 E.ON ERC comprises four institutes from three faculties. With seven professorships, interdisciplinary R&D at E.ONERC focusses on the technical, economic, social/political and ecological aspects of a sustainable energy supply and planned in a primarily urban environment (see Figure 1.2).

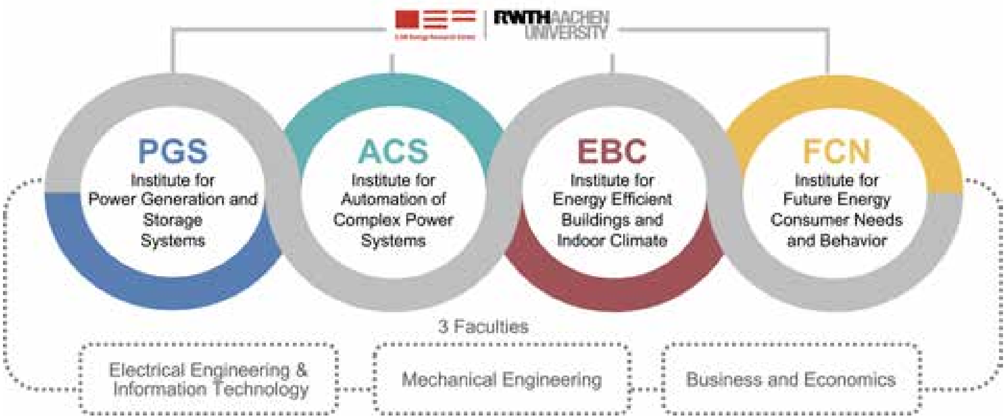

Figure 1.1 E.ON ERC Interdisciplinary R&D topics with four institutes from three faculties, with seven professors. FCN (R. Madlener, A. Praktiknjo), EBC (D. Müller), ACS (A. Monti, F. Ponci), PGS (R. De Doncker, D.U. Sauer).

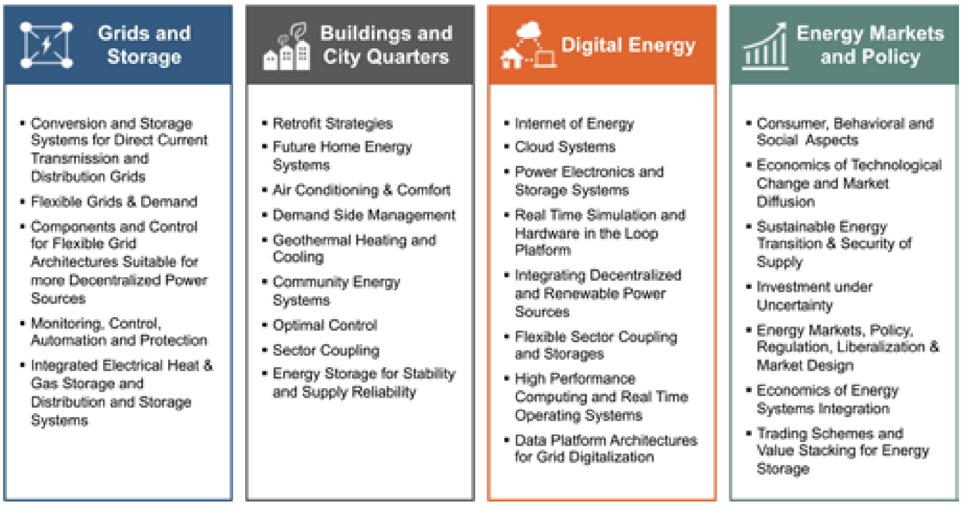

Figure 1.2 Main interdisciplinary R&D at E.ON ERC. Focus on a sustainable energy supply for the urban environment to realize the EU Green Deal.

In the following, a brief overview is given on the major achievements of E.ON ERC during the five-year period 2017-2022. As illustrated in Figure 1.3, during this period the R&D work at E.ON ERC kept growing. Publicly funded projects, i.e. EU projects, German Fed. Gov. or German Science Foundation (DFG) projects, remained stable and amounted to about 13,5 million/year. Despite of the COVID-19 pandemic overall R&D funding remained stable, supporting the work of more than 200 scientific staff members. Thanks to the great effort and support of all chairs at E.ONERC, the on-site laboratory work continued such that projects could be completed as planned. Furthermore, as can be seen in Figure 1.4, the quality of scholarly output did not sufferin a major way from the hygiene measures that were mandated during 2020. On the contrary, it appears that home office enabled the writing of more scientific journal publications rather than attending conferences.

Figure 1.3 R&D funding over the six-year period 2017-2022.

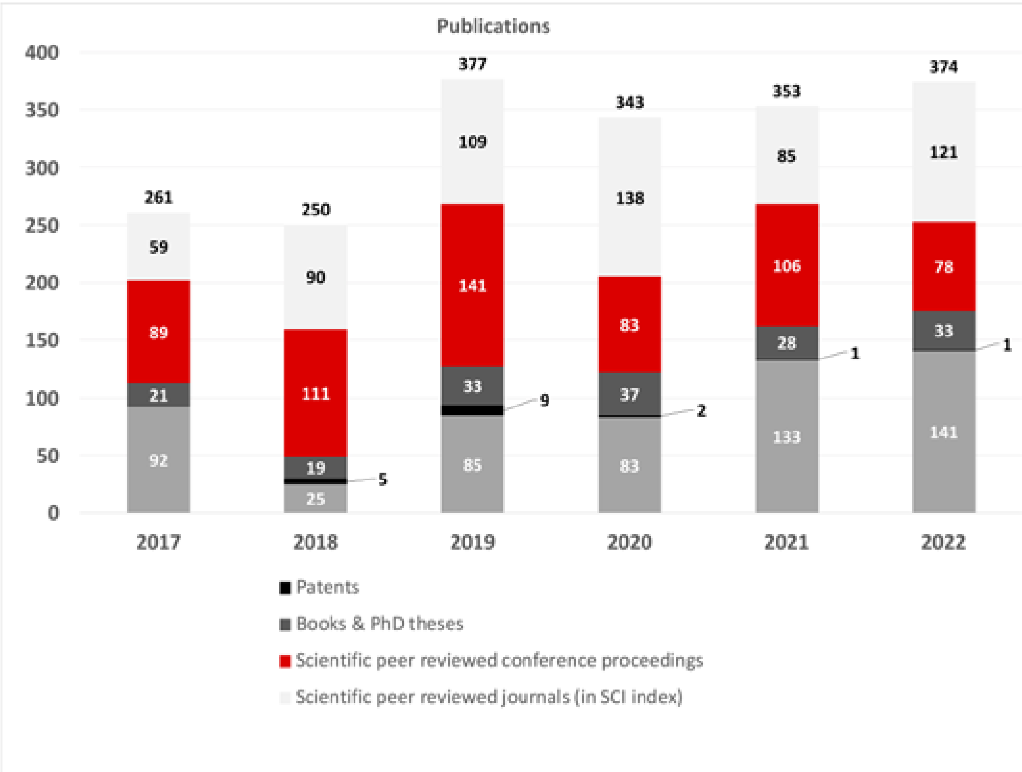

Figure 1.4 E.ON ERC Publication track record over the period 2017-2022.

During the period 2017-2022, a trend towards more automation, control and digitalization in the utility business took place. This trend was clearly noticeable in the operation of electrical distribution systems. The unbundling of power generation, transmission system operators (TSOs), distribution network operators (DNOs) and distribution system operators (DSOs), requires a higher level of automation. In particular, as sector coupling and a substantial amount of volatile renewable power sources are introduced in the distribution grid, the transformation of the distribution grid towards more flexibilization is critical.

Hence, the European Commission encouraged more activity towards demonstration projects. As an example, in the area of monitoring, Prof. Ponci, who leads the Research Area Monitoring and Distributed Control for Power Systems at E.ON ERC|ACS, developed a low-cost synchronized measurement unit (SMU) in the Horizon 2020 EU project HYPERRIDE. In addition, a patented automation blockchain technology in the EFRE NRW EU project BRILLANT for the exchange of measurements and data for distributed automation was developed. Enabling the state of the surroundings of the entire power system and leveraging the penetration of measurements via all feasible paths. For active distribution grids, the integration of these technologies represents an end-to-end monitoring solution that is easy to combine with distributed state estimators. Furthermore, it also offers a novel low-cost data exchange solution for energy communities.

Figure 1.5 The synchronized measurement unit (SMU) and automation blockchain technology, developed by Prof. Ponci, offers a low cost end-to-end monitoring and data exchange solution for energy communities.

Recognizing that the digitalization of the distribution grids is one of the main pillars of the energy transformation, E.ON ERC|ACS developed, under the leadership of Prof. Monti, an innovative software platform called SOGNO to support Distribution System Operators in the energy transformation process. The SOGNO platform has been originally developed in an EU Horizon 2020 project with the same name and further extended in a follow-up EU project called Platone, where also Avacon is involved with a demonstrator. SOGNO proposes a disruptive concept for automation, using a micro-service architecture that facilitates modularity and the creation of open ecosystems (see Figure 1.6 and 1.7). The software is fully open source and has been selected by the Linux Foundation Energy as a representative project for grid automation. As a result, a worldwide community is cooperating with E.ON ERC|ACS on the development and involving also large software enterprises such as Microsoft and Google. The city of Rome has recently selected the SOGNO platform for the digitalization of the distribution network of Rome, which is the largest urban distribution grid in Europe. Recently, the the State of North Rhine-Westphalia, selected SOGNO for its prestigious Innovationspreis 2022. SOGNO, which was technically directed by Prof. Monti, definitely was and is a highlight.

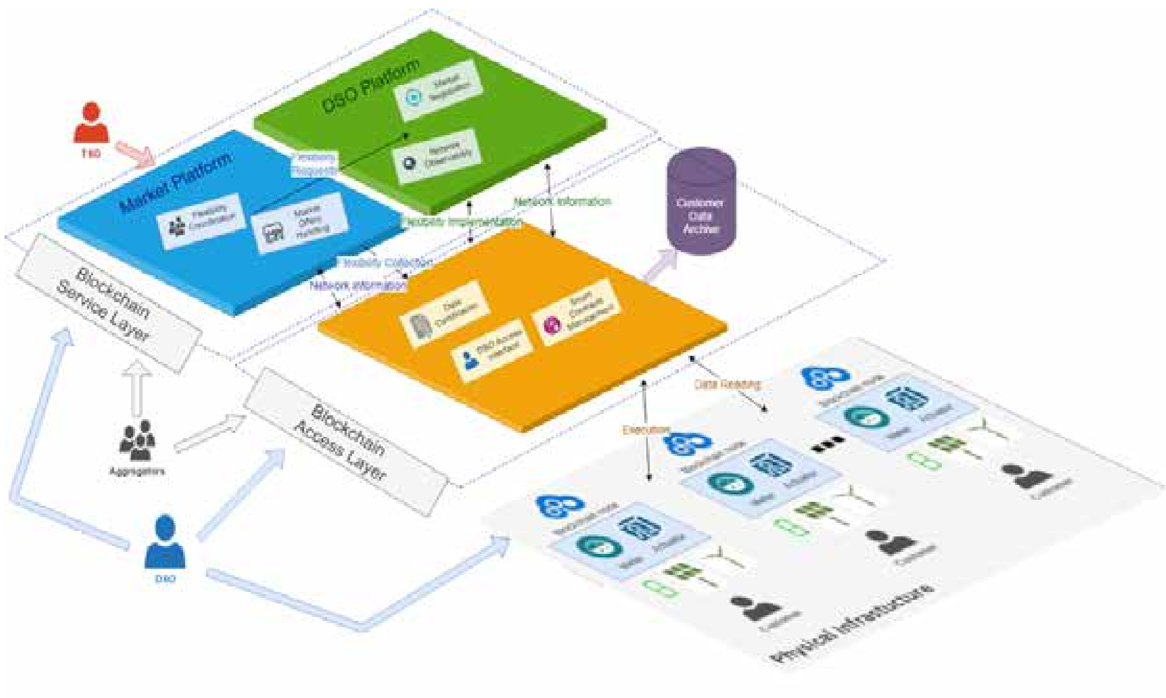

Figure 1.6 The SOGNO architecture supports Distribution System Operators in the energy transformation process.

Figure 1.7 SOGNO uses a micro-service architecture that facilitates modularity and the creation of open ecosystem for energy communities and is currently being demonstrated at Twistringen, NRW, Germany.

Also, the German Federal Government initiated more R&D projects to accelerate innovation. For example, the German Federal Ministry of Research and Education (BMBF) established nine so-called Research Campus Centers, among these the Research Campus Flexible Electrical Networks (FEN) at RWTH Aachen University. At FEN, an international consortium of companies is working with RWTH institutes on implementing new technologies for the future distribution grid. This grid will have to provide reliable energy to all sectors as they become fully electrified. No doubt the amount of energy that must be distributed will increase if more and more vehicles and HVAC systems (heat pumps) become electrified. Next to digitalization, DC distribution systems are key to route efficiently and at low cost the electrical energy from renewable power sources to end-users. E.ON ERC|PGS took the lead in acquiring FEN in 2014. Currently, all four E.ON ERC Institutes are active partners in FEN. A highlight of the first phase of FEN, which ended in 2019, was the design, construction and taking in operation of a 5 kV, 5 MW medium-voltage DC (MVDC) grid connection between the E.ON ERC|PGS test hall and the 4 MW Center for Wind Drives (CWD), see Figure 1.8.

Figure 1.8 The bipolar 5 kV campus grid is installed at RWTH CAMPUS Melaten and creates a MVDC connection between the substations of two laboratories (PGS and CWD). The Center for Aging, Reliability and Lifetime Prediction of Electrochemical and Power Electronic System is scheduled to be connected to the MVDC Grid.

Actually, this MVDC grid realizes a MVDC connection between two AC substations. The inverters that connect to the AC grid can provide grid services, such as VAR compensation and voltage control, while the 5 MW Dual Active Bride (DAB) DC-to-DC converters provide galvanic isolation and power flow control between the substations. This technology demonstrates effectively a so-called Underlay Grid, which doubles for our test facilities the peak capacity. Calculations show that such a MVDC Underlay Grid enables to realize major cost savings, both in infrastructure and operating costs, as compared to increasing the capacity of each individual AC substation with outdated 50 Hz technology. In addition, at 1 kHz operating frequency the DAB converters require about 15 times less copper and electro-steel (see Chapter 8) as compared to classical 50 Hz distribution transformers. Note that copper prices have almost doubled over the past decade, as copper mining is predicted to reach a peak in the coming 30 to 40 years. Hence, these innovative power-electronic-based solutions not only help to save costs but also materials, potentially lowering import dependence and the ecological footprint.

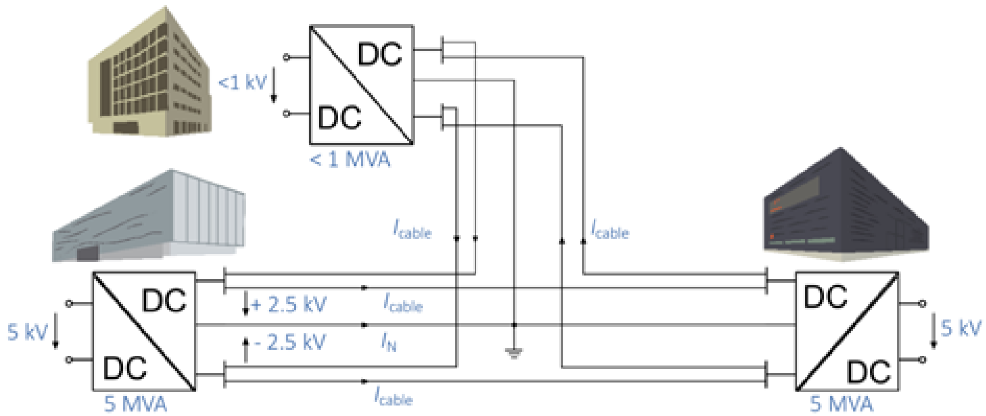

Figure 1.9 Elementary schematic of the 5 kV MVDC grid. By using DC converters an optimal power flow control of electrical energy between the laboratories is possible. This enables to reduce investment and operating costs.

For the increasing conversion of the electricity supply to renewable energies, storage systems are necessary both to ensure grid stability through reserve power and to balance fluctuating electricity generation. Battery storage is the most important option for reserve power and intraday balancing. At E.ON ERC|PGS, under Leadership of Prof. Dirk Uwe Sauer, ideas and concepts for setting up and operating such a battery system for applied research purposes were developed already about 10 years ago. In 2016, our M5BAT system was put int operation, which can be flexibly used with a connected power of 5 MW from 5 different battery technologies built up in 10 strings, each with individually controllable converters. Prof. Sauer states "We are pursuing three main goals with this. We are measuring and analyzing the efficiency of all components in real operation and the ageing behavior of the more than 22,000 battery cells in the plant. We optimize and test the battery management of a hybrid storage system to achieve the lowest possible operating costs, including the consideration of efficiency levels and aging behavior. Currently we operate the plant with a daily 3 MW output in the regular market for primary control power and participate accordingly in the auctions of reserve power on the electricity exchange. All of this together gives us the unique opportunity for a university to conduct research on the ageing and operation of a large-scale battery storage system and at the same time to learn about and experience the real hurdles and challenges of operating such a storage system as part of the critical supply infrastructure in Germany and Europe".

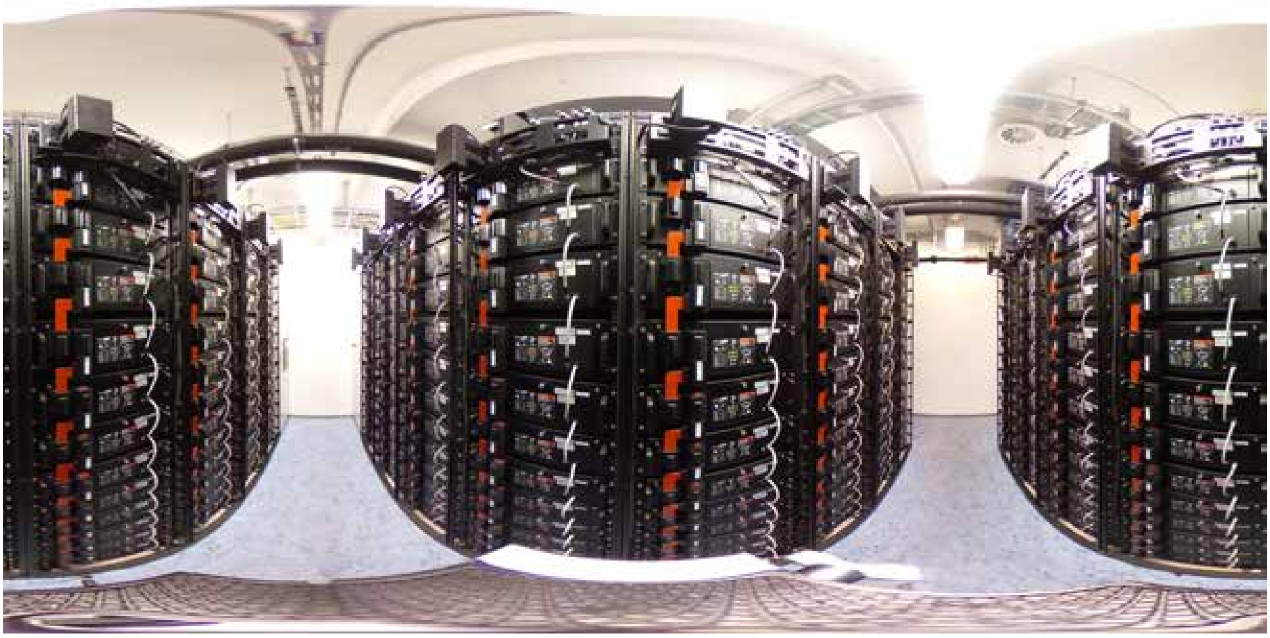

Figure 1.10 Lithium-ion battery as one of 5 different battery systems in our M5BAT grid storage system with 5 MW of usable active power and more than 5 MWh of energy capacity, operated by PGS of E.ON ERC and in regular operation on the grid since September 2016. Live data and a project description of M5BAT can be found on https://m5bat.isea.rwth-aachen.de/.

Furthermore, the German Fed. Gov. Ministry of Economic Affairs and Energy (BMWI), nowadays called the Ministry of Economic Affairs and Climate (BMWK), created Living Labs, so-called Reallabore, which are large reconversion demonstration projects bringing innovative technologies into application and testing them on an industrial scale and under real conditions. Under leadership of Prof. Müller, E.ON ERC|EBC acquired two so-called Living Labs, i.e. TransUrban.NRW and SmartQuart. SmartQuart was the first consortium selected for the living labs of the energy transition ideas competition. The SmartQuart project brings together all the key players in a neighborhood, from planning specialists to residents to energy suppliers. The project‘s central goal is to demonstrate energy-optimized neighborhoods for a decentralized energy and heat transition at the neighborhood level.

TransUrban.NRW is realized by an interdisciplinary team consisting of energy suppliers, district developers, start-ups, and researchers over a period of five years. The primary objective of TransUrban.NRW is to replace the classic district heating supply in traditional mining areas, which is often operated at temperatures of more than 100 degrees Celsius, with more sustainable so-called LowEx networks, or 5th generation heating networks. These networks are designed as energy exchange platforms through which all connected infrastructures can interact with each other. This is made possible by intelligent network designs and decentralized heat pumps, which balance the heating and cooling requirements of buildings and thus increases the efficiency of the overall systems. This technology not only reduces energy losses, it also enables the integration of geothermal heat sources and/or the use of waste heat. Both are available on a comparatively large scale at low temperature levels. Four different district energy systems located in North Rhine-Westphalia are being planned and implemented as part of the TransUrban.NRW Reallabor and are all located in structural change regions characterized by former coal mining.

For the planning and operation of 5^{th} generation heating networks and corresponding district energy systems, the static operating assumptions commonly used till now are no longer sufficient. Therefore, EBC researches novel planning methods from the area of mathematical optimization and thermos-hydraulic simulation, which allow analyzing the dynamic behavior of the whole system in a holistic way. In a second step, those methods are combined with data infrastructures to support the later operation of the systems after implementation. Beyond the technical design of the efficient and low-CO2 district energy systems, TransUrban.NRW also focuses on optimally designing the solutions found from an economic point of view. To this end, business models are being systematically developed to enable the economical operation of the technical innovations used in TransUrban.NRW. Information (in German) can be found on https://www.reallabor-transurban-nrw.de/ueber-uns-2

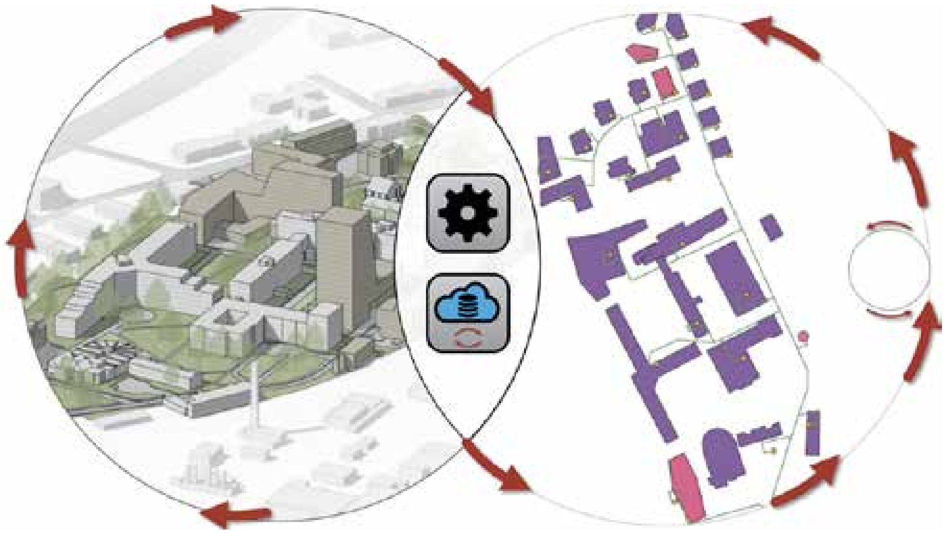

Figure 1.11 Interaction between real neighborhood and digital model for optimized neighborhood operation in the living lab project Trans.Urban.NRW.

FCN (Prof. Madlener) has been involved in the above-mentioned BMBF project “Flexible Electrical Networks (FEN) since 2014. While Direct Current (DC) technologies have a high potential for the sustainable energy transition, due to technological path dependence and lock-in, these have by and large been unable to replace Alternating Current (AC) technologies. DC technologies vary greatly in terms of the technological maturity (Technology Readiness Level, TRL) and thus market readiness. Also, the adoption and diffusion of DC technologies depend on economic and socio-technical aspects related to each specific use case. So far, it is largely unclear which socio-economic factors are necessary or favorable for accelerating the market diffusion of DC technologies in various settings

FCN, jointly with five other non-engineering partner institutions at RWTH Aachen University, investigates the socio-economic and spatial aspects determining the market niche creation and eventual mass market diffusion of DC technologies, focusing primarily on the two use cases “DC Commercial Building” and “DC Quarters”. Drivers and barriers for a successful establishment of DC technologies (and combinations thereof) are investigated. A major aim is to develop an integrative interdisciplinary overall model for the analysis of Niche Readiness of DC technologies and a multidimensional and interdisciplinary approach for analyzing the interaction of Niche Readiness and market diffusion dynamics. To account for increasing uncertainties in the energy systems, assessments of security of electricity supply require computationally highly intensive and time-consuming simulations. In the BMWK funded project KIVi, new artificial intelligence AI-based approaches are developed by Prof. Aaron Praktiknjo, Chair for Energy System Economics (FCN-ESE), to accelerate these assessments. The KIVi project has won several awards, among these , the Study Award of the Körber Foundation in the area Social and Economic Research, the EEX Group Excellence Award, the Award of the German Association for Energy Economics (GEE) and the Best Application Paper Award of the Conference on Computers and Industrial Engineering.

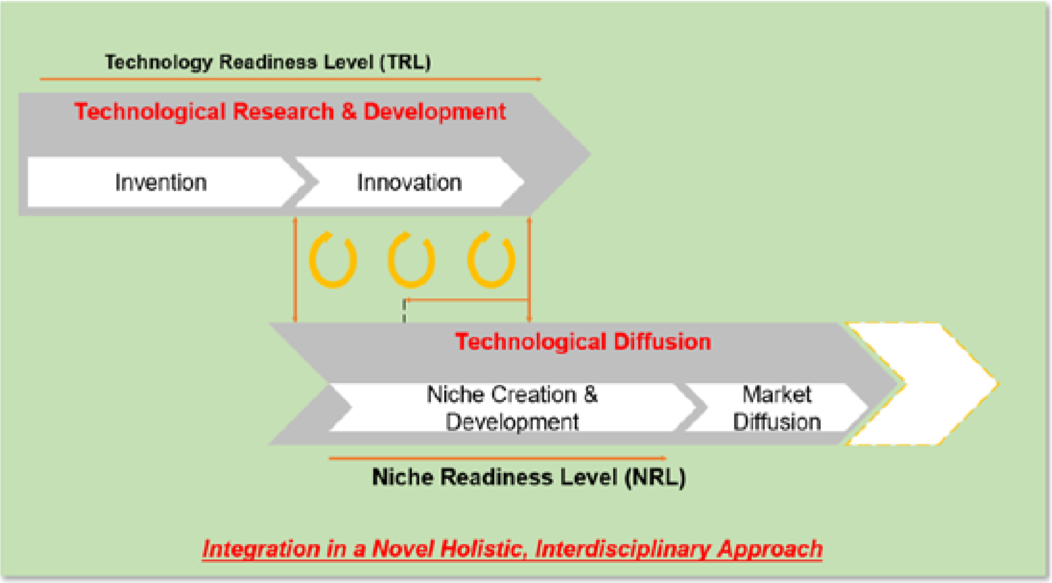

Figure 1.12 From technology readiness to niche readiness and eventual market diffusion.

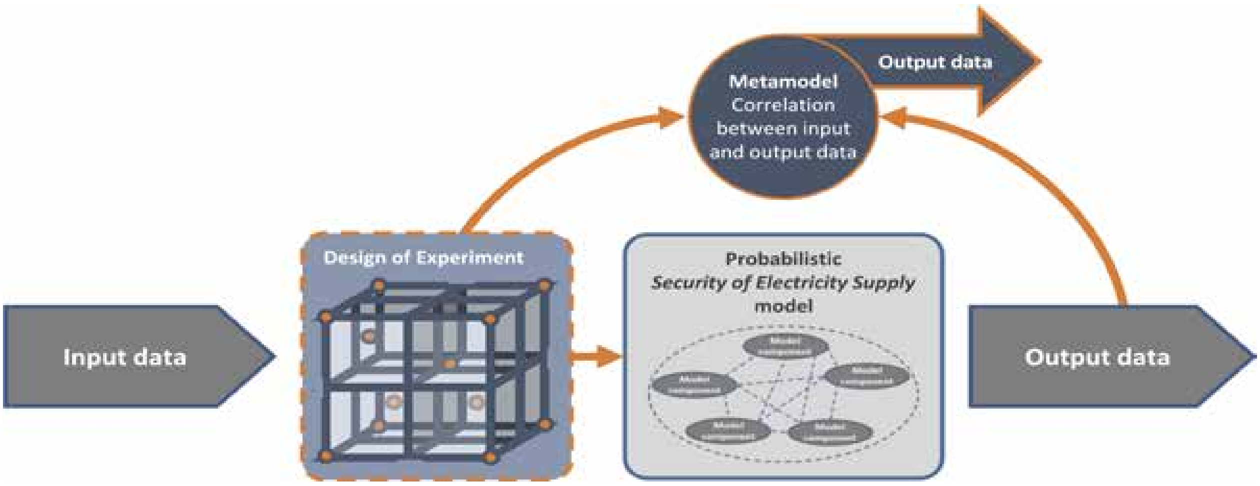

Figure 1.13 The KIVi simulation tool uses new artificial intelligence AI-based approaches to assessments security of electricity supply.

Last but not least, at the closure of the 2nd phase cooperation with E.ON, on June 23, 2021 a joint Press Release was organized. E.ON SE and RWTH Aachen University confirmed the continuation of the PPP cooperation between both partners for another five years. The agreement for this 3rd Phase cooperation was signed on behalf of E.ON SE by Dr. K. Wildberger and by Rector Rüdiger for RWTH. At the occasion of this signing ceremony a podium discussion with online streaming, entitled “Research and Innovation: pathways towards a sustainable energy future” was organized (see Figure 1.14).
This podium discussion can be watched online on Youtube: https://www.youtube.com/watch?v=6uowYuMCwcs

At the start of the 3rd Phase the promotion film edited by the E.ON ERC institutes and sponsored by E.ON ERC gGmbH "Seeing is Believing" went in premiere. This film (English Version) illustrates our vision of pathways to realize the energy transition. The film can be watched in this YouTube channel. We are proud that RWTH selected the German version of our promotion film for the Opening Day of its 150-year anniversary. It premiered at the RWTH Alumni Tag "Lernen, Forschen, Machen".The German version can be watched on this YouTube channel.

Figure 1.14 At the closure of the 2nd Phase and with the start of the 3rd Phase PPP cooperation a podium discussion, entitled "Research and Innovation: pathways towards a sustainable energy future," was organized with live streaming.

Clearly, policy makers realized that lessons learned from demonstration projects could accelerate the marked introduction of known technologies and policies that are essential for the energy transition. As the EU Green Deal was announced by the end of 2019, such acceleration became essential in all sectors, as they all need electrification. Consequently, more time and effort had to be spent on demonstration projects that aspire a clear output, with added marked value, rather than researching and developing new advanced concepts. Hence, most engineering projects that started in this period also researched, next to the social acceptance, the economic and the ecological impact of the technologies demonstrated.

No doubt, these trends in funding shaped our R&D activities, probably more towards "D", i.e. engineering developments. However, at the same time, these demonstration projects broadened our knowledge making clear what is needed in the near-term future, without losing the end-goal, which is a CO_2 neutral society by 2050. The demonstration projects created focus and, in many cases, made clear what the essential drivers are for progress. Also, issues that could hamper the energy transition became visible, such as, among others, regulatory restrictions, missing standards, training of personnel, etc. This is why this Festschrift mainly focusses on what we, at E.ON ERC, learned in our specific research fields, so that we can identify relevant pathways that we, as a society, will need to follow to realize the EU Green Deal.

Chapter 2

Sustainable Energy Development: Looking Both Ahead and in the Rear Mirror

Take-away Messages (Reinhard Madlener)

- All three dimensions of Sustainable Development (economic, social and ecological) may be disruptive, potentially jeopardizing a timely energy transition due to shifts in priority setting
- Climate change (CC) is real; CC, but also other threats to humanity, will alter the situation, perceptions, and action space / room to maneuver drastically
- First-world problems will lose relevance in times of crisis; many business models are based on "scim-the-cream" marketing strategies (e.g., premium brand (electric) vehicles); overall, this may slow down technical progress, as market diffusion dynamics are slowed down and the focus is put more on essentials
- Material scarcity, and exnovation dealing with legacy infrastructure etc., are expected to slow down the sustainable energy transition, and can make it much more expensive than expected
- Major infrastructure projects need enormous financing and sufficient planning security, but may also lead to new technological-ins
- Taking no action, or too little action (e.g., regarding climate change, micro-plastics, pesticides in ground / drinking water) might be much more expensive than taking action (along the lines of the precautionary principle, diversification, redundancy, flexibility etc.) that is not perfect or “no regret”, or too late to keep problems manageable.

Prof. Reinhard Madlener

Introduction

The challenge of reducing anthropogenic (i.e. manmade) greenhouse gas emissions to zero by 2050 in order to stabilize global warming is massive. It will profoundly change many aspects of life and doing business, and requires collective and coordinated action of the global community of people and nations. Without the achievement of the net zero emission goal by the most populous and rapidly developing countries (especially China and India), and others with traditionally very energy-intensive lifestyles (such as the US), it will not be possible not even in the presence of negative greenhouse gas (GHG) emissions enabled by negative emission technologies (NETs), including Afforestation, DACCS (direct air capture) or BECCS (biomass energy plants combined with carbon capture and storage).

Technological change, social acceptance, economic growth, regulatory and institutional boundary conditions and other aspects need to be considered in a systematic way, as these can support, slow down and to some extent influence the sustainable energy transition. Despite major efforts to combat climate change by achieving net zero emissions, it is still a very long way to go.

Whereas the fossil fuel era and pervasive so-called ‘general purpose technologies’ (GPTs) [1], has enabled mankind an unprecedented development cf. Figure 2.1, it has become clear that the development along the economic growth paradigm is unsustainable for many reasons including energy supply and use. Given the large uncertainties about the development globally (e.g. regarding the conflict between China and the US about the world leadership position or the actual consequences of exceeding 2 °C global warming and reaching tipping points with potentially devastating consequences), global trading can be expected to face some major drawbacks and more national and regional thinking and acting a boom.

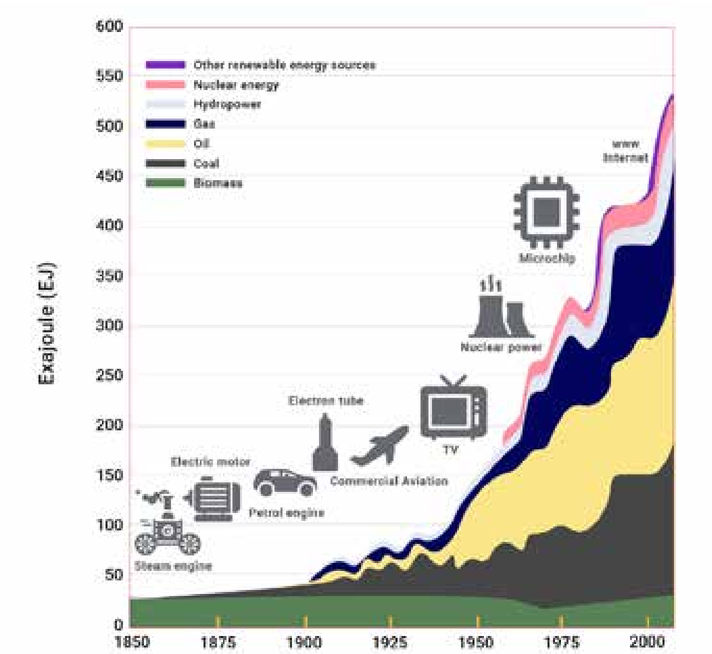

Figure 2.1 Development of global energy consumption in light of key technical innovations [29], adapted.

The other side of the mountain depicted in Figure 2.1 seems much harder to sustain or descend than it was to climb up, despite of further energy efficiency gains. One reason is the still rising world population, another one rebound and still largely materials-based consumerism, both contributing to lessening the decoupling between economic growth and energy consumption. Yet another reason is decreasing energy returns on investment.

In light of global warming and dwindling low-cost fossil fuel resources the world community is committed to the transition to a more sustainable energy system, which also implies a better management of energy supply and demand [27]. Such a transition will require some smart combination of renewable energy use, energy efficiency, carbon capture and storage (or utilization), and possibly continued use of nuclear power, which is (and likely remains, at least in the foreseeable future) highly controversial, not least due to the emergence of flexible small modular nuclear reactor (SMR) concepts.

Apart from sustainability studies along the lines of the “planetary boundaries” and the 17 Sustainable Development Goals (SDGs) of the United Nations [30], there are also innovation studies that investigate new processes, products and services to improve human wellbeing without jeopardizing the environmental support systems [26]. The multi-level perspective on socio-technical transitions mentioned above facilitates the analysis of the broader problem framing of innovating entire systems of production and consumption (such as all energy supply systems, but also mobility, sanitation, food, entertainment etc.). The regime of centralized power generation on the basis of fossil and nuclear fuels is an example regime, comprising artefacts, actors, and institutions that gain stability and are characterized by path dependence.

Redefining the energy trilemma

The analysis of alternative pathways for a sustainable energy transition requires interdisciplinary knowledge and research, for instance regarding the potentials and positive and negative implications of advanced emerging energy technologies (e.g., e-vehicles, renewable energy conversion plants, energy storage) and systems (e.g., energy, economic, social, biogeophysical, political) supporting the transition [2]. In that vein, the role of externalities and economic performance of energy systems has to be acknowledged.

Several attempts have been made to benchmark countries with regard to their sustainable energy transition status and/or progress. Examples include the 2005 scheme of Energy Indicators for Sustainable Development (EISD) of the International Atomic Energy Agency (IAEA) [16], the 2012 Energy Development Index (EDI) of the International Energy Agency (IEA) [17], the Sustainable Energy Development Index (SEDI) proposed by Iddrisu and Bhattacharyya [19], or the Sustainable energy transition readiness (SETR) index suggested by Neofytou et al. [24], which accounts for social, economic, technological and political/regulatory aspects in a multi-criteria decision analysis (MCDA) framework that uses a consistent set of eight evaluation criteria.

Other initiatives focused more on energy justice measures, such as the Energy Trilemma Index (ETI) of the World Energy Council (WEC) [33], the per capita total primary energy supply (TPES) shares by country (IEA) [18], or the Energy Justice Metric (EJM) and Ternary plots [15]. Still others, along the lines of energy justice/inequality use Lorenz curves for showing population share/energy (or electricity) versus income inequality [20, 32]. Most of these approaches cannot do justice to the enormous complexity of the topic, which will be aggravated by digitalization enabling sectoral coupling and totally new concepts and business models to be established, with expectedly major impacts also on energy equity and justice (see [23] for a further discussion also on trade-offs and energy policy implications).

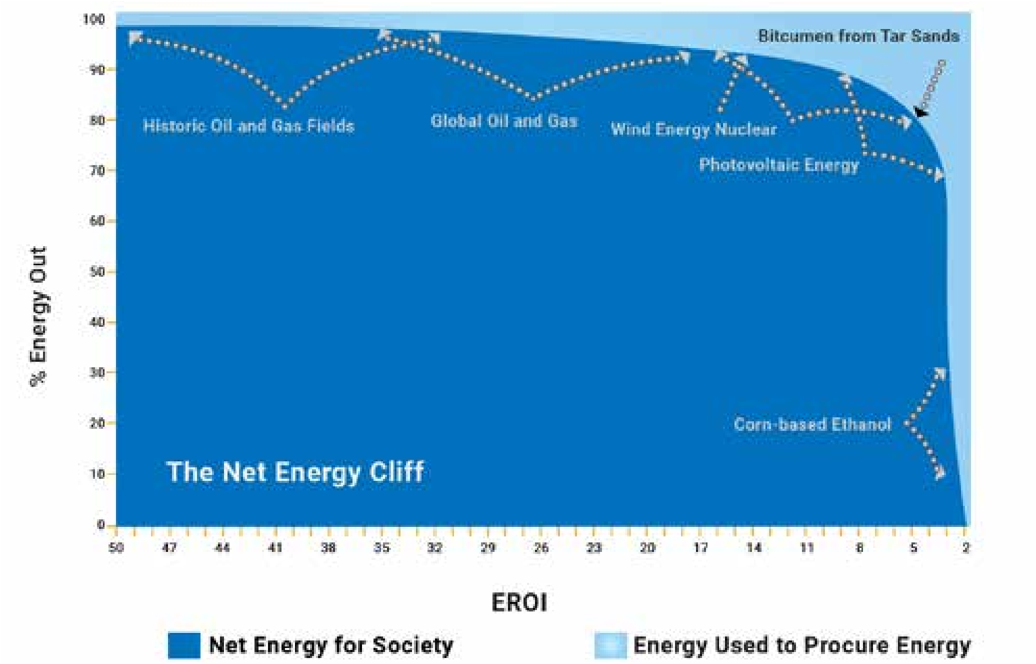

Figure 2.2 The "Net Energy Cliff" - little change of net energy delivered from high to lower values. Large difference for EROI below 10:1 and, consequently, a higher difference to society [14], adapted.

Climate change mitigation has justice implications, and a failure to tackle global warming will make sustainable development goals (SDGs) harder to achieve. It implies that there must be an equitable distribution of the gains and burdens of the transition, judged by fair and inclusive processes. There are justice implications of rapid climate change mitigation and also a risk that, in light of increasing urgency of a rapid sustainable energy transition, top-down technocratic approaches are adopted that neglect basic human needs. Not obeying equity and justice considerations may cause resistance to climate policy action; put differently, accounting for justice as a guiding principle may increase political feasibility and social acceptance [3], and positively impact the sustainability of energy transition processes.

Transition and transformation pathways

Socio-technical transitions, including the ongoing sustainable energy transition towards phasing out fossil fuels in favor of renewable energies, can be evolutionary, revolutionary, and transformative [9]. In any case it has to be analytically and empirically examined in a thorough and ideally broad and interdisciplinary manner. A useful and proven concept for the analysis is the so-called multi-level perspective (MLP) approach attributed to the Dutch sociologist Frank Geels (Figure 2.3) [9].

The development and refinement of socio-technical systems always comes along with interests, perceptions, values and norms, but also preferences, strategies and resources available (ibid). A change in a socio-technical system is never induced by technology alone but rather numerous complex interactions between different actors, societal groups, and the alignment of specific factors. Overall, such a 'socio-technical transformation' (e.g., use of mobile phones, fully automated or autonomous driving) can change a society fundamentally in its practices, attitudes, norms and values (Figure 2.3).

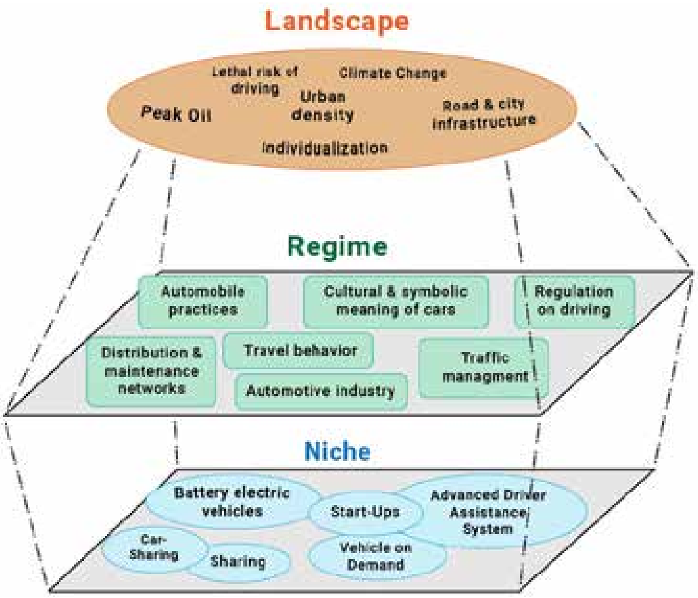

Figure 2.3 A multi-level perspective on the automobility transition [9], adapted.

"Exnovation", the counterpart of the much better known term innovation, was coined by [22] in the context of energy justice and the energy transition. It encompasses processes in the course of eliminating specific technologies, routines, and techniques as legacies to be removed in the course of energy transitions and based on stakeholder re-evaluations of technology (see also [4,5,6], for a more recent discussion and coverage of related literature).

Industry 4.0 – an IT-driven, i.e. highly digitalized modern manufacturing system – can contribute to a more sustainable development, and has attracted much interest in recent years from the perspectives of the triple bottom line, sustainable business models, and the circular economy [21]. Triple bottom line studies often focus on the adoption and diffusion of Industry 4.0 but also sustainable supply chains, sustainable factories, and sustainable cities. Cyber-physical systems (CPS), the Internet of Things (IoT) and other technologies recently developed, in combination with big data and artificial intelligence (AI), often creating mind-blowing new pathways for the next industrial revolution, enabling to raise productivity and efficiency of manufacturing at massive scale, and being a new and expectedly very powerful engine of economic growth. Smart grid technologies will enable major change in the ways energy is supplied and used, but needs to be well managed and regulated, and properly understood in terms of social justice and social welfare implications [7], behavioral change needed for promoting a sustainable energy transition [28], as well as environmental sustainability of emerging technologies [8].

Today, already some 55% of the world population live in cities (in Europe approximately 74%), a share expected to increase to almost 70% by 2050; the European Commission has identified cities as ideal laboratories for transformative and sustainable solutions [25].

Criticality of resources in the global energy transition

The ongoing global sustainable energy transition encompasses a shift to new technologies and different natural resource mixes. Comprehensive, scenario-based assessments of the expected resource needs, coupled with resource economics modeling and assumptions about recycling potentials, are needed [13]. In scenario-based assessments without much resource economics modeling and background, for example, lithium criticality has been studied for achieving a sustainable energy transition globally. Based on a comprehensive analysis using 18 scenario variations and some material flow analysis until the year 2100, find that lithium supplies must indeed be expected to be critical for the energy transition, and that a balanced supply-demand relationship throughout the 21st century requires well-established (battery) recycling systems, vehicle-to-grid integration, and the realization of transportation services with lower lithium intensity [13].

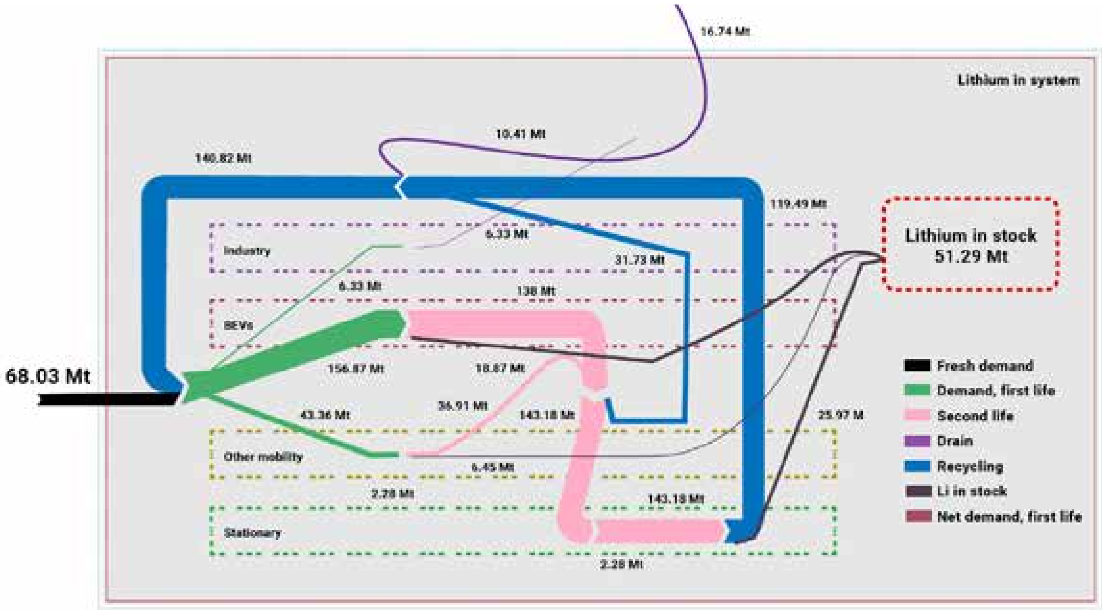

Figure 2.4 Lithium material flow analysis until 2100 [13], adapted.
Notes: Base Case demand, assuming a fresh Li inflow of 68.03 Mt, split into four supply streams (industry, BEVs, other mobility, and stationary batteries). A strong recycling loop keeps the lion's share in the system. Only 16.7 Mt of Li flows out through the channel of industrial applications (no recycling) and losses during the recycling processes.

"Greenflation" is a term coined for the part of the inflation that is driven by the sustainable energy transition. Consumers have to pay more as demand for energy, other natural resources, and technology rises as a consequence of induced technological change here due to "demand-pull" triggered (or caused) by sustainable energy policy measures. The risk of poverty of additional societal groups can be aggravated by greenflation if consumers have to pay a markup for green technologies (e.g., e-vehicles or renewables-based heating systems being more expensive than conventional ones).

Amongst the materials desperately needed are copper, lithium, cobalt, nickel, manganese and rare earth materials. Price rises, however, do not necessarily indicate an increased scarcity of the resources in nature as such, but can also be a sign of insufficient (or delayed) investments into production and processing capacities, or of geopolitical disruptions. Such disruptions, for example, are the War in Ukraine and the sanctions imposed on Russia as a countermeasure, or the increasing chasm between China and the Western world that increasingly jeopardizes and reduces global trade potentials. Rising prices of natural resources also increase production, as the economic potential (which is a subset of the theoretical and technical potentials) rises.

Over time, it can be expected that Europe will aim at significantly reducing both its import dependencies and the sometimes enormous supplier concentration (e.g. about 70% of the cobalt needed in the European Union comes from Congo and 40% of the nickel needs in Germany came from Russia when the Russian invasion of Ukraine was launched in early 2022). Geopolitical strategies and competition (or in a more extreme form trade wars) amongst industrialized nations can also limit resource supplies (e.g., China deliberately limited the global supplies of rare earth materials in 2010/2011, which led to major problems especially in Europe and Japan).

The European position can be strengthened by ramping up exploration and production in Europe. There are vast geological lithium resources in many parts of Europe where sometimes production can start right away, or where more systematic and thorough exploration is deemed necessary first. Another strategy is the installation of buying syndicates (joint purchasing) that increases market power and thus the bargaining position in the global markets.

Deep ocean mining of resources needed for the sustainable energy transition, such as manganese (which could be produced jointly with copper, cobalt, nickel and zinc), seems problematic in light of the expected devastating damages done to the oceanic ecosystems, which are of enormous significance as a carbon sink. The UN Agreements on marine ecosystems is a step in the right direction to protect oceanic resources and ecobalances, and to avoid reaching tipping points beyond which climate change will become unmanageable for mankind.

Conclusions and outlook

The energy and climate policy challenges are enormous. In a seemingly increasingly unstable world, which is drifting to new geopolitical alliances and balances, policy-makers often easily get “distracted” by new shocks requiring attention (e.g., Covid-19 Pandemic, War in Ukraine, shortage of skilled and unskilled labor, inflation), which makes it even harder to accomplish the set targets.

Likewise, issues that are potentially detrimental to cost minimization or profit maximization but beneficial to the mitigation of financial risks – such as flexibility, redundancies and supply- and demand-side portfolio diversification – are gaining importance.

Comprehensive interdisciplinary analysis of the energy-economy-society-environment nexus of the sustainable energy transition is still scarce, and studies that focus on one particular aspect of a sustainable energy system often still dominate [2].

Since the establishment of E.ON ERC and FCN in 2007, the Chair of Energy Economics at RWTH Aachen University has educated hundreds of young talents, which are often engineering-economics students, in the fields of energy economics, environmental & resource economics, economics of technical change, economics of technological diffusion, and other related fields. This eventually enhances the knowledge base in firms or public administration entities, dealing with the above-mentioned challenges if they hire such well-educated students from RWTH Aachen.

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Chapter 3

System Aspects of Sustainable Energy Pathways

Take-away Messages (Aaron Praktiknjo, Lars Nolting, Jan Priesmann, Christina Kockel)

- Defossilization in the heating and mobility sectors is harder than in the power sector; thus a trend to electrify both sectors using carbon-free electrical energy exists
- Weather dependency and supply security: Energy supply security and reliability of energy systems are being challenged by high shares of variable renewables (VRES); given these circumstances economic optimality can only be achieved through a much more flexible energy demand
- Shifting dependency on resources: Fossil fuels are increasingly replaced by other resources (incl. minerals); a smart use of such resources (e.g., recycling, circular economy) is needed
- The energy transition brings substantial cost; a just allocation of these cost is crucial for social acceptance of the energy transition
- Tendency to increase model complexity as energy systems become increasingly complex; however, more complex models are not superior per se and model complexity needs to be carefully dosed

Prof. Aaron Praktiknjo

Future energy systems: an all-electric world?

The German government has defined ambitious green house gas (GHG) emission reduction targets to mitigate climate change: The German energy system is planned to be GHG emission neutral by 2045, and even negative emissions are targeted in 2050. To achieve these ambitious targets, distinct goals for the share of renewables in the total final energy consumption as well as for the share of renewables in the electricity sector have been defined in a recent regulatory amendment. These goals as well as the historic development are shown in Figure 3.1.

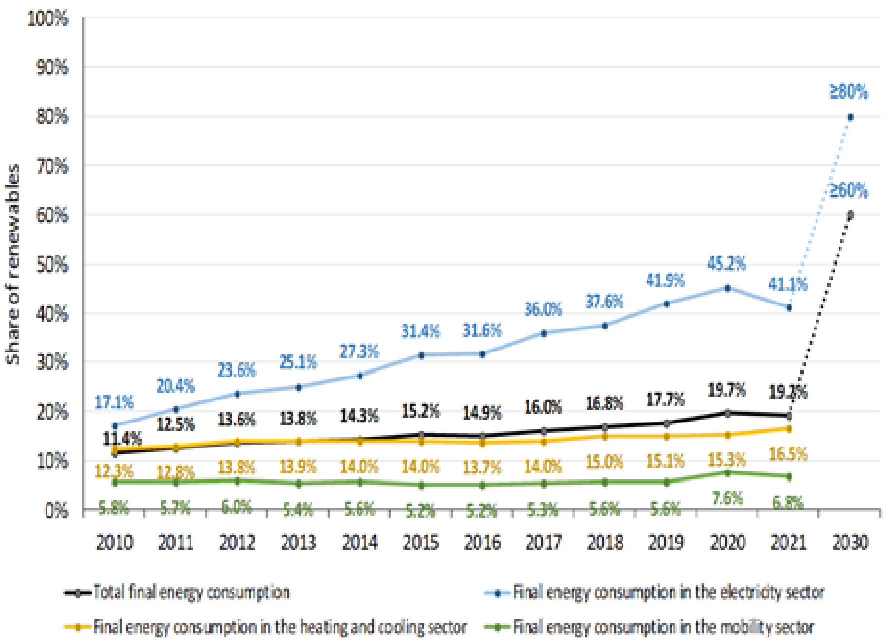

Figure 3.1 Share of renewable energy in the electricity, heating and cooling, and mobility sectors of Germany. *: Targeted shares of renewables according to “BMWK Easter Package”. Source of data for historic development in years 2010 to 2021 [1].

The very ambitious goal for the share of renewables in the electricity sector takes account of the fact that the integration of renewables in this sector is per se easier to achieve than in other sectors such as the heating and cooling sector, as well as the mobility sector. The historic development of the shares of renewables in Germany underlines this as the share of renewables in the electricity consumption has been at similar levels to the overall final energy consumption in 2010 but has increased much stronger since then. In 2021, the share of renewables in the electricity sector was more than twice as high as the overall share of renewables in the final energy supply (41.1% vs. 19.2%).

While progress in reducing greenhouse gas (GHG) emissions is noteworthy in the power sector, realizing such reductions in the transportation and in the heating sector seems much more difficult. A strategy to propagate potential GHG emission reductions from the power sector into other energy sectors is sector coupling (see [21]). As outlined by Robinius et al. [20], there are different definitions of sector coupling. In general, the term refers to “the energy engineering and energy economy of the connection of electricity, heat, mobility […], as well as their infrastructures”[1] [5]. Technologies that are frequently being discussed in this context include heat pumps, electric vehicles and fuel cells.

Generally, demand for useful energy (e.g., mechanical energy in the transportation sector or thermal energy in the heating sector) can be fulfilled by different types of final energy (e.g., gasoline, diesel or heating oil, natural gas, or electricity). However, different pathways for the provision of final energy are associated with different infrastructure requirements for energy systems. In this context, so-called direct and indirect electrification are two strategies for implementing sector coupling. With direct electrification, final consumers directly purchase renewable electricity for their appliances such as battery electric vehicles or electric heat pumps [7, 23]. With indirect electrification, consumers purchase fuels and gases such as hydrogen or synthetic methane which are produced from renewable electricity (see for example [15, 24]). Therefore, direct electrification would shape energy infrastructure mainly towards electricity grids while indirect electrification emphasizes pipelines or other means of transportation for gaseous and liquid fuels.

To assess these interrelations, energy balances are a frequently used tool as they depict statistical data on the energy flow within given system boundaries. Figure 2 shows an exemplary illustration of an energy flow chart based on energy balances. Typically, energy balances differentiate between primary energy (i.e., energy carriers that have not undergone any man-made conversion steps such as crude oil), final energy (i.e., mostly energy converted from primary energy and sold to end users such as gasoline), and useful energy (i.e., energy that has undergone a

1 Own translation from German.

final local conversion process in end-user appliances such as motion energy). Therefore, the demand for final energy is only an intermediate one corresponding mostly to commercial energy to provide utility (i.e. useful energy) such as heat and cold, mechanical energy, data processing in information and communication technology (ICT) services, or lighting to the end-user [26].

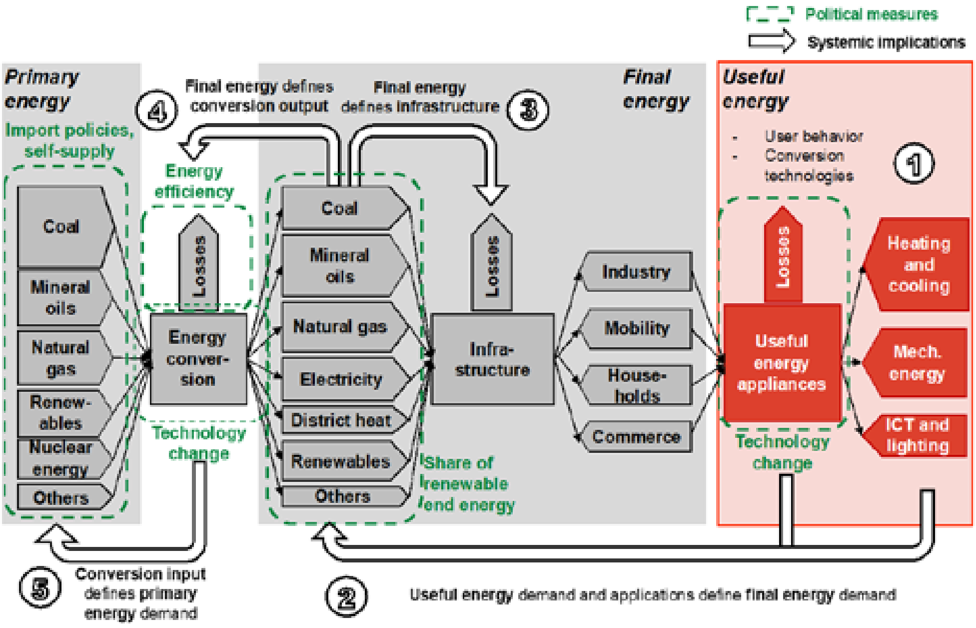

Figure 3.2 Systemic implications and political measures in energy balances of national energy systems based on [26].

In the following, we illustrate the systemic implications of sector coupling technologies using electric heat pumps that directly link the heat and the electricity sector as an example. Figure 3.3 illustrates the effects on a systemic level using an energy flow chart as introduced above.

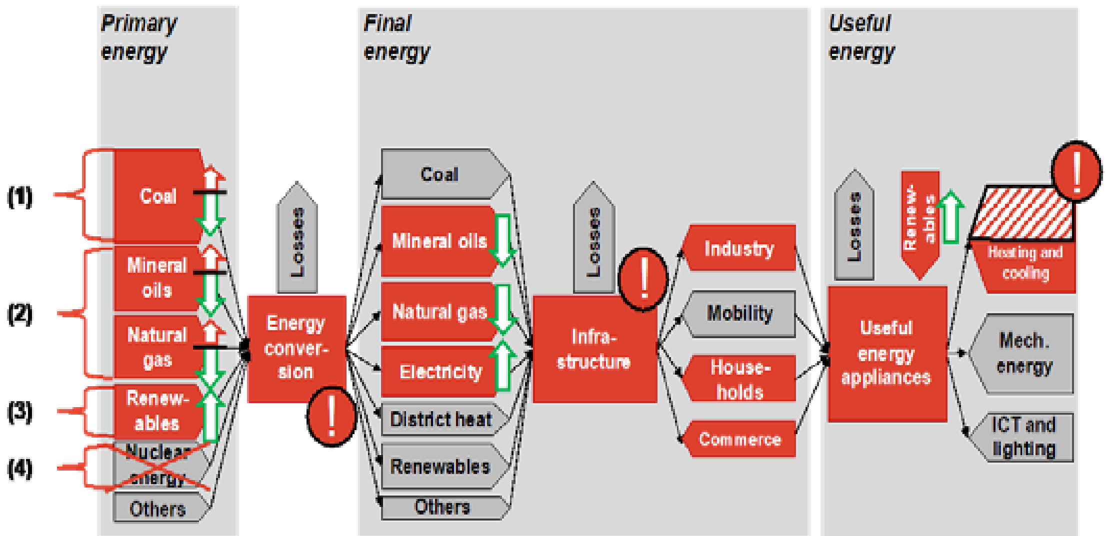

Figure 3.3 Integration of heat pumps into the energy system based on [26].

Electric heat pumps use electric energy to increase the temperature level of a renewable heat source and supply this heat at the required temperature level e.g. for room heating (red-white shaded area in (Figure 3.3). Figure 3.3 illustrates that the integration of heat pumps has several long-term implications for the future energy system, which are marked in the figure by exclamation marks:

- First, the amount of renewable energy that is directly integrated into the end consumer sites is increased (see green arrow on the right-hand side of the illustration).
- Second, the demand for final energy is shifted from mineral oils and natural gas to electricity, causing a change in infrastructure requirements (i.e., further expansion of the electricity grid, see green arrows in the middle of the figure).

- Third, the composition of primary energy sources and thereby the required energy conversion plant portfolio is changed (see green and red arrows on the left-hand side of Figure 3.3): (1) the demand for coal is increased due to increased demand in electricity[2]; (2) the demand for mineral oils and natural gas is reduced as conventional heating appliances are replaced, however, increases in the electricity demand partially compensate for this; (3) the amount of renewables increases due to the increased demand for electricity produced from renewable sources such as wind and solar.

Overall, we find that sector-coupling technologies provide high potential to propagate high shares of renewables in the electricity sector to those sectors that are harder to decarbonize. On the other hand, the diffusion of electricity-based sector-coupling technologies comes with additional demand for electricity as illustrated in Figure 3.4. It can be seen that even when accounting for efficiency gains in industry and imported hydrogen, an additional domestic electricity demand of ~80 TWh is to be expected in Germany by 2030. This is also reflected in the recent substantial increase in the German government's renewable electricity production targets: While the annual feed-in from renewables in 2030 was estimated to be ~380 TWh by the German Government in 2019, the new goal is to have an annual feed in of ~600 TWh. It remains to be seen whether the expansion of renewable generation required to achieve this level of output will proceed at a sufficiently rapid pace in order to maintain the ambitious goals.

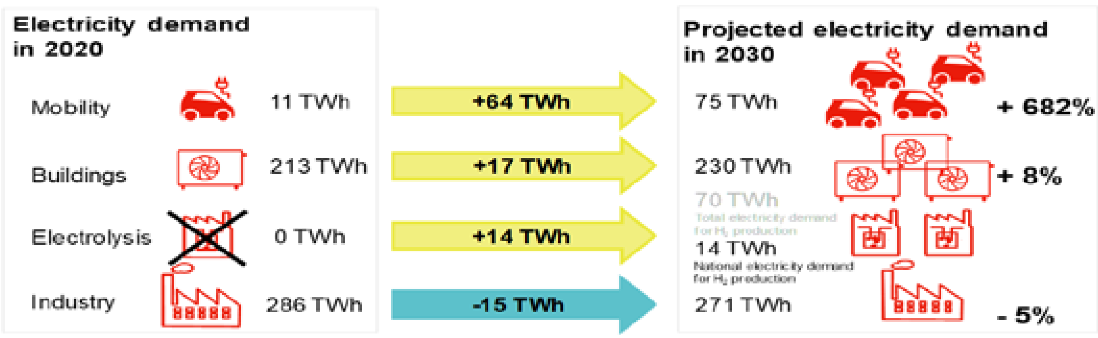

Figure 3.4 Additional electricity demand by sector-coupling technologies. Assumptions: mobility: +7 million BEV/PHEV; buildings: +3.4 million heat pumps; electrolysis: hydrogen demand of 70 TWh in 2030; industry: progress in energy efficiency.

Weather dependency and security of energy supply

While historically the German energy system was characterized by the presence of excess generation capacity, the interaction of the two changes mentioned above has substantial influence on: (1) the regulatory framework comprising politically defined expansion as well as deconstruction pathways; and (2) incentives to invest in dispatchable peak capacities. Figure 3.5 shows the historical development as well as forecasts for the amount of installed electricity generation capacity[3]. In addition, the domestic peak load for a cold winter season is indicated in this figure.

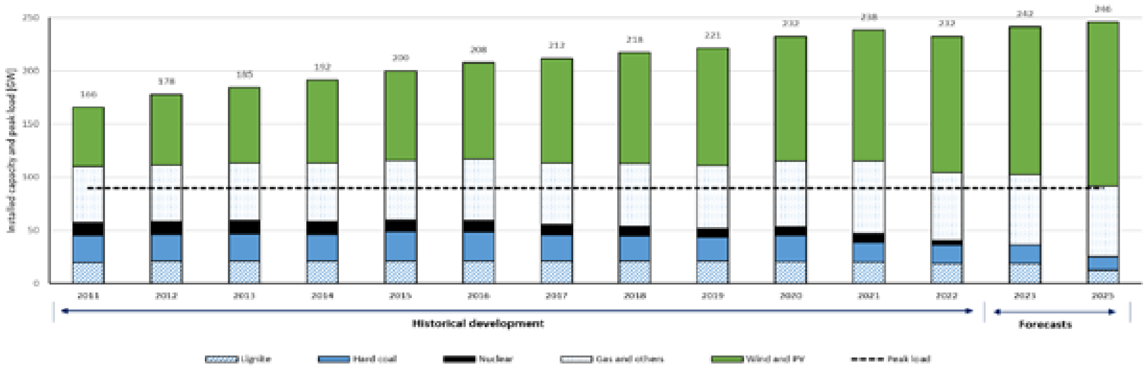

Figure 3.5 Installed capacity of different power plant types. Sources of data: Power plant list by Federal Network Agency, list of power plant closure notifications, coal-exit law, nuclear-exit law, Net Development Plan 2030, Mid-term Adequacy Forecasts 2018 and 2019 as well as own calculations.

2 However, exogenous effects such as a compulsory phase-out of coal-fired power plants in Germany reduce the demand for coal as a primary energy carrier. The nuclear phase-out in Germany constitutes a further exogenous effect erasing nuclear energy as a primary energy source.

3 The depicted forecasts are based on current regulation and do not yet reflect the increased expansion rates for renewable energies as described in the Easter Package by BMWK.

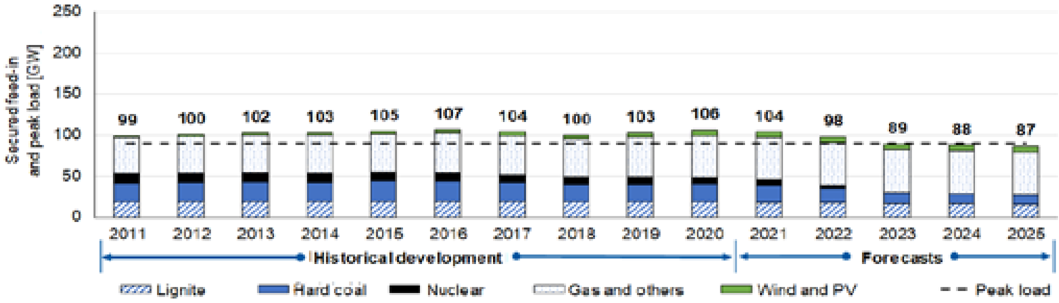

Figure 3.6 Secured feed-in of different power plant types. Own calculations based on data shown in Figure 3.5.

As can be seen in Figure 3.5, the amount of installed capacity substantially exceeds peak load in Germany. However, when accounting for non-availabilities due to (1) planned and unplanned maintenance of controllable conventional power plants and (2) the fluctuating feed-in of renewables, the secured feed-in during the peak load hour can drop below peak load as shown in Figure 3.6. The low levels of secured feed-in from renewables can essentially be attributed to two main causes: first, the German peak load hour usually occurs during a cold February evening after 5 pm. Hence, the feed-in from photovoltaics is close to zero. Second, the secured-feed in from wind turbines can be estimated to be 7% of the installed capacity during this hour, based on statistical evaluations.

While Figure 3.6 illustrates the results of a deterministic approach towards assessing security of supply in Germany focusing on the peak load hour and a national viewpoint, we have also implemented and applied more detailed, probabilistic simulation models. These models are evaluated in hourly resolution for different meteorological conditions (so-called weather years) and depict the stochastic nature of (1) electric load, (2) the (non-)availability of conventional power plants, and (3) the feed-in from renewables. Results from these models indicate that the historically quasi-absolute levels of security of electricity supply are unlikely to be maintained in medium to long-term forecasts with the current market structure (focusing on years 2022-2025 for the medium term and 2030 for the long-term developments). In addition, the model results show a substantial impact of the proliferation of storage capacities as well as of the flexibilization of demand on future levels of supply. Adjustments to the market design are therefore necessary to provide incentives for their spread [16].

However, moving away from the absolute levels of supply security that have prevailed up to now can also lead to a reduction in overall economic costs. As Figure 3.7 shows, both the costs arising from load shortfalls and the costs of building up excess capacity to ensure security of supply at all times must be taken into account. Praktiknjo and Dittmar show that a cost optimum is reached when the marginal costs of a further increase in supply security equal the marginal costs of a further load shortfall [19].

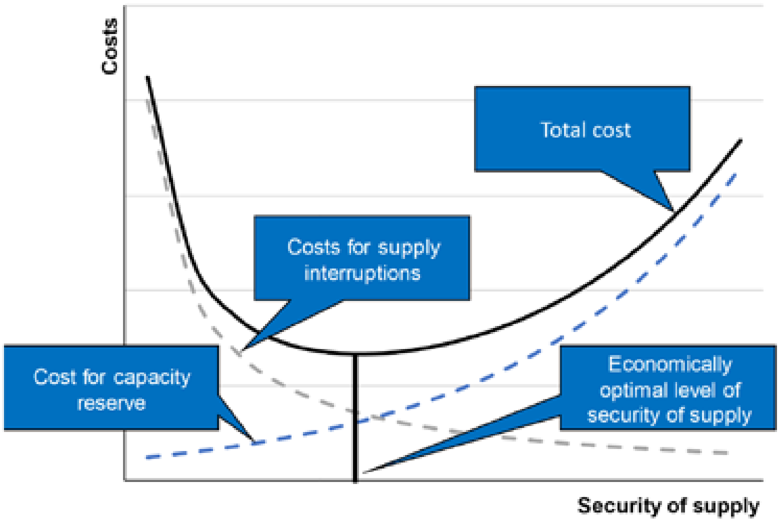

Figure 3.7 Sketch illustration of the interrelationships for minimizing total costs in the energy system.

Shifting dependency on resources

The energy transition aims at decarbonizing the energy system, meaning a shift from a fossil fuel-based energy supply system to one based on renewable energy resources. Renewable energies have the great characteristic that, unlike their fossil-based counterparts, they do not emit any greenhouse gases during their use.

However, looking at their entire life cycle they bind more mineral resources than conventional energy power plants. In particular, the demand for the minerals cobalt, copper, and nickel is increasing drastically compared to fossil-fueled power plants, as IEA showed in their latest report [11]. Wind onshore and photovoltaic power plants need two times as much copper as natural gas power plants and offshore wind power plants require even six times as much. Furthermore, all wind power plants utilize over 5 000 kg of zinc and photovoltaic power plants about 4 000 kg of silicone per installed megawatt. Nuclear power plants need close to five times the total amount of minerals per installed megawatt compared to natural gas power plants and almost double that of coal power plants, but still less than photovoltaic and wind power plants. Hydropower and biomass power plants require smaller amounts of minerals; however, these power plant types have greater constraints regarding locations or availability of fuels (cf. Figure 3.8) [11].

In addition, as the energy transition progresses, power generation will become increasingly volatile due to greater dependence on the weather. Storage technologies can provide a more time-independent power supply. Furthermore, sector coupling technologies offer the opportunity to transfer the decarbonization potential of renewable energy power plants to other sectors. However, this also requires further resource-intensive components. Sectors with stationary technologies such as the heating sector show fewer challenges arising from the demand for minerals. For example, geothermal heat pumps require a relatively little amount of steel and are more likely to be designed with plastic pipelines or, possibly, copper for more efficient heat transfer.

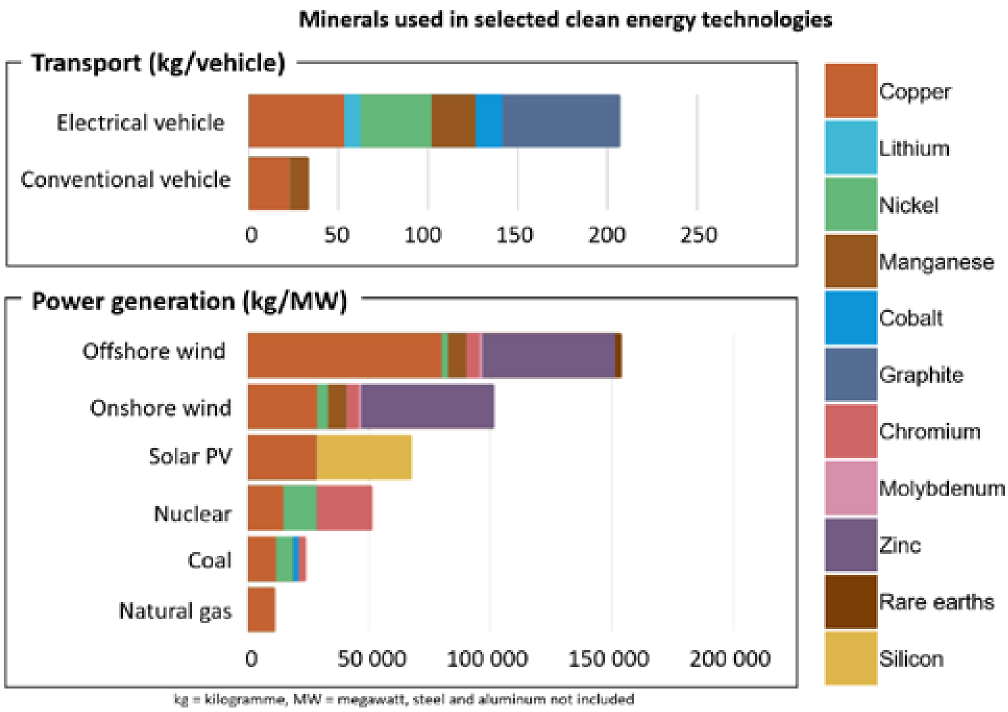

Figure 3.8 Minerals used in selected clean energy technologies [11].

The mobility sector has a high storage demand since it is inherently non-stationarity. Currently, the two types of technology being considered for the mobility transition are the same as those being debated for electricity storage: (1) secondary batteries and (2) hydrogen. For secondary batteries, technologies based on lithium will be particularly relevant. In addition to the active material lithium, the battery packs contain a number of other minerals such as nickel, cobalt, and manganese in the cathode, graphite for the anode, and copper as the current collector [3]. The exact demand depends, of course, on the specific battery technology for which further development steps are expected in the next few years. Furthermore, the motors of electric vehicles are very mineral intensive, especially the most utilized permanent-magnet motors. They require neodymium, and other rare earth elements as well as copper, iron, and boron [4,8,18, 22]. This leads to a total amount of over 200 kg of minerals per Vehicle compared to far under 50 kg for conventional vehicles [11].

For fuel cells, especially the rare metal platinum is needed. However, the platinum demand for fuel cells will probably still be smaller than the one for catalytic converters by 2040 - provided that innovation in the research area of fuel cells occurs as expected. Nevertheless, more mineral resources are needed for electrolyzers, although this depends strongly on the technology. Alkaline electrolyzers are produced with high shares of nickel and zirconium. Solid oxide electrolyzer cells (SOEC) utilize additionally Lanthanum and Yttrium but have the potential to reduce the total required amount with future developments drastically. The currently more widespread proton exchange membrane (PEM) electrolyzers demand the materials platinum, palladium, and iridium. Efficiency also plays a major role in hydrogen use. Depending on the electrolyzer, a fuel cell vehicle requires 3 times as much electricity generation as an electric vehicle - which also means more material is needed to build the power plants [11].

Therefore, to achieve the currently set goal of Net Zero in 2050, the demand for minerals – especially lithium, cobalt, nickel, copper, and rare earth elements – will increase enormously. A scenario by the IEA states a demand in 2040 for all mineral resources that is six times higher than in 2020. The exact amount is, of course, based on the various implementation paths chosen and is heavily dependent on policy and investment. Especially copper is an essential element in almost all clean energy and sector coupling technologies as well as in the powerlines.

It is therefore evident that the availability of these mineral resources is an elementary part of the transformation of the energy system. Currently, there are several risks as to why a shortage could occur for each mineral resource. Existing copper mines are currently running close to their capacity due to deteriorating ore quality and reserve exhaustion. However, it currently takes an average of 16 years to build a new mine after the discovery of the resource. As a result of the more difficult mining conditions, in addition to the increasing pressure for sustainable and socially responsible mining, the cost pressure on producers is increasing. This is also the case for smaller lithium producers in the last few years. In addition, existing lithium and copper mines in South America and Australia have an increased risk of being affected by climate and water stress. For lithium, the only bigger alternative production sites are in China, where also most the lithium is processed accounting for 60% of the global market (80% of lithium hydroxide). For cobalt, China shares 70% of the market for processing with the Democratic Republic of Congo. For rare earth elements, China dominates not only the mining market but also large parts of the process value chain and magnet production. (IEA, 2022)

Thus, on the one hand, the transformation of the energy system will free old dependencies on fossil fuels, but on the other hand, it will create new ones on the producers and processors of these mineral resources. In comparison with oil and natural gas, the number of suppliers for mineral resources is lower, and in particular, for cobalt, rare earth elements, and lithium, the three largest suppliers have a share of more than 75% of the world market. In terms of processing, China is the largest supplier of all mineral resources and dominates more than 50% of the market for cobalt, lithium, and rare earth elements. Thus, the distribution of countries with mining and processing is more concentrated than with fossil fuels. However, the dependencies shift from permanent dependency in operation to one-time dependency in investment. If, for example, the resource investments for a wind turbine have been made once, no further materials – except for maintenance – are required.

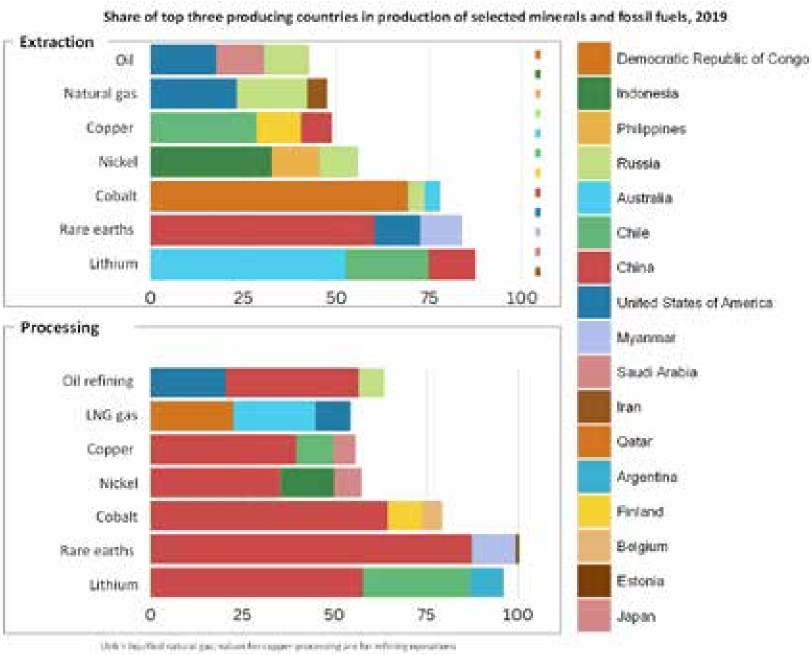

Figure 3.9 Share of top three producing countries in the production of selected minerals and fossil fuels (2019) [11].

Ramping up recycling and increasing process efficiencies is an important building block on the one hand for reducing the geopolitical dependencies and on the other to reduce the environmental impact during production as recycling produces often lower emissions and waste than the mining process itself. Secondary life or circular economy approaches can therefore be an important part of the transforming energy system. Concepts that use fewer materials, such as DC grids that require less copper (e.g. as shown in [12] and [13]), could address resource scarcity. Moreover, analogous to the economic costs in the chapter above, a deviation in the absolute level of supply security could also lead to a reduction in the scarcity of resources.

Cost and social acceptance

With ~2.5 bn tons of global carbon dioxide (CO_2) emissions in 2020, the energy sector is decidedly the largest emitter of GHG in the European Union (EU 27) with a share of ~81.1%. Despite a reduction of CO_2 emissions in the energy sector by 29.9% in 2020 compared to 1990 levels, further efforts are needed to achieve the goals of the Kyoto Protocol and the even more ambitious Paris Climate Agreement.

Therefore, the transition from fossil-based to renewable energy systems is a priority for societies committed to reducing GHG emissions. However, such fundamental transitions require substantial investment and financial efforts. These investments into a mostly renewable energy system will probably lead to decreasing energy cost in the long-run. However, in the short to medium term, the cost of the energy system is likely to increase. This may challenge the social acceptance of renewable energy transition and require regulators to consider the distributive effects of the energy transition.

Figure 3.10 compares the levelized cost of electricity (LCOE) for various renewable and conventional power plants. The LCOE represents the price that a power plant would have to realize for the electricity it generates to cover its investment and operating costs over its entire lifetime. The LCOE values are given in ranges based on varying investment cost, full load hours, and CO_2 certificate prices (EU-ETS $CO2_2$ price). For conventional power plants, the CO_2 certificate price is the major driver for variation in LCOE. If GHG emissions are not internalized, conventional power plants such as lignite, hard coal, or combined cycle gas turbine (CCGT) power plants can have cost advantages over power plants based on renewable energy sources (RES), such as photovoltaic (PV) or wind power plants. If GHG emissions are internalized, new RES-based power plants can even have lower LCOE compared to existing conventional power plants (given cost assumptions as of 2021).

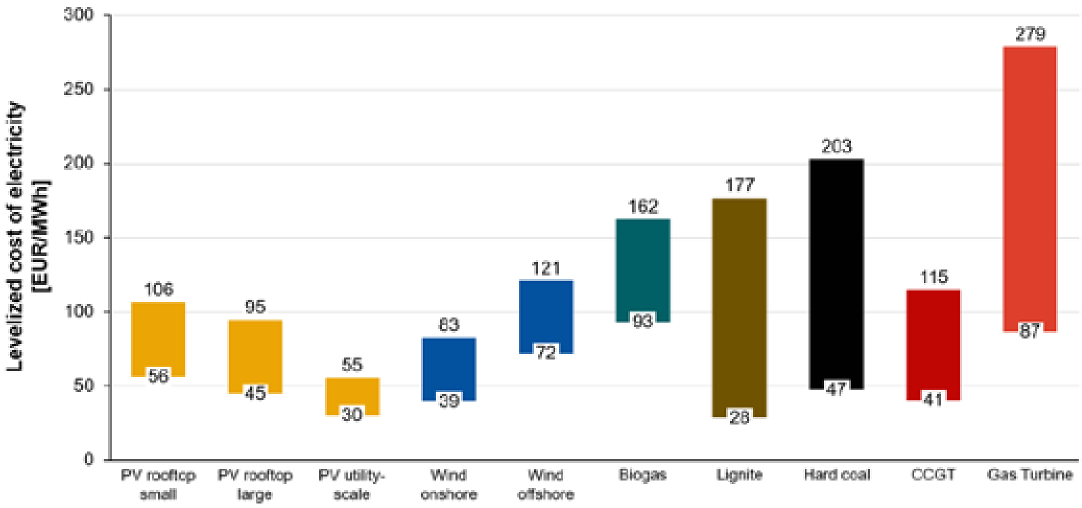

Figure 3.10 Levelized cost of electricity for various renewable and conventional power plants in Germany. Own calculation, the data and visualization are based on [14]. A range of 0 to 150 EUR/ t (CO_2 -eq.) is assumed for the CO_2 certificate price. All other assumptions refer to values from 2021.

As can be seen in Figure 3.11, residential electricity consumers witnessed a rapid increase in electricity prices in Germany from 2006 to 2022. Until recently, RES-based electricity generation has been mainly subsidized via the regulated RES support levy. The levy represents additional financing needs that cannot be covered by consuming or selling generated electricity.

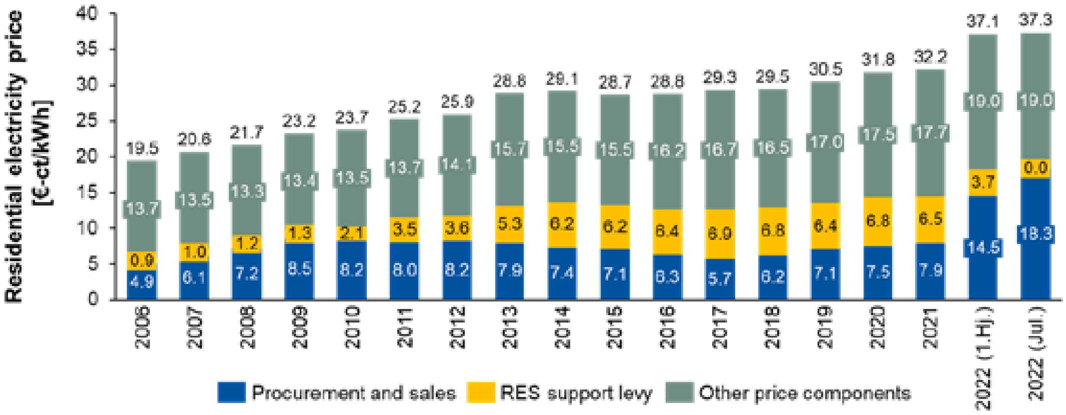

Figure 3.11 Development of electricity prices for households in Germany.

As electricity generation from RES is weather- and location-dependent, further costs occur for backup capacities, distribution capacities, and flexible system technologies such as storage to maintain security of supply. Haucap et al. estimate that between 2000 and 2025 approximately EUR 520 billion will be required for the transition in the power generation sector in Germany [10]. However, energy transition does not only affects the electricity system: the heating sector (residential and industrial demands), the transport sector, and the non-energy use of energy sources are also being transformed. Galvin argues that countries with stable and resilient currencies can afford to finance this transition. He estimates an annual cost of 5-8% of GDP per year over 15 years [9].

Resulting cost are often passed on to end consumers which can lead to higher energy expenditures. Figure 3.12 (left) shows the change in share of households' net income spent on electricity. While all consumers are directly affected by increasing energy cost, the severity of the impact differs depending on the individual income and capital situation of the households with the least wealthy households being affected the most. In addition to economic inequalities, there are other inequalities, such as large regional differences in network charges (cf., Figure 3.12 (right)).

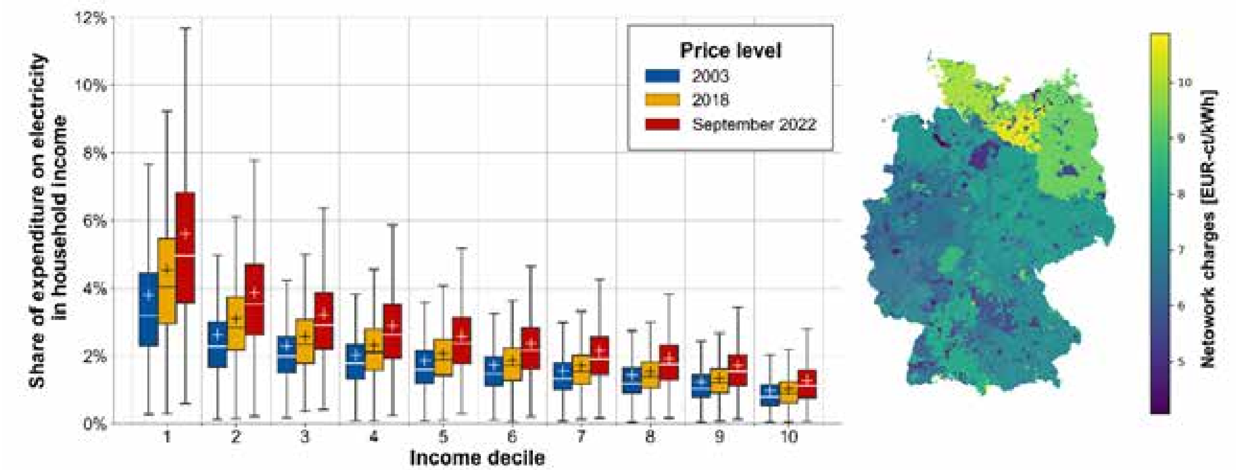

Figure 3.12 Left: Share of residential electricity expenditure in net income. Private households are grouped into income deciles according to the OECD equivalence scale. Right: Network charges for residential consumers with an annual electricity consumption of 3,500 kWh in 2018.

Economic inequalities also create investment thresholds that make it very difficult for poorer households to benefit from positive or avoid negative transition effects. For example, Winter and Schlesewsky show how the majority of feed-in-tariffs flow to higher-income households [25]. In the case of internalizing the cost of CO2 emissions into the heating and mobility sectors, low-income households are likely to be more affected as they would tend to own less efficient appliances. Higher-income households are less affected by price increases as they substitute parts of their electricity consumption, most likely with more energy-efficient appliances or through self-generation of electricity.

In consequence, allocating the cost of the energy transition can widen the equity gap in societies. This can lead to an increase in income inequality, (energy) poverty, and, accompanying them, (perceived) social injustice, which might eventually reach levels that are unacceptable for society. Perceived social injustice in the allocation of the energy transition's cost burden can impact the willingness of consumers to contribute directly or indirectly to the decarbonization of the energy system [3].

Analysis of complex energy systems

Energy systems are complex systems. The main characteristics of complex systems include (1) the existence of agents in the system, (2) networks connecting different agents and physical components, (3) dynamics in the sense of a system state changing over time, (4) self-organization in the sense of autonomous adaptation to external changes, (5) path dependence including lock-in effects, (6) emergence describing an emerging behavior of the macrostructure of the system, (7) coevolution in terms of coexistence and interdependence with other systems, and (8) learning and adaptation. Current developments in the energy system increase these drivers for complexity as illustrated in Figure 3.13.

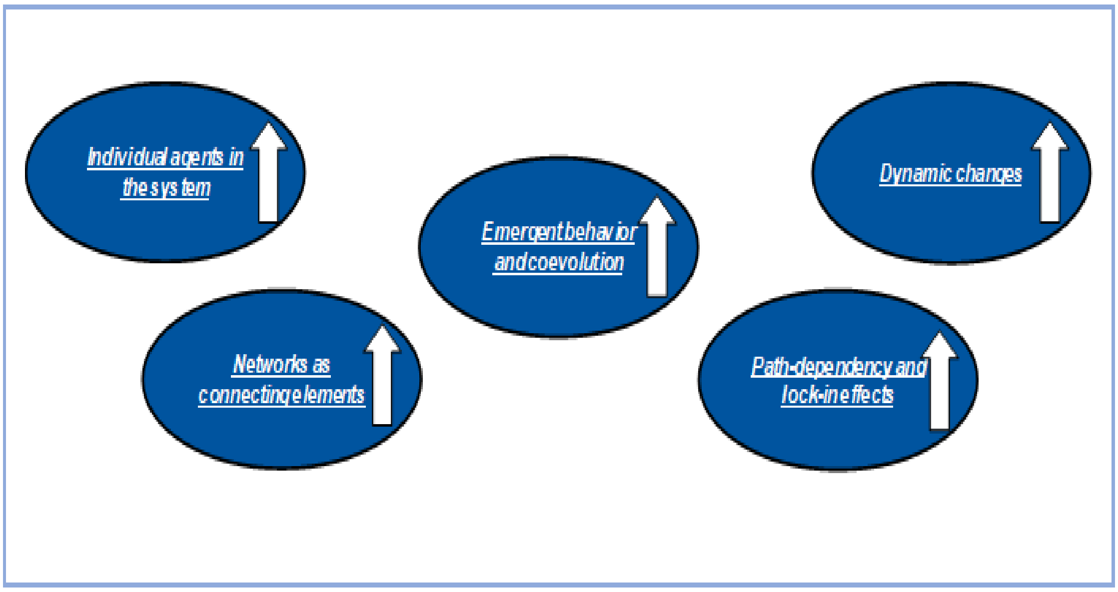

Figure 3.13 Increasing drivers of complexity in the energy system.

The representation of an increasingly complex energy system also increases challenges for energy system modeling. As depicted in Figure 3.14, the modeling process can be summarized as the abstraction from the underlying energy system to models that depict the interrelation between a set of input data and a set of output data. Hence, the complexity of modeling approaches inherently increases with the complexity of the energy system.

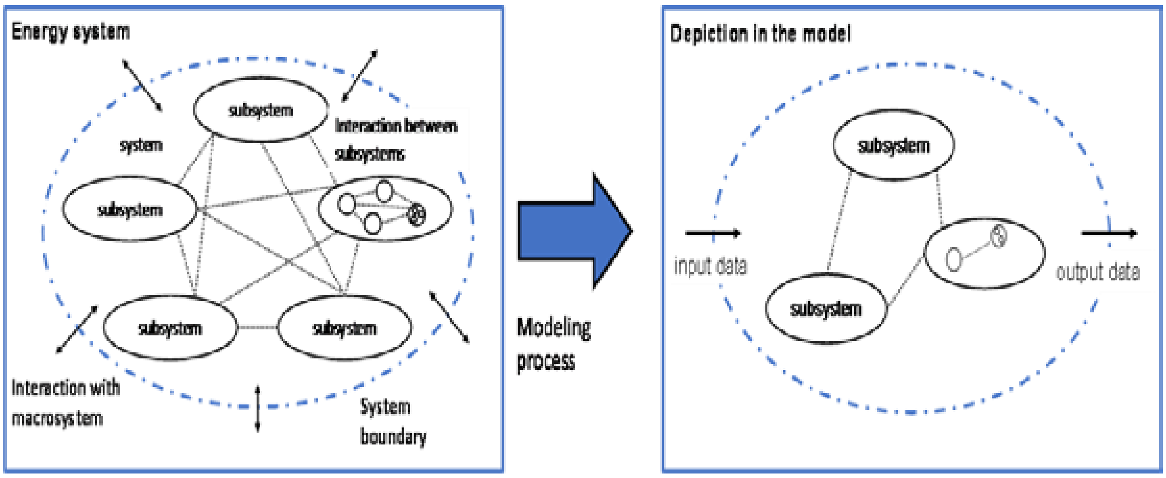

Figure 3.14 The modeling process.

When choosing the level of detail that a modeling approach should use in order to depict the energy system, both the costs of increasing the model complexity and the benefits from a more accurate depiction of the underlying system should be accounted for. As shown by Nolting [16], more complex modeling approaches are not per se superior for evaluating the security of electricity supply from an economic perspective (maximizing net benefits). Accounting for this and for the growing dynamics in system changes, our recommendation in energy system modeling is to move away from a pure focus on an ever-increasing level of detail in mapping to an appropriate consideration and communication of uncertainties.

Table 3.1 summarizes the complexity dimensions and their increase due to current developments in the energy system.

Table 3.1 Drivers for complexity in the energy system [16].

Complexity dimension	Drivers (non-exhaustive)
Existence of agents in the system	•Increase in the number of independently acting agents in the course of unbundling •Expansion of decentralized generation plants on the supply side •Creation of new types of agents on the demand side, such as prosumers
Networks as connecting elements	•Separation of social networks between different players in the energy market (unbundling) and thus increase in existing interfaces •Sector coupling as a driving force for further integration of previously independent system elements •Increasing importance of cross-border transmission networks for international load balancing (see [17]) •Increased pressure also on national grid infrastructures due to the integration of renewable electricity generation plants
Dynamic change processes	•Change in the regulatory framework and the associated change in planning processes and operational management in the power supply system •Technological change through new, renewable generation facilities as well as regulatory definition of expansion targets and phase-out paths to shape the transformation of the energy system (transformation process)
Self-organization and autonomous adaptation	•Increasing competition as a driving force of self-organization •Increased flexibility on the demand side through the expansion of thermal and electrical storage facilities
Path dependence and lock-in effects	•Prohibition of the implementation of individual technological solutions through strict unbundling •Regulatory definition of exit paths and capacity mechanisms, technology-specific support and bans •Increase in sunk-costs due to historical investments in now obsolete technologies
Emergent behavior of the macrostructure	•Distributed responsibilities in the course of unbundling lead to a change from „known unknowns" to „unknown unknowns" (see [6]) •Increasing unpredictability of future electricity generation and demand scenarios in the transition process
Coevolution with other systems	•Digitization as a parallel development •Climate change is increasing societal pressure for rapid transformation as part of the energy transition, as well as the frequency of occurrence of common mode outages due to extreme weather events
Learning and adaptation	•Adaptation of the individual players to their separate business areas created by unbundling •Increased availability of information and thus enabling adaptation of consumption to the supply of renewable energies (e.g. smart meter rollout) •Adaptation of the energy system to changes in the structure of societal preferences with regard to energy policy goals.

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Chapter 4

Energy Efficiency and Rebound Effects

Take-away Messages (Reinhard Madlener)

- There are still large untapped energy efficiency potentials, but these are not always easy and fast to tap, some involve large rebound effects, and economic analyses on the welfare-optimal levels of energy efficiency are still scare
- In energy efficiency policies and strategies, it is paramount to take exergy considerations into account as well
- After 40 years of research, energy efficiency initiatives are generally perceived as highly effective. Innovation has contributed to lowering energy technology costs and increasing energy productivity
- Energy efficiency programs in many cases have reduced energy use per unit of economic output and have been associated with net improvements in welfare, emission reductions, or both. Rebound effects at the macro level still warrant careful policy attention, as they may be nontrivial
- Complexity of energy efficiency dynamics calls for further metholological and emprical advances, multidisciplinary approaches, and granular data at the service level - for research in this field to be of greatest societal benefit

Prof. Reinhard Madlener

At least since the 1970s, the huge potential of increasing energy efficiency has been recognized. Back then, many governments realized that energy demand and economic growth were highly correlated, and that action for (relative or absolute) decoupling seemed necessary. As a consequence, many government agencies and energy efficiency promotion programs were established (and many programs and budgets were slashed again in the 1980s when oil prices turned out to be low another time).

Nowadays, energy efficiency typically features prominently in energy and climate policies and forecasts alike, often still totally ignoring rebound effects (see further below) which can significantly reduce energy-saving potentials. In light of the important role attributed to energy efficiency it seems useful to discuss some of the typical misperceptions amongst experts and laypersons alike, different disciplinary views among researchers, and policy-makers' pitfalls when they design and implement energy efficiency programs or energy efficiency as part of the solution to reach energy policy goals (energy efficiency was the only goal not reached in the European Commission's endeavor to reach the "2023" policy targets aiming at a 32% share of renewables, a 40% reduction in greenhouse gas emissions, and a 32.5% improvment in energy efficiency).

In a recent endeavor, 19 well-known international researchers in the field have come together to intensively reflect on the last 40 years of energy efficiency research [13]. In the following, a synopsis is provided of the selected parts of the review article published as an outcome of that initiative.

Engineers and physicists tend to think about the energy efficiency of systems transforming energy to provide energy services in terms of first and second law of thermodynamics efficiencies, i.e. either in terms of the ratio of useful energy output per energy input (1st law) or in terms of the quality (i.e. exergy or ability to perform physical work) of energy inputs and outputs. They are interested in improving the energy efficiency of a system relative to the theoretical maximum efficiency. Energy economists, in contrast, distinguish between engineering (technical) efficiency and economic energy efficiency. The latter controls for the levels of other production input factors and considers cost-effectiveness and profit (firm) or utility (private household) maximization and the efficiency with which inputs are used. Engineering efficiency compares the quantity of inputs, to produce given outputs (or vice versa if energy intensity is studied) in comparison to some best practice or frontier level (what economists would call productivity). Economists emphasize that enhanced energy efficiency is not necessarily in line with improved economic efficiency, as the latter considers all production input factors, their costs, and the mix of outputs generated.

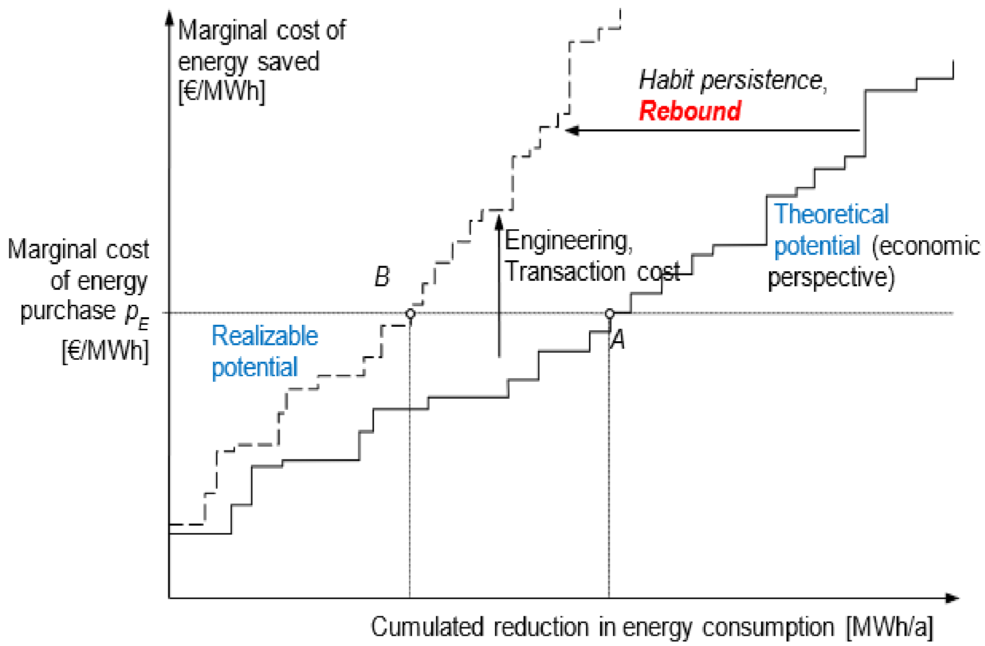

Figure 4.1 Theoretical energy efficiency potential (determined by energy price vs. marginal cost of energy saved) and detrimental factors [5], adapted.

The literature on energy efficiency has for a long time dealt with the so-called "energy paradox" or "energy efficiency gap" [8], which refers to the observation that firms and private households seemingly underinvest in cost-effective energy efficiency technologies – relative to what is privately or socially optimal. In their seminal paper, Jaffe and Stavins [7] propose two different perspectives, one being some engineering optimum (if all barriers to technology adoption are removed) and an economic optimum based on cost and considerations of market failure. Market failure is typically attributable to a lack of information, market power (abuse), or externalities (i.e. costs not reflected in the market price). Policy-making can also lead to energy efficiency gaps, e.g. if subsidies or taxes create distortions that are detrimental to social welfare maximization. Along these lines, estimates of the size of the energy efficiency gap have proved to be very useful both for research and development (R&D) and policy guidance. Note that definitions and metrics for energy efficiency may be more or less clear, and energy efficiency gains more or less uncertain. At the device or appliance level, there are plenty of studies clarifying what efficiency means and how to best measure it, whereas concepts and metrics for energy efficiency measurement and assessments of actual versus predicted energy efficiency gains become much more challenging and complex as system boundaries and system complexity increase [6].

Inappropriately used definitions or measures can easily lead to erroneous interpretations of outcomes. At larger system levels like homes, factories or city quarters/regions, uncertainty is large and, for complex large systems such as cities, regions, or nations, appropriate metrics to understand the level of energy efficiency are still lacking.

Market failures have been subdivided into such occurring on energy markets (e.g. environmental externalities, average instead of marginal cost pricing), information market failure (e.g. principal-agent problems such as the landlord-tenant dilemma in housing), capital market failure (e.g., credit rationing), and innovation market failures (e.g. R&D spillovers, preventing innovators to reap the full benefit of their effort). Market failures also include misplaced incentives, bounded rationality, transaction costs, and lack of access to financing (which likely affects mostly low-income households). In addition to the different potential market failures just mentioned above, non-market failures have also been discussed in the literature, which include consumer heterogeneity (one size does *not* fit all), uncertainty related to product performance and future prices, unobserved costs and benefits, as well as rebound effects. Consumer heterogeneity also involves potentially very different discount rates, whereas product performance and unobserved costs and benefits includes the often not very well-understood longer-term persistence of energy and energy cost savings (which might be attributable to extrinsic or intrinsic behavioral change including changes in lifestyle and social norms, technical performance deterioration including wear and tear, or external shocks to society).

In recent years, more attention has also been put on behavioral factors that help to explain the energy efficiency gap. Here, the use of behavioral economics and environmental psychology (as it is done at the author's institute FCN) helps to analyze and better understand anomalies or apparent irrationalities due to the fact that we often act more like *homo psychologicus* than the *homo rationalis* or *homo oeconomicus*. Still, much more empirical research is necessary to find out whether unexplained anomalies do cause systematic deviations between decision utility and actually experienced utility, and whether these help to understand why energy efficiency opportunities are often ignored. In light of motivational, behavioral, but also market and policy heterogeneity, policy interventions and behavioral analysis will always have to be tackled in a context-specific manner. Overall, well-guided policy intervention aimed at improving energy efficiency is not as straightforward as many think, or hope for, if social welfare optimization is the goal (which it should be especially when taxpayers' money is being spent to improve an existing situation).

Rebound effects partly offset the energy-saving effects of gains in energy efficiency. They are, generally speaking, not negligible and a complex phenomenon (and thus a challenge to measure and understand in detail) [10]. A common typology is *direct rebound* (a price effect – goods and services can be consumed because they have become cheaper thanks to efficiency gains), *indirect rebound* (an income effect – one can consume more goods and services of any kind if one good or service has become cheaper thanks to efficiency gains), and *economy-wide rebound* (relative prices change throughout the economy, leading to demand and supply reactions and a new equilibrium; in some sectors economic growth will lead to additional energy demand, in others there could be savings achieved, sometimes referred to as "super-efficiency"). Recent research investigating the economy-wide rebound for the post-WW II U.S. and Europe has found evidence of rebound in the order of 78–101% [2] or even more [12], using a great variety of models, approaches and system boundaries [4]. A useful recent overview of the evidence and implications of economy-wide rebound for policy-makers in business and public administration is given in [3].

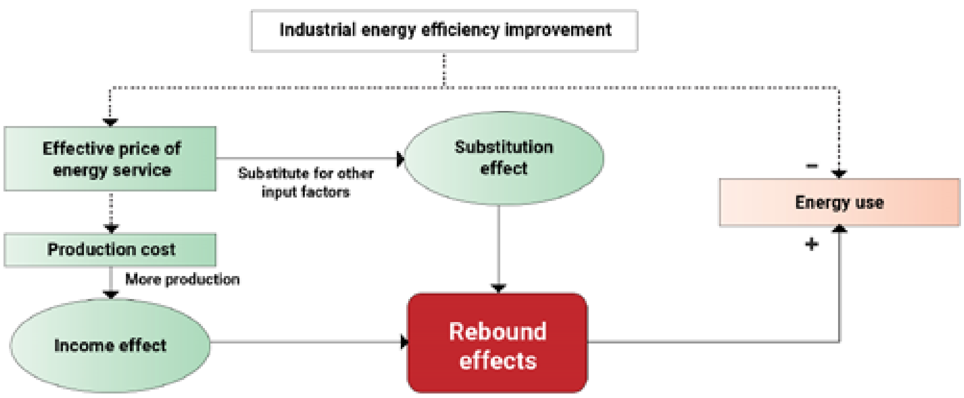

Figure 4.2 The mechanism behind rebound effects in industry [9], adapted.

Aside from economic explanations, psychological ones have also been used. For instance, “moral licensing” or “greenwashing” effects (if someone consumes more goods and services because he/she has acted “green” in one area of life, e.g. switching to LED lighting is used as a moral license to drive or fly more). Recent rebound research interest has expanded further to prosumer households [8], [1] and smart homes [11]. The latter, using an agent-based model, life-cycle assessment and an extended input-output model of the economy, find modest indirect rebound (of about 5%) but also that rebound effects are much higher when economically optimized load-shifting is performed, and that rebound effects are higher in winter and on weekdays. Hence the sustainability contribution of smart homes depends crucially on how these are managed.

Even in the context of renewable energy use rebound effects are likely (referred to as “green rebound” or “solar rebound”) if owners of renewable energy systems take that as a license to consume more electricity because it is perceived as green, and maybe additionally as cost-free due to zero operating costs [1].

Finally, the literature on both industrial energy rebound effects and economic gains is still scarce [15]. Using a state-of-the-art computable general equilibrium model, dynamic modeling of energy efficiency gains is possible. This author finds, for instance, that both industrial energy rebound effects and economic gains from energy efficiency increases are heterogeneous, and sizable. Rebound is found to be particularly large in energy-intensive manufacturing sectors, but negative ("super-efficiency") in the fossil fuel supply sectors (oil and natural gas). The fine-grained analysis enabled by sectoral decomposition enables the introduction of more detailed and targeted (i.e. sectoral or subsectoral) energy policy measures than for the case of much broader studies, and complements policies aimed at the residential or the automobile sector only (which for many years have been the main target of rebound research).

An interdisciplinary approach to tackle the energy efficiency gap is warranted. For instance, there is little benefit of using price mechanisms to tackle an unexpectedly high heat energy demand that is actually the result of a poorly constructed house, or if there is a poor match between the recommended, technology-specific consumer behavior and the heating technology installed (e.g. airing by opening the windows when a ventilation system is actually in place). A great variety of economic and socio-technical models and frameworks are available for being used, and that can help to explain the impact of broader technical and cultural factors alongside more context- and location-specific aspects. At the micro level, for instance, a better of energy consumer choice and behavior can be reaped by using advanced metering and sensing infrastructure, and then combining engineering insights with such gained from using economic / utility theory, theory of choice, and behavioral economist’s models.

Last but not least, it is well known that technically and economically superior new technologies are often not immediately adopted but that the market diffusion takes time and typically follows a sigmoid or S-shaped diffusion curve. Such diffusion phenomena are driven by complex mechanisms related to barriers and drivers (in the economics domain costs and benefits) and need thorough analysis to be well understood. This applies all the more when more complex energy systems are involved.

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Chapter 5 Mobility and Storage

Take-away Messages (Dirk Uwe Sauer, Florian Ringbeck, Christopher Hecht, Sebastian Zurmühlen)

- The mobility sector needs a massive transition (less cars, more cycling and public transport etc.) to achieve climate policy targets; even with 15 million e-cars on German roads, 2/3 would still be conventional ones in 2030
- Hydrogen and fuel cell cars will only play a minor role in 2030; e-fuels should not be used for cars but other areas with much higher CO_2 savings potential per unit of electrical energy used
- For heavy goods transport, range and fuel costs play a central role. Fuel cell and battery drives will play a role, the latter one have a real potential, provided very efficient charging hubs along motorways are established (policy action!)
- For both long-haul aircraft and large maritime vessels, green fuels are key
- For coastal and inland waterways shipping (incl. ferries), battery-electric vessels are already an option; again, an efficient charging infrastructure is required
- A sufficient (public and private) e-vehicle charging infrastructure is para mount; cost-reflective pricing will reduce congestion problems; subsidization will be needed at least temporarily (esp. in rural/remote regions, and for fast charging)
- 'Miracle battery technologies' should not be expected in the foreseeable future

Prof. Dirk Uwe Sauer

The mobility sector contributes around 20% of CO_2 emissions in Germany and around 25% worldwide. According to current legislation, the mobility sector in Germany is supposed to save about 42% of emissions from 2020 to 2030. If there is not either a massive change in mobility demand in the sense of less mobility or a shift to cycling and public transport, at least in urban transport, the emissions reduction target will not be achieved. Even if more than 80% of newly sold passenger cars are electric by 2030 and 15 million electric vehicles are on the road by then, more than two thirds of passenger cars will still have a conventional drive.

Two-wheelers, passenger cars, light commercial vehicles and city buses with new drive technology will have almost completely battery-electric drives in 2030. Hydrogen and fuel cells will play only a marginal role in road transport. There will be no good reasons to change this after 2030. "eFuels" to replace petrol or diesel in vehicles with combustion engines should not be used in the mass market. The energy required for this and the green hydrogen produced are needed in other areas with a much higher CO_2 savings potential per unit of electrical energy used.

In the area of heavy transport, technical developments and infrastructure considerations continue. A nationwide and Europe-wide overhead line system for long-haul trucks is not considered to have much chance of success. Battery-electric and fuel cell-electric drives are being pushed forward by various manufacturers and manufacturer groups. Here, considerations of range on the one hand and fuel costs on the other play a central role. It is also important that the truck segment, due to the smaller unit numbers, looks much more at global solutions that can then be rolled out as uniformly as possible. At present, however, there is a growing realization among many vehicle manufacturers that battery-powered long-haul trucks are the faster and easier solution. As an example, Volvo, a declared proponent of fuel cell trucks, now wants to offer battery-electric trucks as a transitional solution until fuel cell vehicles are ready for the market. The central prerequisite for this is very efficient charging hubs along the motorways. Charging power in the order of one MW is required per truck to recharge the vehicles for a trip of 4.5 hours of highway driving within less than 45 min. Central political decisions will be needed to enable and secure these investments.

Liquid hydrocarbons, liquid or gaseous methane or e.g. ammonia produced from green hydrogen, together referred to as "eFuels", represent the options for climate-neutral operation for long-haul aircraft or large ships. Since the CO_2 savings efficiency of using eFuels is significantly lower than for many other direct uses of electricity, defossilization of these sectors should be at the end of the conversion chain. The first battery-electric solutions with the corresponding charging infrastructure are currently being introduced to the market for small aircraft or air taxis as well as for coastal ferry traffic or inland navigation.

The charging infrastructure for cars can be divided into three groups: The home charging stations ("wallbox"), which have been or will be installed by all electric vehicle owners who have their own house, garage or parking space, will handle the bulk of vehicle charging in terms of volume. For the users, this is easy, the power is already more than sufficient even at 7 or 11 kW and the price for the electricity is the same as the household electricity price. For those who do not have a home charging infrastructure, the public charging stations with 22 to 50 kW will be of great importance. Here, however, the business models will remain difficult in the foreseeable future because the quantities of electricity sold will remain relatively small. However, charging during weekly shopping can become an important option. In this case, the shops benefit from customer loyalty and the electric vehicle drivers from an easy recharging option. The third group of charging stations are the high or ultra-high power charging points with charging capacities between 120 and 350 kW along the main travel routes. For infrequent journeys over long distances, these allow energy for 100 km range to be recharged in 3 to 10 min. High prices per kWh must be expected here. Overall, the charging infrastructure is part of the public infrastructure, just like the roads themselves, and it will be necessary to support non-economically operable locations on the part of the state as well.

Lithium-ion batteries are and will be the dominant battery technology for at least the next decade. This is also because within the class of lithium-ion batteries there is a large variety of material variations, which on the one hand enable evasive movements in the case of critical raw material availability such as cobalt or nickel, and on the other hand enable a separate cell technology for almost every requirement profile. Thus, there is already an ever-increasing differentiation of performance parameters, e.g. for hybrid vehicles, for passenger cars with compact and mid-range segments on the one hand and in the luxury segment on the other, or for trucks. Distinguishing features are charging speeds, energy densities or cycle lifetimes. "Miracle battery technologies" that could play the role of "game changers" are not to be expected. The central goal is primarily to reduce costs. At the same time, the structures for a circular economy must be established. Currently, the framework conditions for this are being coordinated and decided at the EU level.

CO_2 emissions and energy consumption of the mobility sector today

The greenhouse gas emissions of the mobility sector in Germany in 2020 amounted to about 146 million tons of CO_2[1]. However, due to the Corona pandemic, 2020 was also a year with significantly reduced transport performance. While specific emissions per transport have decreased from 1990 to 2019, overall CO_2 emissions have not decreased over this period because all efficiency progress has essentially been neutralised by increasing transport performance. This highlights the extraordinary challenge in the transport sector.

1 https://www.bundesregierung.de/breg-de/themen/klimaschutz/klimaschonender-verkehr-1794672

The German government's current goal is to reduce CO_2 emissions in the transport sector to 85 million tonnes by 2030. While the transport sector in Germany accounts for about 20% of CO2 emissions, the transport sector worldwide contributes about 25% to total CO_2 emissions. Road transport accounts for almost 74% of these, air transport for about 12%, shipping for almost 11% and other transport services for a good 3%[2], which includes rail transport in particular.

While the share of shipping and air transportation can be determined very well on a global basis, this is more difficult for the individual nation states due to the cross-border traffic in these areas and because the allocation of emissions to individual states are disputed. Of the total road transport emissions in Europe in 2019, cars and motorbikes accounted for about 62%, heavy trucks and buses for about 27% and light commercial vehicles for about 11%[3]. This clearly shows that in order to achieve the climate targets, the focus in the transport sector is primarily on road transport. Here again, the passenger car sector dominates in Europe with a good three fifths of emissions, but alternatives must be developed and introduced just as quickly for freight transport. In 2020, almost 92% of the primary energy demand in the transport sector in Germany was covered by mineral oil products, a good 6% by biofuels and just under 2% by electricity. Gases hardly play a role at 0.3%[4]. In Germany, the energy consumption of the transport sector in 2020 was 637 billion kWh and thus accounted for around 27.5% of final energy consumption.

Changes in mobility use

Discussions about the future of mobility go much further than simply replacing drive technologies or fuels. Possible approaches to changing traffic volumes in local transport include a shift in mobility from individually used cars to public transport, bicycles and scooters or even walking. In long-distance transport, shifting both freight and passenger transport to rail would lead to significant emission reductions. A change in the settlement structure could also bring residential and work locations closer together and reduce the corresponding transport performance. In industry, transportation of semi-finished products to production sites spread over different countries and continents could be reduced. Long-distance tourist trips or weekend excursions by plane could be made more expensive and thus reduced by increasing taxes on aviation fuel or CO_2 taxes. The demand for mobility will also change due to demographic changes in the population (fewer and older people). Another change, but towards higher traffic volumes, could occur through the introduction of autonomous driving vehicles of Level 5. This will make individual mobility possible without driving oneself. Driving no longer means wasting time. Longer distances between home and work are no longer a problem. Mobility also becomes much easier for older people. Even long distance journeys in one's own car can be more attractive for some people than traveling by train. In the transport sector, autonomously driving trucks can manage without drivers, which on the one hand eliminates a significant cost factor and on the other hand removes the limitation of transport performance that can already be seen today due to the lack of drivers. More favorable transport costs without restrictions due to a lack of drivers can lead to an increase in transport performance. In sum, autonomous driving with Level 5 has the potential to increase transport performance.

All in all, there are a multitude of approaches or developments to reduce transport performance or to shift it to lower-emission modes of transport, or perhaps even to be able to increase it. A large number of initiatives will be launched for this purpose. Here, however, we want to concentrate on the consideration of alternative drive and fuel concepts.

Energy sources and energy demand in the transport sector with CO_2- free drive technologies

In order to achieve climate neutrality, new drive energies are necessary. Various concepts and energy carriers are available for this purpose, or at least the technologies are known how these can be made available. Currently, the vast majority of road transport, shipping and aviation is powered by gasoline (typically hydrocarbon molecules with 5 to 10 carbon atoms), diesel (typically 10 to 22 carbon atoms per molecule), paraffin (typically 9 to 17 carbon atoms per molecule) or heavy fuel oil (typically 20 to 70 carbon atoms per molecule). In order to realize CO_2-free mobility, there are basically four different energy sources available:

- Electricity from renewable electricity generators and nuclear power plants for direct use via batteries or overhead lines or conductor rails.
- Hydrogen produced from CO_2-free electricity or other direct processes using solar irradiation and brought into vehicles either directly in gaseous form (typically 350 or 700 bar), liquid form (produced by the Joule-Thomson process at -253°C or 20 K) or in bound form, e.g. as ammonia (produced with nitrogen extracted from the air by the Haber-Bosch process) or LOHC ("liquid organic hydrogen carrier").
- eFuels ("synthetic fuels") from CO_2-free hydrogen produced with the addition of CO2 ("Fischer-Tropsch process"), which either comes from concentrated CO_2 sources, e.g. from industrial processes or the combustion of biomass, or is obtained by filtering from the air ("direct air capture").

2 https://de.statista.com/statistik/daten/studie/317683/umfrage/verkehrsttraeger-anteil-co2-emissionen-fossile-brennstoffe/

3 https://www.destatis.de/Europa/DE/Thema/Umwelt-Energie/CO2_Strassenverkehr.html

4 https://www.umweltbundesamt.de/daten/energie/energieverbrauch-nach-energietraegern-sektoren#entwicklung-des-endenergieverbrauchs-nach-sektoren-und-energie-tragern

- Biomass for the production of liquid biofuels, typically by fermenting sugar beet, grain or sugar cane into alcohols ("bioethanol") or from vegetable oils (e.g. rapeseed or palm oil) into "biodiesel", biogas from the fermentation of energy crops such as corn, manure or organic residues, or synthetic biofuels via "biomass-to-liquid (BtL) processes", in which the biomass of complete plants or plant residues is thermo-chemically converted.

Apart from biofuels, whose sustainable potential is limited, the other energy sources are each based on CO_2-free electricity.

Energy demand for battery and fuel cell vehicles

How much electricity is needed for a certain transport performance depends on the energy source used in the vehicles. The following simple calculation examples are intended to show, by using the example of passenger cars, how much energy is needed when using CO_2-free energy sources in relation to current consumption. To do this, we make the following assumptions:

- The average fuel consumption of passenger cars in Germany in 2020 was 7.7 liters for gasoline vehicles and 7.0 liters for diesel vehicles[5] per 100 km in each case. This corresponds to an energy consumption (calorific value) of about 65.5 kWh/100 km for gasoline vehicles and 68.6 kWh/100 km for diesel vehicles. The higher consumption of diesel vehicles despite the higher efficiency of diesel engines is due to the higher average weight of vehicles with diesel engines. The extraction, processing and provision of the fuel consumes additional energy. Here, up to 6 kWh of energy input per liter of gasoline is mentioned[6], which, at 7.7 liters/100 km consumption, would amount to a further consumption of 46.2 kWh/100 km. These figures are disputed, but it is clear that the total energy demand is considerable. In the further consideration of electricity as the basis of CO_2-free propulsion fuels, we neglect the provision energy for fossil fuels in the comparison and, in turn, the energy expenditures for the production of wind power and photovoltaic systems. A comprehensive consideration must take all aspects into account; for a rough estimate, it is particularly important to be aware of the simplifications used.
- The electricity demand of electric vehicles has a similar range as that of vehicles with combustion engines. The reasons for this are different efficiencies of the drive trains, weight and wind resistance of the vehicles. In January 2022, the ADAC determined the real electricity consumption, including losses during charging, of more than 40 electric vehicles, some of which include different equipment variants of the same vehicle types[7]. As with the fuel consumption figures above, these are not the manufacturers' figures for the standard cycle, but rather consumption figures for real-world operation. In some cases these correspond very well to the manufacturer‘s specifications, but in others the real data exceed the manufacturer's specifications by 50% or more. According to the ADAC, based on data from the Federal Motor Transport Authority, the ten best-selling electric vehicles were, in descending order[8]: Tesla Model 3, VW e-Up!, VW ID.3, Renault Zoe, Smart EQ Fortwo, Hyundai Kona Elektro, Skoda Enyaq, VW ID.4, Fiat 500 e and BMW i3. If we take these ten best-selling cars and the electricity consumption from the above-mentioned study by the ADAC for these vehicles and determine the average electricity consumption weighted with the sales figures, this results in a real electricity consumption of about 19.2 kWh/100 km including charging losses. It follows that only about 28-29% of today's energy consumption needs to be provided as electricity. If the 637 TWh of final energy consumption from 2020 were consumed in passenger cars alone and these were converted to battery electric vehicles, the electricity demand to be covered would accordingly be around 182 TWh. De facto, the electricity demand will be somewhat higher because the energy use of the fuel in trucks is somewhat better than in passenger cars. Accordingly, as a rule of thumb, only about one third of today's final energy consumption in the transport sector needs to be replaced by energy as electricity. In public debates, the current final energy demand is often mentioned and then it is suggested that this must be replaced by electricity generation. 637 TWh would indeed be more than today's gross electricity production in Germany. It is true that the entire transport sector would need a good 200 TWh of electricity today if it were to switch to electric propulsion, and much less in the future due to the considerable efficiency gains expected from electric vehicles. The electricity demand for passenger cars can also be estimated differently:

    - Passenger car population in Germany on 01.01.2021: 48.25 million[9]
    - Average mileage per car: 13,700 km/year[10]
    - Of the passenger cars with combustion engines, 67.6% had a petrol engine and 32.4% a diesel engine in 2020[11]
    - This results in a final energy demand of 48.25 million vehicles x 13,700 km/year x (65.5 kWh/100 km x 67.6% + 68.6 kWh/100 km x 32.4%) = 439.6 TWh if all vehicles have an internal combustion engine (as indicated above, smaller parts of this are provided by biofuels).
    - This results in an electricity demand of 48.25 million. vehicles x 13,700 km/year x 19.2 kWh/100 km = 126.9 TWh

5 https://de.statista.com/statistik/daten/studie/484054/umfrage/durchschnittsverbrauch-pkw-in-privaten-haushalten-in-deutschland/

6 https://www.carmart.ch/elektro/unmengen-an-energie-fuer-die-diesel-und-benzinproduktion/

7 https://www.adac.de/rund-ums-fahrzeug/tests/elektromobilitaet/stromverbrauch-elektroautos-adac-test/

8 https://infogram.com/b2716788-f22f-43e2-89c1-f9e07b49bdaf

9 https://de.statista.com/statistik/daten/studie/12131/umfrage/pkw-bestand-in-deutschland/

10 https://de.statista.com/statistik/daten/studie/246069/umfrage/laufleistung-privater-pkw-in-deutschland/

11 https://www.umweltbundesamt.de/daten/verkehr/verkehrsinfrastruktur-fahrzeugbestand#pkw-bestande-nach-kraftstoffart

- The hydrogen consumption of a Toyota Mirai is given in one source as 1.11 kg/100 km[12]. Assuming an efficiency of the fuel cell system of 55% and an energy content of 33.3 kWh/kg, this results in an electrical energy consumption for driving of 20.3 kWh/100 km. For a vehicle of this size, this is comparable to the consumption of corresponding battery-electric vehicles, and accordingly the assumptions seem plausible. If all vehicles of all classes were equipped with fuel cell propulsion, the consumption would be somewhat lower, as the Toyota Mirai is a rather large car. The efficiency of the electrolysis is estimated here at 75% and the losses in the compression of the hydrogen at 10% (efficiency of the compression of 90%). This results in an electricity demand of 1.11 kg/100 km x 33.3 kWh/kg / 90% / 75% = 54.8 kWh/100 km for the example vehicle. De facto, the practical efficiency of electrolysis will be somewhat lower at present, but 75% is certainly a realistically achievable value. If we compare the electricity required to operate the Toyota Mirai with, for example, the Tesla Model 3 (19.5 kWh/100 km) and take into account grid losses of 5.7% on the way from the electricity generators to the charging station for the electric vehicle[13], the electricity requirement for the hydrogen drive is 2.65 times higher.

Some aspects on hydrogen for the mobility sector

The advantage of hydrogen is that it can be produced anywhere in the world and can be stored. If there is no pipeline between the production site and the point of consumption, e.g. in Germany, further losses must be taken into account for the transport of the hydrogen.

- The storage capacity of hydrogen is repeatedly put forward in favor of hydrogen vehicles and it is argued that the electricity for electric vehicles must be provided from storage facilities. These storage facilities ("long-term or seasonal storage") will be hydrogen or methane gas storage facilities. In order to achieve 80% electricity generation from renewable energies in Germany in 2030, according to the plans of the German government, about 200 GW of photovoltaics, 30 GW of offshore and 100 GW of onshore wind power plants are necessary, in total more than 300 GW of installed electricity generators[14]. This means that for a large part of the year there is sufficient power available to directly charge the battery-electric vehicles. In addition, due to the size of the batteries (on average at least 60 kWh according to current developments) and the expected average daily consumption (at 37.5 km average daily mileage and 19.2 kWh/100 km consumption, this results in 7.2 kWh/day and vehicle), a time shift of the charging process within 24 to 48 hours can be considered problem-free[15]. This means that in the worst case, a quarter of the electricity for charging the electric vehicles must be provided from storage. For one kilowatt-hour of electricity from a hydrogen storage unit, 1 kWh / (75% electrolyser efficiency x 90% storage efficiency x 40% reconversion by a gas turbine) = 3.7 kWh of electricity must be used. This means that the primary electricity demand would increase from 19.2 kWh/100 km to 32.2 kWh/100 km. This in turn means that the electricity demand for the pure hydrogen car would "only" be 1.7 times higher. But these are worst-case assumptions. With 100% renewable energies and an overall high electricity demand, it can be assumed that storage facilities will have to be used at most 15% of the time and that the efficiency of the reconversion can be achieved with fuel cells or combined cycle plants and an assumed system efficiency of 55%. This results in a factor between fuel cell vehicles and battery-electric vehicles of just under 2.3. The hydrogen for the long-term storage can also be imported or, in times of surplus power, come from wind power and photovoltaic plants in Germany or Europe. It is therefore clear that the primary electricity demand for the operation of fuel cell electric vehicles is, roughly speaking, two-times higher compared with battery electric vehicles.

The argument put forward for the use of hydrogen in passenger cars is that PV systems in sunny locations generate at least a factor of two more electricity and thus compensate for the lower efficiency in the overall chain of fuel cell vehicles in terms of the installed capacity of renewable electricity generation capacity. At a first glance, this is correct, but in an overall consideration from the perspective of climate protection and economic efficiency, two further aspects must be taken into account.

1. Transport: The transport of pure hydrogen from the sunny regions outside of Europe will largely have to take place in liquefied form by ship. This currently requires an additional electrical energy demand of 0.3 to 0.4 kWh per kWhH_2 of hydrogen (see e.g. https://www.oeko.de/fileadmin/oekodoc/Wasserstoff-und-wasserstoffbasierte-Brennstoffe.pdf or https://energiesysteme-zukunft.de/publikationen/analyse/transportoptionen-wasserstoff-2030). Optimization possibilities down to 0.22 kWh per kWhH_2 are seen. In addition, there are losses during transport of 0.3 to 0.5%/day, because no thermal insulation of an insulated vessel is perfect. With a travel time from sunny regions of at least 10 days, there is at least another 25% of electrical energy demand per kWh of hydrogen. In the short term, we would have to calculate with 35%. In addition to the losses, however, it must also be taken into account that there are currently neither ships in a commercial size beyond demonstration ships nor corresponding loading terminals. So it will be at least a few years before pure hydrogen can be imported in large quantities. Therefore, at the moment, transport as ammonia is preferred for the start of hydrogen imports. There is a high direct demand for ammonia, and nitrogen for its production can be taken from the air much more easily (approx. 78% N_2 share in the air) than CO_2 (approx. 0.04% share in the air), so that e.g. eFuels or methanol can be used as transport vectors. The recovery of pure hydrogen from ammonia also involves considerable thermal energy input. Therefore, it seems more sensible for the coming years to use ammonia where it can be used directly. This would be possible, for example, in the chemical industry, in the production of fertilisers

12 https://motor.at/tests/toyota-mirai-das-wasserstoff-auto-im-test/401470459

13 Generation. Balance - Monthly report on electricity supply. In: Balance. Federal Statistical Office, 2019, retrieved 10 July 2019 from https://de.wikipedia.org/wiki/%C3%9Cbertragungsverlust#cite_note-1

14 https://www.germanwatch.org/de/21247

15 These considerations are always about the fleet means. Of course, it must and will always be possible to charge vehicle that needs to be recharged for the next journey.

or in the future, for example, in ship propulsion systems.

2. The primary reason for the energy transition and the introduction of a hydrogen economy is climate change. Accordingly, the global focus must be on the reduction of greenhouse gas emissions, especially CO_2. Therefore, hydrogen and its derivatives should not be produced anywhere in the world as long as power plants in these places are still operated locally with fossil fuels (coal, natural gas, oil derivatives). The use of electricity from renewable energy plants makes a much greater contribution to the avoidance of greenhouse gases compared to the use of electricity from fossil energy sources than if the electricity is first converted into materialized energy carriers. In the coming years, electricity from renewable energy sources should be consistently used where it can have the greatest effect on reducing greenhouse gases or dependence on energy imports from politically critical regions. In addition, electricity and hydrogen or its derivatives must also be used in applications that do not yet make a maximum contribution to the reduction of greenhouse gas emissions at the moment, but where an industrial conversion that often takes decades is necessary to get on the path to zero emissions. This applies, for example, to electromobility, but also to the use of hydrogen, e.g. in the steel industry or the production of new precursors for organic chemistry.

Vehicle efficiency

However, reducing the energy consumption of vehicles will also be very important. The perception of insufficient range or running time of a battery-powered device is always the result of battery size on the one hand and energy consumption on the other. More range can therefore be achieved through a larger battery or lower specific energy consumption. Battery size now reaches 100 to 120 kWh in luxury cars. This means a high material and energy input and also corresponding costs and additional weight for the vehicle, and it should not be the goal to keep expanding the battery size.

However, there is still considerable potential on the energy efficiency side of the vehicles. In April 2022, Mercedes Benz showed which potentials can still be raised here. With a prototype of the Vision EQXX, an average consumption of 8.7 kWh/100km could be achieved on a journey of about 1000 km from Munich to the Cote d'Azur via the Alps, according to the company[16]. Concept vehicles rarely come onto the market one by one, but it shows what potential can still be raised through good engineering. The competition between vehicle manufacturers for the greatest range is no longer determined solely by ever larger batteries. In addition to lightweight construction, low air resistance plays a particularly important role. In this context, the elimination of a radiator grille in particular plays a central role, which becomes possible due to the low losses in the battery, power electronics and electric motor.

Another element to increase satisfaction with the range of electric vehicles is fast-charging technology. With a charging power of 350 kW and an energy consumption of 10 kWh/100 km, the energy for a 100 km range can be recharged in around 100 seconds or energy for around 400 km in seven minutes. This should be sufficient for all practical vehicle applications.

Various fields of mobility

There is a multitude of mobile applications and when the question of the appropriate drive concept or fuel is discussed, it is important to look at the different areas in a differentiated way. It then also quickly becomes clear that there will not be one solution to the drive problem of the future. In the following, different mobility areas are analyzed and the various drive solutions are discussed under technical aspects, the question of alternatives and specific requirements resulting from the application. There is no question that there are exceptions and boundary conditions in all areas that can lead to solutions other than those discussed here.

Two-wheelers

Electric bicycles are now an important source of revenue for bicycle dealers in Germany. In 2020, around 1.2 million electric bikes were sold in Germany, bringing the total to 7.1 million electric bikes. Around 5.1 million households had at least one electric bike[17]. In the motorbike sector, the share of electric drives in Germany is still quite limited. In the meantime, however, all major motorbike manufacturers are developing battery-electric variants and an expansion of market shares is to be expected in the coming years[18]. In China, electric scooters dominate more, which in turn do not play such a big role in Germany. In China, the use of scooters with combustion engines was completely banned in city centers in 2015 to improve air quality. Currently, around 36 million new scooters come onto the market in China every year, of which around 80% have an electric drive. Chinese manufacturers also dominate the export market for electric scooters[19].

16 https://www.manager-magazin.de/unternehmen/autoindustrie/elektroauto-mit-rekordreichweite-mercedes-prototyp-schafft-1000-kilometer-mit-einer-ladung-strom-a-8a15f904-1d12-45a4-b5ef-3455a8b2deda

17 https://www.destatis.de/DE/Presse/Pressemitteilungen/Zahl-der-Woche/2021/PD21_38_p002.html

18 https://www.motorradonline.de/ratgeber/report-zweirad-elektromobilitaet-bestandsaufnahme-ausblick/

19 https://www.energie-klimaschutz.de/elektro-roller-china/

The two-wheeler market in particular is characterized by a very wide range in the quality of the drive systems and batteries used. Cheap products pose a much greater risk here and should be treated with caution. In the rarest of cases, people are seriously injured by the batteries while riding. But especially if charging takes place inside houses, battery fires - like all fires - can result in high damage[20]. However, an absolute assessment of the additional safety risk is difficult here as well. In Germany, in the past years there have been always about 175,000 to 200,000 fires per year[21]. Defective electrics in domestic installations or electrical appliances are the most frequent cause of fires. In this respect, the battery and charger are simply additional electrical devices in a household and it will have to be observed in the coming years whether battery systems pose a higher risk than other electrical household devices.

Passenger cars

The drive concepts for passenger cars have already been discussed in detail above. The further development of battery technology, the increase in vehicle efficiency and the expansion of the charging infrastructure will make battery electric vehicles a suitable, efficient and affordable technology for virtually all everyday requirements of passenger cars by the end of the decade. Accordingly, it is not foreseeable today or cannot be logically justified why hydrogen and fuel cell drives or combustion engines with eFuels should conquer parts of the passenger car market after 2030. It is important to realize, for example, that the capacities for the development of combustion engines are already being massively reduced. This begins at the universities, where the number of students in the field of combustion engines is declining massively and where classic institutes for combustion engines are cutting back research in the core area. At the same time, a consistent restructuring is taking place at the classic vehicle manufacturers. For Europe, a new generation of engines is still being developed that will meet the EU exhaust emission standards that will apply from 2025. After that, there will essentially still be model updates, but no more major further developments. The corresponding development departments will focus on the new topics of electric drive technology, autonomous driving and the creation of a dedicated software ecosystem around the operation of the vehicle and the offerings around the vehicle over its lifetime, such as intelligent charging strategies and vehicle-to-grid or vehicle-to-home concepts.

Another factor that should not be neglected is that the basic design of battery electric vehicles is relatively simple. This is expressed, for example, in potentially low maintenance requirements but also low cooling requirements due to the high efficiency of all components. It means that the radiator grille, for example, is dispensable. Fuel cell vehicles, on the other hand, are much more complex due to the gas and water supply and also have to dissipate a relatively large amount of heat at a significantly lower temperature level compared to combustion engines. In addition, the 700 bar pressurised hydrogen gas tanks preferred today are much more difficult to accommodate in the vehicle than the batteries. Today, batteries are usually housed in the underfloor area and the overall height including the battery pack is only about 11 cm in some vehicles. Today's pressurized hydrogen tanks for passenger cars have a diameter of at least 30 cm. Developments towards thinner storage tanks are progressing, but the overall advantages and disadvantages of this are not yet clear.

There are therefore good reasons to assume that the battery-electric drive will dominate the passenger car market at least until the middle of this century. Same is most likely for light and heavy trucks and buses for local and long-distance transport. It is not likely at all that battery-electric vehicles will only be a transitional technology on the way to hydrogen-powered vehicles. Once the electric charging infrastructure is established, battery-electric propulsion will be inexpensive to operate, simple in vehicle design and maintenance costs will be unattainable.

Aircrafts

Air traffic in the European Union causes almost 3.8% of total CO_2 emissions[22]. Accordingly, solutions for CO_2-free propulsion energy must also be developed and implemented here. Even more than in all other mobility fields, the weight of the energy source and drive system is of central importance. A higher weight of energy carriers and drive systems almost automatically leads to a reduction in transport performance, be it cargo or air passengers. The weight of the energy carrier becomes more and more important with increasing distance.

Air taxis, helicopters and short-haul aircrafts

Electric propulsion concepts are currently being developed for small, light and relatively slow aircraft in many places around the world. This applies to drones of various sizes up to air taxis[23], but also short-haul passenger aircraft. Hybrid propulsion systems are also being developed for medium-range aircraft or helicopters[24], in which the electric part can primarily provide the peak power during take-off, allowing the conventional propulsion systems used for en-route operations to be operated in optimal efficiency ranges as they must not be designed anymore for peak loads. For manufacturers and operators of helicopters, electric take-offs and landings are additionally attractive because the

20 https://www.energie-klimaschutz.de/elektro-roller-china/

21 https://de.statista.com/statistik/daten/studie/155263/umfrage/entwicklung-der-gesamtanzahl-der-braende-in-deutschland-seit-2002/

22 https://www.europarl.europa.eu/news/de/headlines/priorities/klimawandel/20191129STO67756/emissionen-des-luft-und-schiffsverkehrs-zahlen-und-fakten-infografik

23 E.g. Volocopter: https://www.volocopter.com/, Airbus: https://www.airbus.com/en/innovation/zero-emission/urban-air-mobility/cityairbus-nextgen, Boeing: https://www.boeing.com/features/frontiers/2019/autonomous-flying-vehicles/index.page, Lilium: https://lilium.com/

24 https://www.flugzeug-lexikon.de/ILA_2010/Helikopter/Hybrid_Helikopter_-_EADS/hybrid_helikopter_-_eads.html, https://www.cockpit.aero/rubriken/detailseite/news/leonardo-bestaetigt-neue-plaene-fuer-einen-hybrid-elektrischen-hubschrauber/?no_cache=1, https://www.aviationtoday.com/2021/09/28/airbus-moves-toward-hybrid-electric-helicopter-new-engine-backup-system/

turbines have a high noise level during the peak load of take-off. This sometimes causes considerable problems even for rescue helicopters when approaching hospitals in densely populated areas. The electric drive, on the other hand, is very quiet and the overall noise is reduced to the air noise of the rotors.

For battery-electric concepts, batteries with higher energy densities are being sought at high pressure. However, since these must also be sufficiently powerful, fast-charging and safe, the only realistic alternative to the established lithium-ion batteries at present is the lithium-sulphur battery (see also chapter 7.4.2). Especially in aviation, however, the approval requirements are very lengthy and comprehensive. As a result, a battery technology will always be many years old before it can take off with passengers for the first time in a commercial aircraft. What is needed here are novel processes that can demonstrate reliability and safety much more quickly, together with diagnostic algorithms that can comprehensively monitor battery systems during operation and predict potential problems long before they actually occur. Otherwise, innovation cycles will be so slow that an emissions reduction to zero by 2045 seems hardly achievable.

Long-haul aircrafts

There is no question that in the foreseeable future, major intercontinental air travel will not be powered by batteries. This quickly becomes clear when looking at today‘s aircrafts. A modern long-haul aircraft of the type Airbus A350-800 today has a range of just under 16,000 km with a passenger capacity of 270. The maximum take-off weight is given as 259 tons. This then includes a maximum intake of 129,000 liters of aviation fuel. With a reference density of 0.8 kg/liter and a calorific value of about 34.5 MJ/liter, this results in a fuel weight of 103.2 tons with an energy content of about 1.2 GWh. The efficiency of jet engines used in aviation can be estimated at 30%[25]. This means that around 370 MWh of useful energy can be provided from this fuel in the aircraft. If the efficiency of an ideal battery technology is assumed to be 100%, the battery would have to have a gravimetric energy density of just under 3.6 kWh/kg. The aircraft has a maximum payload of 35.7 tons. Even if this weight were still fully available to the batteries, the energy density would have to be just under 2.7 kWh/kg. The best commercial lithium-ion batteries today achieve 0.28 kWh/kg and further development towards 0.35 kWh/kg in the next 10 years seems feasible. Lithium-sulphur batteries may be able to achieve 0.45 to 0.5 kWh/kg. The "holy grail" of battery technology is lithium-air or other metal-air batteries, though, which could perhaps enable energy densities of 1 kWh/kg, but without even a functioning laboratory prototype having been presented. The discussion makes it clear that a battery solution for this area of application is also theoretically not foreseeable. For this area of application, eFuels come into play, which can range from hydrogen to methane and ammonia to liquid synthetic fuel. For propulsion, other options include ramjets or turboprop engines or electric propulsion systems with power supply from fuel cells[26].

From a climate impact perspective, the switch from fossil paraffin to a chemically related eFuel is one of the last steps that should be taken on the road to climate neutrality. The reason for this is that due to the poor efficiency chain, the amount of CO_2 saved per kWh of electricity or hydrogen used is very small. There are few applications where the ratio of energy used to CO_2 saved is even worse. At the same time, however, the engines used today can be converted to eFuels relatively easily because they can be produced with quasi-identical chemical properties. It does not take decades to convert, but the eFuels can be used directly when they are available. In the case of passenger cars, on the other hand, an entire industry has to be converted to the new drive technology, and the vehicles currently on the road cannot be converted to electric drive in any meaningful way. In the automotive industry, the conversion to electric mobility began around 2010 and cars with combustion engines will still be on the road until at least 2045, i.e. 35 years later. In aviation, there is no such latency when using eFuels. It would be different if there were a switch to hydrogen/fuel cell propulsion. Here, complete new missiles with hydrogen tanks and electric propulsion concepts would have to be developed. This would require a conversion time at least as long as in the passenger car sector. The use of eFuels in this decade, enforced by sector targets, is counterproductive from a climate protection perspective and not necessary from a technological perspective.

Stratospheric drones

Stratospheric drones are a completely different type of aircraft whose task is not to transport passengers or cargo, but which can serve as relay stations for digital communication or earth observation platforms. The operating altitude is about 18 to 20 km and thus above the weather-determining atmospheric layers. These drones are designed for operations lasting several months without landing. The energy supply is provided by photovoltaic generators with batteries, which provide peak power, e.g. during take-off, on the one hand, and during the night phases on the other. Carrying classic fuels, whether of fossil origin or eFuels, is not an option here.

Ships

According to various sources, global shipping is responsible for 2 to 2.5% of CO_2 emissions. The European Parliament puts the share of shipping in total emissions for the EU at around 3.6% for 2017[27]. By comparison, Germany contributes a total of around 2% to global CO_2 emissions. Accordingly, ways must be found to install emission-free propulsion systems here as well.

25 https://www.energie-lexikon.info/wirkungsgrad.html

26 https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe

27 https://www.europarl.europa.eu/news/de/headlines/priorities/klimawandel/20191129STO67756/emissionen-des-luft-und-schiffsverkehrs-zahlen-und-fakten-infografik

In addition to various ideas to reduce fuel consumption by using sails or kites as "fuel savers"[28,29], green electricity and green fuels are the main options for propulsion. While wind support can at best take over shares and corresponding projects announced for many years in various forms have so far not really been able to be successfully implemented, more and more projects with battery drives for inland navigation and coastal operations and also drives with green fuels either in combustion engines or fuel cells are being tested. For example, a first ferry with battery propulsion will go into operation on Lake Constance from 2022[30]. The ferry for around 300 passengers will be charged at night and during the day. By 2030, all Lake Constance ferries and passenger ships are to be converted accordingly[31]. In Norway, the largest battery-powered ferry to date, with a length of 139 m, was put into operation in 2021. The ferry has space for 200 cars and 600 passengers and operates in the Oslo Fjord. The battery capacity is 4.3 MWh and can be recharged in about half an hour[32].

However, heavy transport ships for intercontinental trips will need alternatives. Ammonia as a fuel is under discussion as well as liquid hydrogen, liquid organic hydrogen carriers (LOHC), green methane or liquid Fischer-Tropsch products (eFuels). Depending on the fuel, different conversion technologies are discussed, such as adapted combustion engines, high temperature fuel cells or gas turbines.

Submarines have been equipped with battery-electric drives since the beginning of their deployment. Non-nuclear military submarines typically have classic hybrid propulsion systems. During underwater travel, the battery alone powers the submarine. To recharge the battery, however, the submarine must come back to the surface to be able to take in atmospheric oxygen for the diesel drive. The diesel engine then powers the submarine and simultaneously operates a power generator to recharge the batteries. The classic battery technology in submarines is lead batteries. Only in recent years, military submarines with lithium-ion batteries have been introduced[33]. Advantages are the lower maintenance requirements, the higher power density and the larger amount of energy that can be stored in the limited space in the submarine. This means that longer submersible trips can be realized and recharging can also be carried out in a shorter time. Of course, there are special requirements for the safety of the battery in such an application.

Agricultural & Construction Machinery

A very large number of agricultural machines are used worldwide. The most important types of vehicles are tractors, harvesters and loaders. In order to achieve CO_2 neutrality, there are various options for drive concepts and fuels. Loaders are mainly used on the farms themselves, and electric drives can certainly be used here because the individual usage sequences are relatively short and good charging possibilities can be assumed on the farm. In contrast, harvesting machines must be available around the clock during harvesting times. In the fields, an efficient charging infrastructure will be the absolute exception. In addition, the weight of the machines is a critical factor in order to avoid soil compaction. In the future, either internal combustion engines powered by hydrogen, methane, biogas, biofuels, methanol, ammonia or eFuels could continue to be used, or electric hybrid drives consisting of a fuel cell and battery, again with a wide range of possible fuels for the fuel cell. The same applies to tractors.

Similar considerations can be made for construction machinery. While construction cranes are almost completely electrically powered today, this does not apply to other construction machines. For a consideration of the future of drive technology, a distinction must be made between, on the one hand, building construction and large stationary civil engineering construction sites such as bridges, tunnels or underground railway lines and, on the other hand, line construction sites such as roads or railway lines. For building construction and stationary civil engineering sites, direct electric power supplies can be assumed. Accordingly, many construction machines can simply be recharged there or even supplied by cable. If necessary, battery exchange systems with recharging stations can also be used directly on the construction site. In some cases, the peak power of the grid supply will be limited, especially in urban grids, so that temporary stationary storage units will have to be used here for peak-load smoothing. For roadway construction sites in civil engineering, on the other hand, it must be assumed that in many places there is no sufficient power connection available here and, similar to harvesters in agriculture, both combustion engines with different fuel options and power converters can be used.

28 https://www.energiezukunft.eu/mobilitaet/emissionsfrei-ueber-die-weltmeere/

29 https://www.cargo-partner.com/de/trendletter/issue-10/segel-und-kites-unterstuetzen-frachtschiffe

30 https://bsb.de/de/bodensee-schiffsbetriebe-bsb-vergeben-e-schiffe-werft-ostseestaal?result=3

31 https://www.ingenieur.de/fachmedien/bwk/verkehr/die-umwelt-siegt-auf-dem-bodensee/

32 https://www.electrive.net/2021/03/02/oslo-fjord-bis-dato-groesste-elektrofaehre-geht-in-betrieb/

33 https://www.thyssenkrupp.com/de/stories/die-u-boot-revolution-lithium-ionen-batteriesystem-fuer-mehr-leistung

Charging Infrastructure

The most frequently heard arguments against battery electric vehicles are, on the one hand, the lack of recharging options and, on the other hand, the charging time. Both issues must be taken seriously, but whether serious problems actually will arise in the practical use of electric vehicles must be differentiated and considered in the individual case. The average use of passenger vehicles in Germany is 37 km/day[34]. Assuming 19.2 kWh/100 km results in an average of 7.1 kWh/day. This means that everybody with access to the home power system either with Schuko Emergency Charger (see chapter 6.1.1) with about 2 kW charging power or a Wallbox (see chapter 6.1.2) with 3.7 to 11 kW can recharge the daily consumption in less than 4 hours. This simple calculation shows that electric vehicle owners with an own charging opportunity will typically charge at home, which is in most cases also more economical.

The situation is much more difficult for those who do not have access to an own charger. The electric vehicle owners have to search for public chargers typically once or twice a week. As an example, an increasing number of discounters taking this as an opportunity to attract customers. They offer chargers, e.g. with 50 kW, which recharges during a one hour shopping power for about 250 km. Higher power rating can easily overload the local distribution grid. To overcome this problem more and more stationary battery storage systems are offered which get charged at relatively low rate continuously from the grid and can offer higher charging power to vehicles on demand[35].
The other challenge for the charging infrastructure is to support long-distance travel. The range of modern electric vehicles on one battery charge is usually between 250 and 500 km. In the upper class segment, ranges of 650 km can also be achieved at moderate driving speeds. Improvements in the energy efficiency of vehicles may also enable ranges of 800 to 1000 km in the coming years. However, no matter how far it goes, there will always be a desire on the part of users to want to drive even further, especially on the way to their holidays. The question then arises as to what charging time users are willing to accept. Vehicle manufacturers are addressing drivers' concerns with high-power and ultra-high-power charging stations that provide up to 350 kW of power. With an average consumption of 19.2 kWh/100 km, a 350 kW charging station can recharge energy for 100 km driving distance in 3.3 min. This means that 10 minutes of charging time must be planned for every 300 km of driving. For medium-sized cars with smaller batteries, the acceptable charging rate will be probably lower and extends the charging time for the same distance to about 20 min. For many drivers who have not yet driven an electric car, this seems too long and leads to the above-mentioned resentment. In practice, however, it can be observed at the Tesla SuperCharger stations, for example, that at the chargers, which in the past were "only" equipped with 120 kW of charging power, drivers can sit relaxed in their cars and check their emails or communicate or work with their smartphones or tablets. Waiting time is no longer seen as a loss of time because communication and work are possible.

But this example also makes it clear how important it is for people to try out electromobility. An electric car is not a 1:1 replacement for a combustion engine vehicle. There is more to the changeover than switching from gasoline to diesel. Driving an electric car is different, but most people who get into it quickly come to terms with the new form of mobility. So it might make sense to give car buyers the opportunity to experience an electric car for maybe 2 or 3 weeks before the next purchase decision.

There are also differentiated requirements for the charging infrastructure in all other mobility sectors. For example, heavy trucks along the motorways will need a charging infrastructure that can recharge the amount of energy for the next 4.5 hours of driving and thus around 350 km in 45 min in accordance with the mandatory rest breaks for professional drivers after 4.5 hours of driving. This requires charging power in the range of 800 to 1000 kW. Activities to standardize MW charging stations are already underway. In principle, this will only be possible with powerful medium-voltage connections to the motorway rest areas. As charging takes place over 45 minutes, the C-rate[36] is only about 1.3, which is a low charging rate from the battery's point of view. Overall, however, from the investors' point of view, a much higher economic efficiency of the charging infrastructure for trucks can be expected than is the case for passenger cars. For cars, fast charging infrastructure must be provided in sufficient quantities, especially for holiday traffic, where many users travel long distances and then want to use the fast charging infrastructure. During the rest of the year, however, the utilization rate will be low and thus the refinancing of the infrastructure is only possible if very high prices per kWh can be charged. Truck traffic, on the other hand, rolls with great regularity on 6 days a week throughout the year, so that high revenues can potentially be generated. Basically, charging infrastructures for fleets and commercial operations can be designed much more efficiently than those for passenger cars.

Different charger technologies for passenger vehicles

Electric vehicle chargers can be split into four major categories, each corresponding to a specific use case. A brief introduction of each device is provided in the following.

34 For the group of upper class cars in Germany it is more like 42 km/day. The average usage in the USA is also about 42 km/day.

35 https://ecomento.de/2021/09/22/e-on-und-vw-bringen-schnelllader-mit-speicher-batterie-auf-den-markt/

36 Definition see on page 53.

Figure 5.1 The four different types of charging infrastructure: A Schuko emergency charger w(a)[37], a wallbox[38] w(b), a public AC charging station[39] w(c), and a public DC charging station[40](d). All images have been published under CC-by-4.0 and artist names can be found in the corresponding references.

Schuko Emergency Charger

EVs can be charged at a household socket using an adapter. At around 2 kW, the charging power and speed is low. The low power results from household cables often only being able to carry continuous loads drawing 6 or 10 A. Additionally, the low powers create another problem: The rectifiers installed in the car are inefficient when operated at low power, leading to losses of 10% or even more[41].

Wallbox

A wallbox is a compact device that contains the necessary electrical and power electronic components to connect one or two vehicles either 1- or 3-phase via alternating current to the power grid. Considering their compactness and simple design, hardware costs of €500 - € 1000 are typical. The classic applications of a wallbox are the charging of private vehicles at home or at the employer's premises as well as at customer parking lots. In many cases, the electricity is provided free of charge, which makes a billing system superfluous and reduces hardware and operating costs. In principle, however, the same operating modes are possible with a wallbox as with a charging station if the appropriate measurement, communication, and authentication technology is installed.

AC Charging Station

AC charging stations are compact, upright structures with mostly two charging points in Type2 format, at which vehicles can charge with 11 kW or 22 kW three-phase. The devices are primarily installed in public or semi-public areas. For billing purposes, the German ordinance on charging stations ("Ladesäulenverordnung") for instance, stipulates electricity metering in compliance with calibration law and a payment option without a contract ("ad-hoc charging"). The latter is nowadays often solved via a website for which the link is visible on the charging station. For all charging stations installed from July 2023 onwards, a contactless EC or credit card terminal plus keypad is also mandatory. For contract customers, the activation typically takes place via an RFID[42] charging card, or via an app.

37 Elhamjaberansari, Mennekes chargercable. [Online]. Available: https://commons.wikimedia.org/wiki/File:Mennekes-chragercable.jpg (accessed: July 7 2021).

38 Marschmensch, Wallbox Söl 001. [Online]. Available: https://frr.wikipedia.org/wiki/Datei:Wallbox_S%C3%B6l_001.jpeg (accessed: July 7 2021).

39 SPBer, Charging station for e-cars in Spremberg (2). [Online]. Available: https://commons.wikimedia.org/wiki/File:Lades%C3%A4ule_f%C3%BCr_E-Autos_in_Spremberg_(2).jpg (accessed: July 7 2021).

40 Aschroet, Electric vehicle charging station Thörey. [Online]. Available: https://commons.wikimedia.org/wiki/File:Electric_vehicle_charging_station_Th%C3%B6rey.jpg (accessed: July 7 2021).

41 It is worth to mention, that charging at home in low voltage grids with only 120 V as used e.g. in the US is more challenging. Grids are not so strong and the twice as high currents cause additional problems in cables, fuses and plugs.

42 "radio-frequency identification"

Fast-Charging Station ("DC charger")

DC fast chargers mostly deliver power from 50 kW to 350 kW at typically 350 V - 450 V via the DC formats CCS or CHAdeMO. For particularly high outputs, the voltage level is doubled to 750 V - 850 V to prevent cooling problems in plugs, cables or fuses and to reduce the weight of the connecting cables. For power levels above 150 kW, the terms "high power charging" (HPC) and above 350 kW "ultra high power charging" (UHPC) are also used in the industry. In contrast to the other concepts presented, the rectifier is installed within the charging station and directly feeds the poles of the traction battery in the vehicle. Especially at high currents, active cooling of the rectifier and partly also of the cable is necessary. The battery management system of the vehicle battery and the charger communicate to adjust the charging power to the demand, condition and voltage level of the battery, as inside the car no power control besides "on" and "off" is possible anymore. With regard to measurement and payment, the concepts between AC and DC charging hardly differ.

Installed charging infrastructure in Germany

By the end of 2021, EVs could charge at around 50,000 public charging points (CP) (see Figure 2) at roughly 26,000 charging stations (CS) with 75% being AC chargers rated between 12 and 25 kW. The more or less constant annual growth of CP cannot keep up with the accelerating growth in EV sales. In 2021, the overall growth with respect to the number of CP was 13%. This growth was driven by installations with power ratings of 100 to 200 kW (+52%) and above 200 kW (+45%), with all other segments experiencing lower installation rates as compared to the previous year. The growth in CP above 100 kW can be explained by the better economics for fast-charging CP due to a higher occupation rate and governmental support. In addition, almost all new cars are equipped also for DC charging, which was not the case for cars launched several years ago.

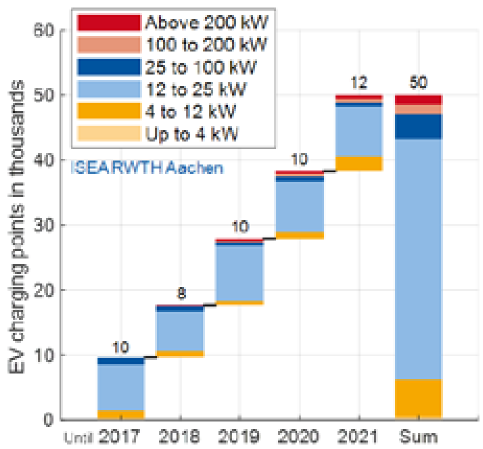

Figure 5.2 Estimated number of public charging points in Germany based on registrations at FNA[43] w(left) and battery electric vehicles (BEVs) per public charging station in Germany[44,45].

The above numbers do not include the privately owned wallboxes. Already today, a vast majority of electrical vehicle owners with own houses have a wall box for home charging.

Current economic challenges for the operation of chargers

As Figure 5.2 shows, the relative small growth in charging points led to an increasing number of electric vehicles per charging point. While in 2018 there were only 10 electric vehicles per charging point, this number has risen to 25 by 2021. This relative slow-down of charging-point installations is likely due to the high investment and operational costs compared to low achievable revenues, particularly for slower AC installations. Such a station will typically see only a few charging events per week and therefore achieve revenues of only a few Euros per week[46, 47]. Particularly installation costs, however, do not appear to decrease with a growing market size and can therefore not benefit from the same economies of scale that EVs are currently achieving. The reason for this is that a large share of installation costs are manual

43 German Federal Motor Transport Authority, Vehicle Registrations. [Online]. Available: https://www.kba.de/EN/Statistik_en/Fahrzeuge_Vehicles/vehicles_node.html (accessed: Mar 8 2022)

44 Kraftfahrt-Bundesamt, Bestand am 1. Januar 2021 nach Zulassungsbezirken und Gemeinden. [Online]. Available: https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/ZulassungsbezirkeGemeinden/zulassungsbezirke_node.html (accessed: Jan 27 2022)

45 Bundesnetzagentur, Ladesäulenkarte. [Online]. Available: https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/HandelundVertrieb/Ladesaeulenkarte/Ladesaeulenkarte_node.html (accessed: Jan 27 2022).

46 Assuming ~11 kWh per charge event, a margin of 9 €ct/kWh and 2 events per week, € 2 of weekly revenue can be achieved.

47 C. Hecht, S. Das, C. Bussar, and D. U. Sauer, "Representative, empirical, real-world charging station usage characteristics and data in Germany," eTransportation, vol. 6, no. 4, p. 100079, 2020, doi: 10.1016/j.etran.2020.100079

labor at the construction site such as cable laying, construction of foundations, etc. Costs may partially even increase if we assume that attractive sites (sufficient grid capacity, simple colling, easy access) were used first. This leaves more unattractive sites for future installations. To counteract lowering installation rates of public charging infrastructure, the German Federal Ministry for Digital and Transport runs several subsidy programs. The most prominent one is the "Deutschlandnetz"[48], a German-wide grid of 1,100 fast-charging stations with planned public spending of 1.9 billion Euros[49]. The target is to have no more than 10 km to the next fast charger wherever the car driver is. In a perfect world, this could be achieved for Germany with 1100 fast charging stations. Fast-chargers are of particular interest since they allow for a wider user base as compared to slower chargers. The Federal government nevertheless also runs several programs for public and private EV chargers to support infrastructure development across all options[50]. Nevertheless, it is also worth mentioning that the electric vehicle manufacturer Tesla sees it as part of the concept and the service of the company to offer their customers a nationwide charging infrastructure for fast-charging during long-distance travelling. Tesla is not waiting for governmental subsidies and operates worldwide more than 30,000 chargers with 120 kW and more[51]. In Germany, there are more than 100 charger stations and it is planned to increase the number by 50% to 60% in 2022.

An alternative way to improve the economic case are greenhouse gas emission quota ("GHG quota") where operators currently get reimbursed from the levies on fuel with currently around 5 to 20 €ct/kWhsold. Similarly, the RED III package currently created by the European Union will likely contain a similar mechanism, but it is not yet clear whether only car owners can claim the benefit or charge point operators as well. Given that these incentives are financed through the sale of conventional fuel, however, it is uncertain how such structures work in a system with mostly EVs.

State of battery technology

The dominant battery technology in mobility is the lithium-ion battery. Due to the wide range of material and design variations, a lithium-ion battery can be produced and purchased today for virtually every area of application. Lithium-ion batteries outperform almost all other commercial battery alternatives in its respective segment from a technical point of view. Reasons for the search for alternatives are, on the one hand, the temporary shortage of raw materials due to the announced very fast ramp-up of electric vehicle production relative to the speed with which new mining capacities including the entire logistics and processing chain can be ramped up. On the other hand, generally the manufacturing costs of lithium-ion batteries and the search for inherently safe storage technologies foster the search for alternatives. In the end, however, only a technology will enter the market if it can outperform lithium-ion batteries in terms of price. Accordingly, the lithium-ion technology will be presented in detail in the following. At the end of the chapter, other repeatedly discussed technologies are briefly examined and their statuses evaluated.

Typical battery load and lifetime requirement

The loads of batteries are always given relative to their size. Either the ratio between the power [W] and the energy capacity [kWh] or between the current [A] and the charge capacity [Ah] is formed. Since current and power, like charge and energy capacity, differ only by multiplication by the nominal voltage, the ratio, which is called the C-rate and has the unit [h-1], is the same in both cases.

Accordingly, when considering the electrical load of the battery, the maximum and average charging (which determines the charging speed) and discharging (which is determined by the power demand of the drivetrain) capacities as well as the installed battery capacity must be determined. Particularly with regard to the average load, the significantly smaller batteries in compact and mid-range cars may be more heavily loaded than the batteries in luxury cars with large battery capacities. Typical average loads during driving today are between 0.05 C (25 km/h average speed in the city with a battery range of 500 km) and 0.5 C (average speed of 120 km/h on the motorway with 240 km battery range). Peak-discharging power is determined by the installed drive motors and ranges from about 2 to 2.5 C (e.g. Renault ZOE with 41 kWh battery and 80 kW motor power or Mercedes EQE with 90 kWh battery and 210 kW motor power). Of course, there are also sports cars with much more extreme loads. For example, the Rimac Nevera with a battery capacity of 120 kWh is said to have a drive power of more than 1400 kW and thus a C-rate of almost 12. This shows what is possible, but the generalizing statements made here refer to series production vehicles for the mass market.

Apart from increased heating and its negative effect on service life, there is no known accelerated damage to lithium-ion batteries at higher discharge powers. The load during charging depends on the strength of the chargers, which can range from the single-phase household socket with 3.7 kW to ultrafast charging with 350 kW. Accordingly, the C-rate ranges from just under 0.1 C when charging a vehicle with 40

48 Federal Ministry for Digital and Transport, "The Deutschlandnetz: Basic principles of the call for tenders for 1,000 locations with high-power charging points based on the Fast Charging Act," 2021. Accessed: Mar 3 2022. [Online]. Available: https://nationale-leitstelle.de/wp-content/uploads/2021/07/deutschlandnetz-konzept-ausschreibung-englisch.pdf

49 J. Figgener et al, "The development of battery storage systems in Germany: A market review (status 2022),". Mar 2022. [Online]. Available: http://arxiv.org/pdf/2203.06762v2

50 NOW GmbH, Funding Finder. [Online]. Available: https://www.now-gmbh.de/foerderung/foerderfinder/?_sft_foerdergegenstand=invest (accessed: Apr 26 2022).

51 https://www.tesla.com/de_de/supercharger

kWh battery capacity at a household socket to 3.5 C when charging a luxury-class car with 100 kWh battery capacity at an Ultrafast-charging station. Tesla's first-generation Superchargers with 120 kW give a corresponding 1.3 C at 90 kWh battery capacity. This makes it clear that the option of fast charging in all cases means a significantly higher load for the batteries than actual driving. This is especially true because charging corresponds to continuous power and must therefore be compared with the average discharge of power.

The cycle loads of the vehicles depend on the use of the vehicles. Therefore, the following considerations are based on the one hand on statistically determined average usage profiles and, on the other hand, on a frequently used guaranteed value of 100,000 miles or 160,000 km. Passenger cars in Germany drive on average about 37 km per day, luxury cars 42 km/day. With current energy consumption rates of 15 to 25 kWh/100 km, this results in daily energy consumption of between about 5 and 10 kWh/day. With battery sizes of between 40 (compact class) and 100 kWh (luxury class), this results in an average daily use of 10 to 12% of the battery capacity or 36 to 44 equivalent full cycles („charge turnover") per year. This in turn results in about 300 to 350 charging turnovers in 8 years and 550 to 650 in 15 years.

Similar results are obtained via the guarantee performance. With a consumption of 15 kWh/100 km and 40 kWh battery capacity, there are 600 charge turnovers and with 25 kWh/100 km (and 100 kWh of battery capacity correspondingly 400 charge turnovers). The cycle requirements are therefore very moderate and considerably lower than those specified by many vehicle manufacturers many years ago. They thus correspond somewhat to the cycle loads required in consumer devices such as smartphones, tablets or laptops. Intensive efforts by vehicle manufacturers to reduce consumption will lead to a further reduction in cycle loads. Mercedes, for example, has presented a concept car the size of the S-Class with a consumption of only 10 kWh/100 km.

For comparison: In stationary applications such as PV home storage systems or systems for primary control power in the electricity grid, around 250 charge turnovers are made per year. Battery cells optimized for passenger cars are therefore no longer suitable for use in stationary applications, which also puts a big question mark behind various concepts in the field of "second life". For trucks, the current loads are also rather moderate because the batteries have to be designed sufficiently large due to the range requirement. For trucks used for long-distance transport, the batteries must last about 4.5 hours. This corresponds to the maximum uninterrupted driving time of professional drivers. This leaves 45 min of legally prescribed driving break to recharge the batteries. This means that the average discharge power is about 0.2 C and the charging power 1.3 C. On the other hand, the cycle load is high, because two full charging cycles per day must be expected. Accordingly, optimized battery cells are needed for this, which must have similar properties as for many stationary storage applications. As a rule, this means a somewhat lower energy density.

Lithium-ion batteries

Lithium-ion batteries are the key to far-reaching hybridization and electrification of drives in very different areas of application. Apart from lead starter batteries for vehicles with combustion engines and for the 12-volt electrical systems of vehicles with high-voltage batteries, other storage technologies currently play virtually no role in the mobility sector. Lead batteries will remain on the market for a while because they have an inherently lower probability of failure and are therefore indispensable for achieving the ASIL D level. However, since lead-acid batteries are virtually no longer used as traction batteries in modern road vehicles, they are not considered here, nor are nickel-metal hydride (NiMH) batteries, which are now only used in a few hybrid vehicles, especially by one vehicle manufacturer.

While, according to the current state of knowledge, the majority of batteries will be lithium-ion technology by 2030, there is now a high degree of differentiation of properties, so that a tailored cell technology is available or being developed for each field of applications. In the following, lithium-ion battery technology is presented with its various forms and their performance characteristics, and an outlook is given on further developments that could possibly play a role in the coming years.

"Lithium-ion" is in itself a collective term for a variety of material combinations that have in common that they contain about 3% lithium w (by weight) and that this lithium takes over the actual charge storage and charge transport between the two electrodes. By choosing different electrode materials, cell designs and manufacturing processes, very different properties can be achieved. Therefore, it is generally not correct to speak of properties of "the" lithium-ion battery. Nevertheless, generalizations in public media are always made because of an assumed need for compactness. Even for a given combination of materials, there are usually products with a very wide range of properties. Therefore, statements such as "material X has a longer life than material Y" are rarely correct in absolute terms. Spider diagrams that can be found again and again, which generally compare the properties of different lithium technologies, have hardly any value and are therefore not presented here. It is necessary to look very closely at the properties of each product in terms of capacity, charge and discharge performance, calendar and cyclic life, safety, temperature operating ranges and cost.

Technology

Lithium is element No. 3 of the periodic table and thus the lightest element that is solid at room temperature. Because the atom is both light and has a high electrochemical reaction potential, it is inherently very attractive for battery concepts. A distinction is made between lithium-ion batteries, in which the lithium is never metallic in regular operation, and lithium-metal batteries. The latter deposit lithium metallically on the anode when charged. This technology plays almost no role in applications yet, but will gain importance in the "solid-state battery". We discuss solid-state batteries in the section "Beyond Lithium-Ion Technology". Lithium-ion batteries are pure intercalation batteries. This means that the lithium diffuses into or out of the existing crystal structures of the positive electrode (called cathode) and negative electrode (anode). While the lithium is present as a positive ion when it moves in the electrolyte, it is neutralized again by the external electron flow after it has been deposited on interstitial sites in the electrodes. The cathode material used in lithium-ion batteries today is predominantly a metal oxide in which nickel, cobalt, manganese and aluminum are used in various stoichiometric ratios. The stoichiometry essentially determines all technological properties and the costs. In particular, there is an effort to reduce the proportion of cobalt as much as possible, because it is the most expensive and scarcest of the materials. Currently, for example, cathode materials with 8 parts nickel and one part each cobalt and manganese are increasingly being used (NMC 811). In addition, lithium iron phosphate (LFP) plays a role as a cathode material, with which significantly lower energy densities are achieved. However, because iron is significantly cheaper than cobalt and nickel, lower costs per kWh can be achieved. In addition, LFP is a material with different electrochemical properties that make it an inherently safer material. More on this in the topic "Battery system design".

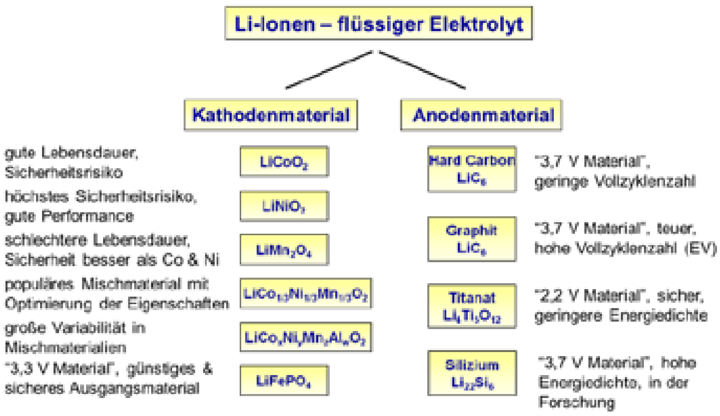

Figure 5.3 Selection of popular material combinations for lithium-ion batteries being manufactured or developed today.

The anode in commercial lithium-ion batteries today consists of various modifications of graphite, whereby some products with particularly high energy densities replace part of the graphite with silicon. This increases the energy density because more lithium can be incorporated per mass of silicon. While graphite has a volume increase of about 10% when lithium is intercalated, this is up to 300% for silicon, which causes enormous mechanical stress and thus problems with the cycle life. Therefore, only parts of the graphite have been replaced by silicon so far. Another anode material is lithium titanate (LTO). Cells with this material have a significantly lower cell voltage and thus also a considerably lower energy density. At the same time, with this material, which has virtually no change in volume during cyclization and top layer formation, lifetimes in the range of 100,000 cycles or very high charge rates of up to 100 C can be achieved. The C-rate expresses the current strength that can be achieved in relation to the capacity. The inverse of the numerical value indicates the duration in hours that is theoretically required for a complete charge or discharge. A typical current of 1 C thus corresponds to a duration of one hour, while 100 C corresponds to a duration of one hundredth of an hour, i.e. 36 seconds. Figure 5.3 shows examples of different electrode materials and a rough indication of the resulting properties.Between the two electrodes there is a porous separator that is insulating for electronic current and must reliably prevent a short circuit between the two electrodes.

Today's commercial lithium-ion batteries contain an organic, water-free electrolyte ("solvent") with a conducting salt that provides sufficient lithium ions for good conductivity. The electrolyte fills not only the pore volume of the two electrodes of about 30%, so that ions can also penetrate into the deeper layers of the active material via the electrolyte without much resistance, but also the pores of the separator and all other free spaces between the two electrolytes. If the moistening with electrolyte is incomplete due to inadequate filling or due to consumption of the solvent by aging processes, this leads to an increase in internal resistance and a decrease in capacity. A large number of additives are usually added to the electrolyte, which have a very significant influence, for example, on the service life and safety of the battery cell. The type, composition and quantity of these additives are among the best-kept secrets of battery cell manufacturers and can hardly be broken down using standard analysis methods.

Electrical performance

Today, lithium-ion batteries are offered in a large number of modifications concerning the electrode materials, the design and the internal structure, which determines the performance. In addition, other factors such as electrolyte composition and additives play an important role, e.g. for the maximum charging currents, low-temperature behavior, safety or cycle and calendar life. Generalized statements about which material combinations are particularly good in terms of individual properties are often suggested in literature and company publications, but de facto it can be seen in the market that there is a very wide range of product properties for almost every material combination. Moreover, the manufacturer‘s specifications often only give a very incomplete picture of the true composition of the battery, as laboratory analyses show time and again. It is therefore worthwhile to systematically examine the products available on the market for their properties and not to automatically exclude products on the basis of specific information from the manufacturer on the materials used. Currently, there is an increasing differentiation of properties in the mobility sector. In the 2010s, vehicle manufacturers were keen to cover a wide range of different vehicle requirements with one cell in order to achieve an economies-of-scale effect. In the meantime, the number of units planned for the coming years is so high that optimization can take place with regard to costs, energy density or other properties for the respective product segment. In the process, much shorter cycle lives are now being accepted. Whereas in the 2010s traditional vehicle manufacturers set requirements for cycle life in the range of 2000 to 4000 full cycles, today 500 to 800 full cycles are usually sufficient. On the one hand, this is a consequence of the Wöhler effect, which leads to a significantly higher energy turnover and thus a higher total mileage when the battery is partially cycled. On the other hand, batteries have become much larger and today typically have a range of between 300 and 500 km. 800 cycles at a range of 300 km are already 240,000 kilometers of driving (without the Wöhler effect) and sufficient for almost all passenger cars. For trucks or typical stationary applications, on the other hand, battery cells with a service life of 3,000 cycles and more are needed, since in these applications the battery capacity is completely used once or even twice a day.

The Ragone diagram in Figure 5.4 compares the specific power density and the specific energy density, each related to the weight of different commercial battery technologies. The volumetric energy density related to the volume is around 2 to 2.5 times higher for lithium-ion batteries than the gravimetric energy density. This clearly shows that lithium-ion batteries are superior or at least equivalent to all other technologies in terms of their overall properties. Very high power densities can be achieved, which come into the range of supercaps. The highest power densities are achieved with LTO batteries. The highest energy densities among the commercially established technologies are currently achieved with NMC cathodes with high nickel contents in combination with graphite anodes with an admixture of about 5 to 15% silicon.

However, the Ragone diagram also makes it clear that the highest power and energy densities cannot be achieved simultaneously for any battery technology. For high performance, the internal resistance must be particularly small, but this can only be achieved if the ionic resistance is as small as possible. For this, the electrodes must be very thin to allow short paths for the ions. With thin electrodes, however, the ratio between the weight and volume of the active masses needed for energy storage and the passive parts of the cell such as current conductors, housing and separators is significantly lower than with thick electrodes. Therefore, the following applies in a simplified way: a) Thick electrode ––> high energy density ––> high internal resistance, b) Thin electrodes ––> low internal resistance ––> lower energy density.

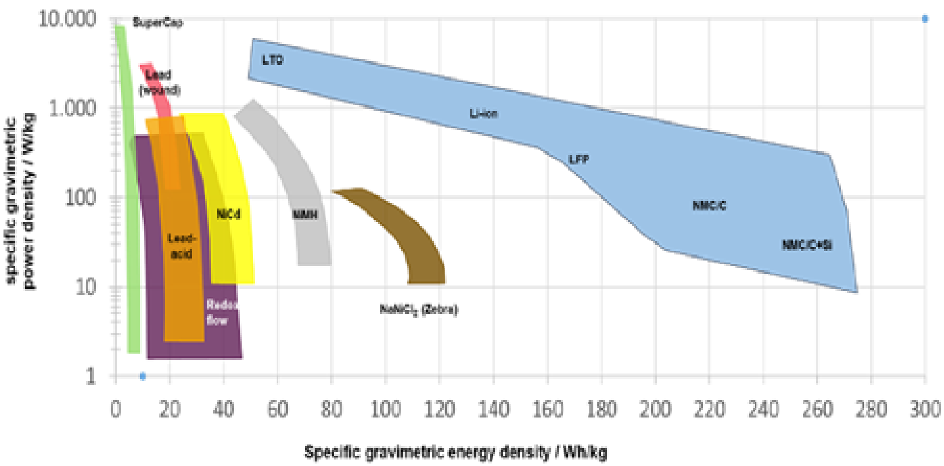

Figure 5.4 Specific power and specific energy for different storage technologies (performance data from various data sheets or own measurements).

For hybrid vehicles, battery cells with very high power densities are primarily used, as high power must be retrieved from small batteries. Cells with high performance can be charged and discharged very quickly. Accordingly, high numbers of cycles per day can be achieved. Therefore, high-performance cells are usually offered as batteries with a high cycle life. Even at high current rates, a high proportion of the capacity available at low currents can be used in lithium-ion batteries. This makes lithium batteries very suitable for high-current loads, such as those found in hybrid vehicles, power tools or uninterruptible power supplies. For all-electric vehicles, on the other hand, high amounts of energy are needed for corresponding ranges and therefore cells with high energy densities are used. The performance for the drive is achieved despite the lower energy densities because the batteries are large. With 60 kWh of battery capacity, 180 kW of drive power can already be served with a 3 C discharge capacity, which virtually all automotive batteries achieve.

The efficiencies of lithium-ion batteries are 90 to 95% and are thus very high compared to all other battery technologies. This is due to the low internal resistance and the high cell voltages of 3.3 to 3.7 Volts for LFP and NMC types, which are thus almost twice as high as , for example, lead-acid batteries with 2.0 V and around three times as high as NiCd and NiMH batteries with 1.2 V. The high voltage level thus also reduces the wiring effort at a given system voltage and has a positive effect on the internal resistance of the battery system. In operation, the efficiency can also be lower at low temperatures, but this then leads to accelerated heating of the battery.

A variety of different processes on both electrodes and the boundary layers between electrolyte and electrode materials lead to the aging of lithium-ion batteries. However, the most important effect in all NMC and LFP variants is the formation of a boundary layer between graphite and electrolyte on the negative electrode ("solid electrolyte interphase",SEI). At the negative electrode potential, the electrolyte is not stable and therefore reacts spontaneously with graphite and lithium. The process is only stopped because the reaction product itself forms a separating boundary layer. This boundary layer is very dense and reduces the reaction rates considerably. This makes it comparable to verdigris on copper, for example. Copper roofs can therefore become very old. The boundary layer also allows long lifetimes in lithium-ion batteries. At the same time, however, the boundary layer must continue to be permeable for the lithium ions during charging and discharging. Therefore, in principle, it continues to grow depending on the voltage level or state of charge, temperature and cycle depth. Since the boundary layer contains lithium compounds that cannot be dissolved again, the growth of the boundary layer deprives the battery of free lithium necessary for charge storage. The available capacity decreases accordingly. At the same time, the internal resistance grows with increasing layer thickness. The growth of the boundary layer thus reduces the capacity and increases the internal resistance.

Basically, the performance decreases significantly towards lower temperatures. The exact temperature at which this becomes critical depends on the battery cell. Cell manufacturers can set the "feel-good" temperature range of lithium-ion batteries in relatively wide ranges. Above all, it is important to prevent so-called lithium plating. This means a deposit of metallic lithium on the anode during charging. At each temperature, there is a maximum charge current rate at which the ions have sufficient time to diffuse into the graphite structure. If it gets colder or the current is higher, a "jam" of ions forms, which are then reduced to metallic lithium on the surface. This metallic lithium then has no protective layer and is exposed to the direct reaction with the electrolyte. This produces insoluble reaction products, which on the one hand hinder further ion transport, which leads to an increase in internal resistance, and on the other hand active lithium is permanently bound and thus removed from charge storage. Therefore, lithium plating leads to greatly accelerated aging. Modern charge management systems must pay particular attention to and prevent this effect, which is additionally dependent on the respective state of charge and the aging state. This is also a major reason why the real charging speed is often below the value possible due to the charging power of the charging station.

Aging and service life

The service life of batteries is defined by two properties:

- Calendar life - indicates how long the battery would live even without load
- Cycle life - indicates the charge throughput the battery can deliver relative to its size.

The end of the service life is defined on the one hand by the increase in the internal resistance and on the other hand by the decrease in the usable capacity. Typically, the end of life is defined by an increase of the internal resistance by 100% or the decrease of the capacity to 70 or 80% of the nominal capacity. In hybrid vehicles with their high-performance batteries, the internal resistance is typically the limiting factor, while in electric vehicles the capacity and thus the range from the user's point of view defines the end of life or corresponding restrictions on use.

The cycle life depends primarily on the cycle depth DOD (= depth of discharge) and the charging current, if the lithium plating described above occurs. The reason for the dependence on the cycle depth is primarily the expansion of the active materials during the storage of lithium. The greater this expansion, the more likely it is that protective layers will tear open, crystal structures will be destroyed or electrically conductive connections between the crystals and the current collector will be torn off. Therefore, the smaller the cycle depth, the more charge conversion is achieved ("Wöhler curve"). The calendar service life, on the other hand, is primarily determined by the temperature and the state of charge. As a rule, the service life is approximately halved with an increase in temperature of 10 K.

The goal is to achieve calendar lifetimes in the range of the vehicle lifetime, i.e. around 15 years. While this is quite realistic in a Central European climate with, for example, an annual mean temperature of about 10 °C as in Germany, it will be a considerable challenge in warmer regions with mean temperatures of, for example, 20 °C. The question here will be whether a universal cell is suitable for all climatic zones or whether it is suitable, for example, for warmer climates. In particular, the question will also arise whether a universal cell should be used for all climatic zones or whether, for example, cells with better lifetimes at high temperatures should be used for warmer regions at the expense of performance at low temperatures.

The cycle life in electric vehicles should enable a minimum mileage of 100,000 miles or around 160,000 km. With today's typical battery ranges of 300 to 500 km, less than 600 or 350 full cycles would be sufficient. However, partial cycling will result in much longer ranges. For example, a battery cell very similar to the one used by Tesla in the first generation has a service life of around 500 full cycles when fully charged and discharged. With a range of 400 km on one battery charge, this corresponds to 200,000 km. However, if the battery is only discharged by 20% at a time, i.e. after 80 km, which could correspond to a typical daily load for the way to work, over 15,000 cycles of 20% DOD corresponding to 3,000 equivalent full cycles were achieved with the same cell. This would then correspond to a mileage of 1,200,000 km. With a daily use of 80 km, this would lead to a useful life of over 40 years. However, this is unrealistic because - and depending on whether the body and the other components of the drivetrain would get that old - the calendar life would then be the limiting factor.

Security

Assessing the safety of lithium-ion batteries is not easy. In principle, there is no question that lithium-ion batteries pose a fire risk. The large amount of stored energy that can be released, especially in the event of internal or external short circuits, can lead to considerable heat generation, as a result of which there is gas formation or direct decomposition of electrode materials and consequent further release of energy. Especially when gases are released due to high pressure, the flammable gases ignite and as a result other flammable materials of the battery such as the organic electrolyte, the plastic separator or the graphite of the negative electrode catch fire. Before considering the causes and effects of fires further, however, it should be pointed out that with high quality standards, the number of fires, e.g. in passenger cars with battery electric vehicles, is considerably lower than in the case with conventional vehicles with combustion engines. Evaluations of the number of fires in vehicles made by the electric vehicle manufacturer Tesla show that in relation to the mileage, the number of fires is around a factor of 10 lower than in conventional vehicles. Tesla reports that between 2012 and 2020, one vehicle fire occurred per every 205 million miles driven. According to data from the National Fire Protection Association (NFPA) and U.S. Department of Transportation, during the same period, conventional vehicles experienced one fire per 19 million miles driven, about ten times more often[52].

The high media attention of electric vehicle fires suggests a significantly increased safety risk. Yet the "normal" incidence of fires in conventional vehicles, to which around 15,000 vehicles fall victim every year in Germany alone, and thus around 90 vehicles per day, is hardly noticed. This is certainly due to the fact that the number of victims in vehicle fires is relatively small, unless the fire is the result of an accident. Then, however, the actual accident is usually the primary cause of personal injury. Otherwise, in the vast majority of cases, the vehicle can be abandoned when a fire breaks out. Chinese legislation even requires that a fire risk be detectable at least 5 minutes before the outbreak of a fire, so that the driver has sufficient time to park and leave the vehicle.

Less quantitative figures on battery fires are available, for example, for the market segments electric bicycles or PV home storage systems. However, it is clear that the risk of fire increases with cheap products. Basically, therefore, compliance with the highest quality standards is of paramount importance. Unlike batteries with aqueous electrolytes, which include lead-acid, nickel-cadmium or nickel-metal hydride batteries, lithium-ion batteries do not have a defined overcharge mechanism that could absorb current in the event of overcharging without damaging the battery. Although this leads to a very high Coulomb efficiency of almost 100% on the one hand, overcharging usually leads to irreversible reactions that result in direct aging and, in extreme cases, a thermal event on the other hand.

In NMC lithium-ion batteries with their layered materials, overcharging a battery cell leads to excessive removal of lithium from the cathode material. If a threshold is exceeded, an exothermic decomposition of the cathode material occurs with the release of high amounts of energy and molecular oxygen. As a result, other gases, some of which are flammable, such as CH_4 , CO or H_2 are formed from the electrolyte and the anode material. This is very likely to lead to a fire in the battery cell if the gas pressure causes the otherwise tight housing to burst open. The organic electrolyte, the graphite of the negative electrode and the separator then further contribute to the fire load. To prevent overcharging of the cells, lithium-ion batteries, unlike other commercial battery types with aqueous electrolytes, use single-cell voltage monitors. In a series connection of cells, the cell with the highest voltage always limits the charging speed or the maximum charge consumption. The discharge of a battery system also ends when the first cell reaches the final discharge voltage, even if the other cells could still supply further energy. This results in a particularly high requirement for the uniformity of the cells in production and the highest possible temperature homogeneity in the battery pack, so that individual cells do not age considerably faster due to higher temperatures and thus then limit the overall performance of the pack.

However, decomposition of the NMC cathode material can also be triggered by high temperatures in the 200 °C range. These can be caused either by heat transfer from the outside or by internal and external short circuits. A mechanical impact ("crash") on a lithium-ion cell can trigger such a short circuit, as can manufacturing defects in the separator or cell stack or the formation of metallic dendrites by metallic lithium deposits ("lithium plating"). It is particularly critical if, as a result of the breakdown of a single cell, the neighboring cells are heated up by the released heat to such an extent that the critical temperature threshold is exceeded. Then a chain reaction can occur, which is also called "thermal propagation". While the pressure, the amount of gas and the heat of a single cell can be contained in well-designed battery packs, this becomes almost impossible in the case of a multiple release by a large number of cells. Accordingly, when designing the battery pack, special attention must be paid to suppressing or at least slowing down the heat transfer from cell to cell as much as possible.

Lithium iron phosphate (LFP) batteries are considered to be safer. The reason for this is that the cathode material has an olivine structure that does not exhibit instability with exothermic reaction. Accordingly, a major source of energy and thus the risk of fire in the event of moderate overcharging of a cell is eliminated. However, with the organic electrolyte and the graphite of the negative electrode, fire loads remain that can lead to a fire, e.g. through strong heating from the outside or internal short circuits. In the event of significant overcharging, LFP batteries also catch fire. However, this should be prevented by the battery and charge management systems. Basically, in all lithium-ion batteries used today, the electrolyte can evaporate at high temperatures. The resulting high pressure can cause the cell to burst and when the gases escape, it is easy for these flammable gases to ignite.

52 Green Car Reports: "Fires are less frequent in Teslas and other EV's vs. gas vehicles", published on www.greencarreports.com on 17.08.2021 by Bengt Halvorson, last website access on 20.11.2021

Falling below the final discharge voltage does not lead directly to a potential hazard. Short-term undershoots, e.g. during acceleration phases, are not considered as critical overall. However, if lithium-ion batteries with copper arresters are stored at too low voltages for a longer period of time, corrosion processes can occur on the electrodes, which can later become the cause of short-circuit bridges. Therefore, batteries that have been stored for an unknown period of time at voltages below the final discharge voltage specified by the manufacturer are generally no longer considered safe for further operation. Proper battery management is absolutely essential for safe operation. In particular, good temperature monitoring of the battery can at least very reliably prevent personal injury by providing a timely warning.

Cell designs

Today, three different cell designs are produced and used (Figure 5.5). For round cells, the electrodes and separators are wound from continuous rolls and placed in a cylindrical housing. These cells are traditionally used in consumer products and were initially used by Tesla in the 18,650 size (18 mm diameter, 65 mm height) for their vehicles. Today, the 21,700 format is increasingly used in vehicles and a 46,800 format has been announced for the next generation. Compared to the 18,650 cell, this will have a volume that is around eight times larger and also a correspondingly higher capacity.

In the case of flat or pouch-bag cells, the electrodes are stacked and welded in a foil (see also section "Production technology"). Here, very different designs with regard to height, width and thickness and thus also capacities from less than one to well over one hundred Ampere-hours (Ah) are known. The contacts can be attached to one side but also to opposite sides of the cell.

In prismatic cells, cubic housings are used, which for vehicles are almost always made of metal. The electrodes are either oval-wound cell stacks or layered designs as in pouchbag cells. There is currently a trend towards layered stacks, which on the one hand allow a higher volumetric utilization of the cell volume and, on the other hand, enable much more uniform pressure conditions and mechanical loads. Extreme cell designs are sometimes used to house the batteries, with cells barely 10 cm high but up to one meter wide.

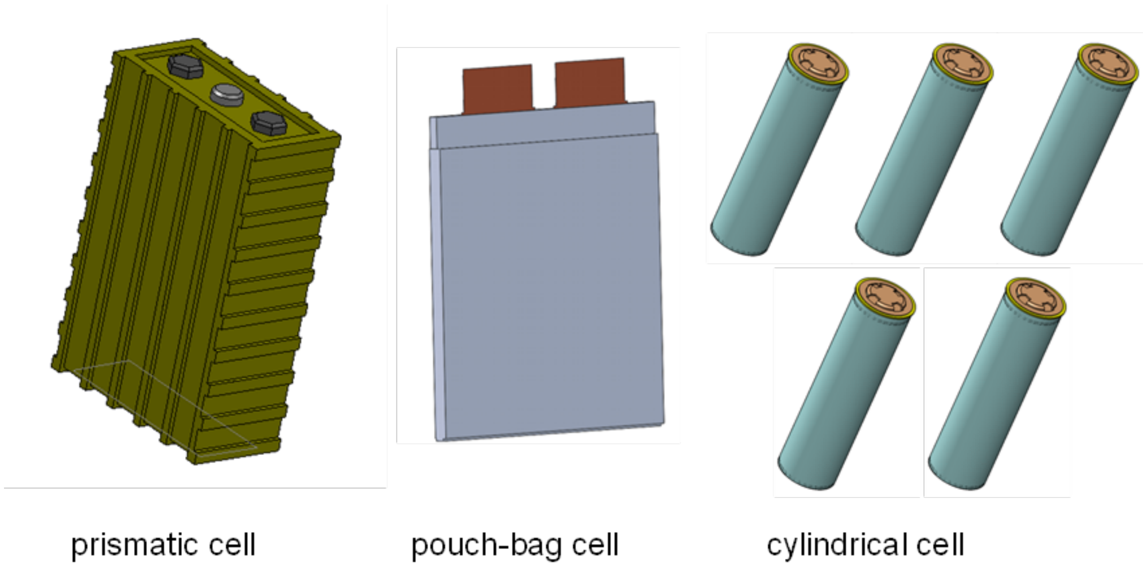

Figure 5.5. Prismatic cell design, flat cell and round cell.

Due to the change in volume of the materials during charging and discharging as well as possible gas formation, prismatic and pouchbag cells are usually braced in vehicles today. This makes it possible to achieve longer service lifes. This is not necessary for cylindrical cells, as the housing builds up this pressure itself due to the geometry.

The cell designs have different properties with regard to cooling in the battery pack. In principle, however, almost all electrode materials can be used in all three cell designs. So far, it is not clear that one of the three cell designs would prevail in the automotive sector to the detriment of the others, or that one of the three designs would be eliminated in the foreseeable future.

Material availabilities & recycling

All the raw materials necessary for an almost complete conversion of vehicles to battery-electric variants are available in principle. This is shown by the known resources of the most important metals lithium, nickel, cobalt, iron, manganese, aluminium and copper. Rare earth metals are not used in the battery cells themselves. The proportion of cobalt is being reduced further and further, and various manufacturers have cobalt-free cells on their roadmap for the second half of the 2020s, which will then make do with nickel and manganese. In addition, there are lithium-iron phosphate cells (LFP), which require neither nickel nor cobalt.

One challenge, however, is the sufficient supply of raw materials in the coming years with the very strong expansion of production figures for battery electric vehicles that is now planned. The National Platform "Future of Mobility" (NPM) currently assumes that by 2030 there will be around 14 million electric vehicles on the road and that the market share for new registrations must be around 80%. With a global market share of 25%, which could be achieved around 2026, an annual production of 20 million passenger cars would be equipped with batteries. Assuming an average battery size of 50 kWh per vehicle, this results in a demand for 1,000 GWh of battery capacity per year. In Table 5.1 the demand for metals is shown, assuming an NMC 811 cathode material. If this demand is put in relation to the current world production of the required metals, insights are gained into the necessary increase in world production. According to this, nickel demand increases by 41%, cobalt demand doubles and lithium production must be tripled. This does not include increasing demand, for example, in the areas of stationary battery storage, railways, ships or logistics. These are enormous challenges for the entire value chain, from mining and logistics to the production of electrode materials.

Table 5.1 Material requirements for a modern NMC 811 lithium-ion battery and projection of global material requirements.

Material	Demand for 100 kWh battery capacity [kg]	Demand in metric tons for 700 GWh battery capacity/year	Demand in metric tons for 1000 GWh battery capacity/year	Demand in metric tons for 1200 GWh battery capacity/year	Todays production per year [metric tons] (Source: US Geological Survey 2017)	Share at 1000 GWh/year of today's annual production
Nickel	85.5	598,500	855,000	1,026,000	2,100,000	41%
Manganese	9.7	67,900	97,000	116,400	16,000,000	1%
Cobalt	11.1	77,700	111,000	133,200	110,000	101%
Lithium	9.2	64,400	92,000	110,400	43,000	214%
Aluminum	37.9	265,300	379,000	454,800	60,000,000	1%
Copper	73.9	517,300	739,000	886,800	19,700,000	4%

This makes it all the more important to deal with the recycling of materials at an early stage. Considerable efforts are being made for this, both in research and in industry. There is no question that the technical possibilities exist to recover all metals from lithium-ion batteries with high efficiency. The question is at what cost this can be done. For example, recycling lithium itself is not economically viable today compared to extraction from primary sources. However, recycling quotas, at least in Europe, will probably be set less by economic efficiency than by corresponding regulations. The EU Battery Regulation currently in preparation, which has been presented by the European Commission as part of the European Green Deal, provides for a 100% collection quota for traction batteries and, from 2026, a recycling quota of 90% for cobalt, nickel and copper and 35% for lithium. In 2030, these quotas are expected to rise to 95% and 70% respectively.

However, even in the long term, new batteries will have to be built largely from primary materials. Batteries produced today should not be so worn out before 8 years, or better in 10 years or later, that recycling remains as the last stage of the circular economy. Figure 5.6 shows for an assumed market ramp-up curve for Germany what proportions of recycled material can be expected in new electric vehicles from end-of-life vehicles with assumed lifetimes of 8 to 10 years. Both a 100% collection rate and a 100% recycling rate are assumed. From this it can be seen that in 2035 a maximum of 40% (assuming only 8 years of life) of new batteries could be made from recycled material and only 20% if the batteries live 10 years to be recycled. All figures are based on the assumption that the chemical composition of lithium-ion batteries remains essentially unchanged. However, a switch to solid-state electrolyte batteries would have very little impact on the metal content of the battery, for example. The expansion of and access to primary sources will therefore continue to be of central importance in the next 15 years and beyond.

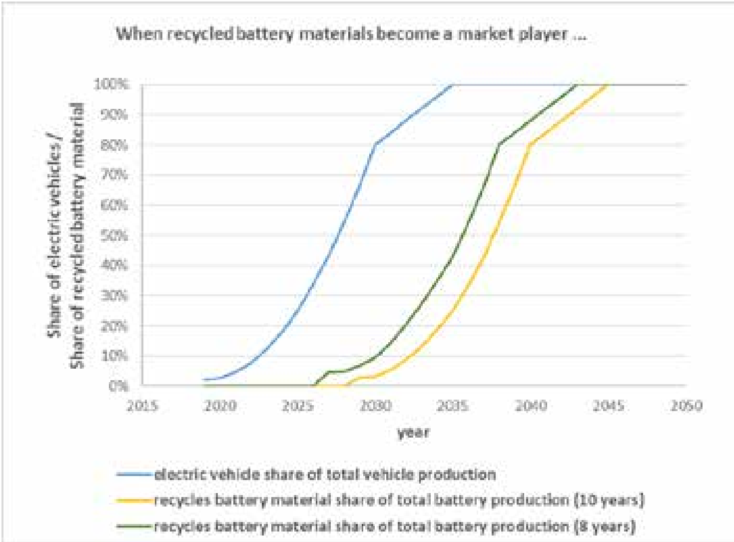

Figure 5.6 Assumed ramp-up curve for the share of electric vehicles in the total market and share of battery material available from recycling of batteries from electric vehicles at an assumed lifetime of 8 and 10 years, respectively.

Costs

When they were launched in 1991, lithium-ion batteries were priced at around US$3,000/kWh. Now, battery cells are priced below US$100/kWh for major customers such as mobile device manufacturers and car makers. Tesla's roadmap envisages a further reduction of cell prices to less than half within 5 years through a variety of measures in cell design, composition of anode and cathode materials, production technology and vehicle integration. Since the individual measures envisaged seem plausible, achieving the target does not seem unrealistic. However, the costs of lithium-ion batteries are increasingly determined by material costs. Especially at the beginning of 2022, raw material costs have risen, in some cases considerably. Table 5.2 shows a comparison of the raw material costs for the metal components in an NMC 811 lithium-ion battery between December 2021 and March 2022. The price increases are partly due to speculation and partly due to the expected significant increase in demand as a result of the announcement by many vehicle manufacturers to ramp up the production of electric vehicles much faster in the course of this decade than was envisaged a short time ago. The comparison shows an increase of almost 69% in just three months. Towards the end of 2022, lithium prices further increase whereas Cobalt became cheaper. Nickel showed decreasing prices until autumn 2022 and now shows again a certain increase, but still with a lower level compared to March this year. There have been reports that battery prices in 2022 increase by about 6% compared to 2021. This is not a lot but for the first time since many years the cell prices did not decrease any more.

Table 5.2 Raw material costs according to the trading rates of metal exchanges in London and China for the necessary material quantities for a NMC 811 lithium-ion battery.

Material	Demand for 100 kWh battery capacity [kg]	Price at metal exchange [€/ton]	Material cost per kWh **27.03.2022**	Material cost per kWh **21.12.2021**	**Change in costs [%]**
Nickel	85.5	32.276 €	27.60 €	14.83 €	**86.1%**
Manganese	9.7	4.830 €	0.47 €	0.45 €	**3.0%**
Cobalt	11.1	74.620 €	8.28 €	6.89 €	**20.3%**
Lithium (77% used)	9.2	368.150 €	33.87 €	16.85 €	**101.0%**
Aluminum	37.9	3.281 €	1.24 €	0.93 €	**33.5%**
Copper	73.9	9.008 €	6.66 €	6.29 €	**5.8%**
Summe			**78.12 €**	**46.25 €**	**68.9%**

However, many vehicle manufacturers have hedged against the dependency of the daily price for raw materials through long-term direct supply contracts. In addition, analysis of raw material availability shows that there is no fundamental shortage of raw materials, but current mining capacity is subject to significant limitations. This is clearly evident from the data in the last column of the Table 5.1. According to this, increases in the extraction of raw materials of 40 to over 200% are necessary, especially in the areas of nickel, cobalt and lithium. It can be assumed that investors now have confidence in long-term demand, but it typically takes several years until new mining capacities can be developed and put into operation. In addition to the pure extraction of raw materials, complex logistics chains for the operation of the mines and the transport of raw materials often have to be set up. It is therefore very difficult to predict the prices for lithium-ion batteries in the coming years. What is clear, however, is that in the event of sustained high prices for nickel and cobalt, lithium iron phosphate (LFP) technologies will be further developed in applications where the highest energy densities can be dispensed with. In the meantime, many vehicle manufacturers have announced LFP batteries for their models that are sold with lower battery range in a cheaper price segment. The same could be true for the introduction of sodium-ion batteries in the coming years. With energy densities more in the range of LFP batteries, this could reduce dependence on lithium. Since otherwise the same production facilities can probably be used for the cells, the introduction of Na-ion batteries would be relatively low-threshold. The packaging of the battery is estimated at a premium of about 25 to 30%. This share increases as the number of units becomes smaller. In special applications, the packaging costs can be higher than the costs for the cells.

Battery system design

Only in the area of small devices (e.g. smartphones) and consumer products are battery systems consisting of a single cell sometimes used. In all other cases, a large number of identical battery cells are connected in a pack. The cells must be selected to meet the requirements discussed above. Particular care must be taken to ensure that the required average or maximum power is also achieved for a given battery size.

The battery packs have a variety of tasks. The pack is the mechanical structure for holding the cells and integrating them into the vehicle, the protection against direct mechanical impact on the cells in a crash, and the carrier of the thermal management to achieve a uniform temperature within safe temperature limits. If overheating is imminent, the thermal management cools, while at low temperatures it may also ensure that the battery pack heats up, especially before charging. In the event of a fire in one cell, the battery pack must also be able to absorb the pressure wave and prevent the neighboring cells from heating up beyond critical limits. In the following, aspects of the interconnection of the cells in the pack and the tasks of the battery management system will be discussed.

Wiring

Lithium-ion batteries can be connected very flexibly both in series and in parallel. This means that very large battery systems can be built from relatively small cells by connecting the cells appropriately. In principle, battery systems are self-similar. Cells are usually interconnected to form modules, modules to form packs and packs to form systems. It therefore makes no sense to specify an upper limit for the size of a battery system. Limitations may result from available volumes or upper weight limits, but in stationary applications, where container solutions are typically used, there is no limit to the number of containers and thus the size of the storage system.

First, the system voltage and thus the number of elements connected in series are determined for the interconnection. Elements can be individual cells or cell clusters connected in parallel. Typical system voltages in vehicles today are 12 V for the conventional electrical system, 48 to 150 V for mild hybrids, 400 V for full and plug-in hybrids as well as for fully electric battery vehicles with charging powers up to about 150 kW, and 800 V for battery-electric vehicles for charging powers up to 350 kW. For even larger batteries or charging capacities, system voltages up to a maximum of 1500 V with a fully charged battery are also being discussed. If the battery voltage does not exceed 60 V during operation, protection against contact can be dispensed with. Between 60 and 1500 V, the battery system is considered a high-voltage battery. For compliance with the voltage ranges defined by standards, the maximum voltage achievable during operation applies. For lithium-ion batteries, this is currently between 3.6 V/cell (LFP) and up to 4.3 V/cell (NMC), depending on the cell chemistry. For system voltages that are far enough away from the limits, the number of cells is usually calculated by dividing the system voltage by the nominal voltage of the cells, which are between 3.3 V/cell (LFP) and 3.7 V/cell (NMC).

Special training in occupational safety is necessary for work on high-voltage batteries. It must always be taken into account that battery cells are extremely powerful current sources and cells in the automotive sector generally do not contain fuses. For example, currents of up to 2000 A can flow briefly in a 12 V lead starter battery when short-circuited with a spanner. This causes the metal to glow red hot. But an 800 V system also means at least 200 cells connected in series. Basically, the more cells are connected in series, the shorter the pack life. In practice, several cells are often connected in parallel and these units are then connected in series. In parallel connections of cells, the current of the total string is divided among the cells according to their internal resistance and open-circuit voltage. Therefore, weak cells in a parallel circuit are relieved and supported by stronger cells. In a parallel circuit, on the one hand, in principle the sum of the power and the capacities of the cells can always be used. In a series circuit, on the other hand, the weakest cell or unit always determines the performance of the entire battery string.

From the battery‘s point of view, the specific load ("C-rate") on the battery cells always remains the same for a given total energy capacity of the battery, regardless of the system voltage. The efficiency also does not change, to a first approximation, if the battery is configured differently from the same cells and the same number of cells. Since service life and reliability decrease with increasing system voltage and thus increasing number of cells connected in series, the optimum from the point of view of the battery system is at very low voltages. However, this leads to very high currents, which pose a challenge for charging cables, plugs, fuses or contactors. Accordingly, these components can be designed smaller and cheaper at high voltages. Power electronics, too, are generally more efficient and cheaper at higher voltages and correspondingly lower currents. A systemic optimum must therefore be considered, taking into account all components and aspects, including the weight of the charging cable and plug. For this reason, battery systems around 800 V are used for 350 kW charging power, for example, in which between 400 and 500 A occur during charging. However, it should be emphasized once again that the battery life and reliability decrease with increasing voltage. All the advantages of high voltages must therefore be derived from the other system components.

Battery management system

The battery management system (BMS) consists of various functional parts that are required for a safe and reliable operation of the battery system:

- Battery monitoring: measurement of currents, string and cell voltages, temperatures and impedances.
- Thermal management: Passive or active thermal management in the battery pack for uniform cell temperatures and operation within a safe temperature range that is as ideal as possible for performance and aging.
- Battery diagnostics: Evaluation of all information from the battery pack to determine the state of charge (SOC), state of power (SOP), state of function (SOF) or state of health (SOH) using diagnostic algorithms on the BMS and, if necessary, also in the cloud as the basis for information to the vehicle users and the vehicle's energy management system.
- Charge balancing system: Balancing the state of charge of the cells by means of charge balancing systems that are mostly passively controlled today, as the fullest and emptiest cell in each case determine the overall utilization of the battery pack during charging and discharging. Only active charge balancing systems can also compensate for different aging states.
- Switchbox control: Control of the contactors for switching the battery pack on and off for a safe connection to the power electronics without destructive inrush currents during switch-on and emergency shutdown in the case of crash or safety-critical battery overload.

There are various topologies for battery management systems. Frequently used are so-called master-slave topologies, in which slave boards are distributed throughout the battery pack, often one per module, which measure voltages and temperatures locally and also provide the charge balancing function. The slaves then report the measurement data via a bus to the master, which also has the current measurement data available. The master also contains the diagnostic algorithms and controls the contactor box. Safety-critical functions and those that have to be executed very quickly in terms of time must be implemented on the BMS itself. Alternatively, the determination of the current aging state or updates to operating characteristics such as the maximum charging current to avoid lithium plating can also be carried out on a central cloud computer. There, comparative data from a large number of identical or similar systems can be used to determine the condition.

Beyond Lithium-Ion Technology

Hardly a week goes by without news of major breakthroughs in battery technology that supposedly represent a revolution. The fact is that all developments that have come onto the market in recent years are evolutionary, consistent further developments of existing technology. When announcing new developments, it is important to ask whether, in addition to one particular characteristic (e.g. charging speed, energy density or service life), all other characteristics necessary for successful product use are also sufficient. This is often not the case, as a positive property usually has to be bought by compromising on other properties.

In order to evaluate the various product announcements, it always makes sense to look at which additional benefits can be generated for the user or customer that are noticeable compared to products already available on the market. In the following, four repeatedly discussed technology variants are briefly considered from this point of view.

Solid-state batteries

Many hopes are associated with the so-called "solid-state batteries". These are initially based on the classic structure of the NMC lithium-ion battery, but the otherwise used liquid organic and thus also flammable electrolyte is replaced by a polymer or ceramic solid electrolyte. This is said to have a positive effect on the safety and energy density of the cells. A significant effect in terms of energy density is only achieved when the higher electrochemical stability of the solid electrolytes at the interface to the negative electrode is utilized by replacing the graphite with metallic lithium. Since in lithium-ion batteries the graphite makes up about 90% of the active material of the negative electrode, this measure can be used to significantly increase the energy density. If lithium is only introduced as part of the cathode material during the production of the battery cell, we also speak of "anode-free" batteries, because there is then no active material on the current conductor of the negative electrode in the discharged state and during the construction of the cell. During charging, metallic lithium is then deposited from the negative current conductor. So far, however, this leads to dendritic accumulation of the lithium, especially at higher currents, and overall the volume changes in the cell due to the construction and dissolution of the anode lead to considerable mechanical stress. It is also unclear how the high charge rates in the range of 3 to 5 C can be achieved with the metallic anodes while at the same time achieving long lifetimes.

While solid-state batteries with polymer electrolytes have been offered commercially by at least one manufacturer for many years and are or have been used in passenger cars and buses, those with ceramic electrolytes have been announced but are not yet available as commercial cells in formats that are interesting for passenger cars. The commercial polymer electrolyte batteries require an operating temperature of 60 to 80 °C and must be kept at this temperature by thermal management. A market launch by the end of this decade is quite possible, but here, too, a revolution in electromobility is not to be expected. The market launch will initially be rather unnoticed by vehicle customers - apart from corresponding marketing campaigns. For example, the performance data announced by a developer of solid-state batteries, who also works closely with major vehicle manufacturers, hardly show any improvement over the performance data that can realistically be expected with NMC lithium-ion batteries in a few years' time.

Lithium-sulphur batteries

Lithium-sulphur batteries are characterized both by the use of overall very cheap raw materials and a fundamentally high weight-related energy density. However, the achievable volume-related energy densities as well as the cycle lifetimes are significantly lower than those of today's lithium-ion batteries. As a result, the interest of car manufacturers in the technology is currently not overly high. It seems that lithium-sulphur batteries initially have a future in the niche of applications where the weight of the battery is the most important characteristic and larger volumes and shorter cycle lifes are acceptable. This is especially true for flight applications such as drones, air taxis or small electric aircrafts. It is currently difficult to reliably predict when lithium-sulphur batteries could replace NMC lithium-ion batteries in this segment. Large-scale use of lithium-sulphur batteries in passenger cars seems unlikely, at least in this decade.

Lithium-air and metal-air batteries

Metal-air batteries, and lithium-air batteries in particular, are something like the holy grail of battery technology. The reactants are only oxygen and a suitable metal. If oxygen from the air is used in an open system, the battery is lighter in the charged state than in the discharged state after the oxygen has been incorporated into the metal oxides. The theoretical gravimetric energy density of lithium-air batteries is about five times that of lithium-ion batteries.

However, the intensive research work of recent years has shown that no breakthroughs can be expected in the very short term. One problem in particular is the very reactive singlet oxygen, which is formed in certain operating ranges of lithium-air batteries and easily destroys the cathode material through corrosion. By limiting the operating range, the formation of singlet oxygen can be avoided, but then the available capacity and thus also the achievable energy density is relatively low. In addition, according to current estimates, the volumetric energy density will hardly reach that of the classic NMC lithium-ion batteries. Accordingly, the interest of the automotive industry is currently not very high, at least in the area of passenger cars or trucks, and a market entry in series products is not to be expected at least in this decade. In addition, current estimates also show that the charging rates will be relatively low, so that the high charging rates targeted today will hardly be achievable.

Current trends in basic research on this type of battery, which are turning to sodium or potassium instead of lithium as the metal, are interesting. Since less or no singlet oxygen is produced here, stable battery systems seem possible. However, this choice of material is at the expense of energy density. Whether battery systems could be developed for the passenger car sector that would bring noticeable added value from the customer's point of view cannot be seriously stated at present.

Sodium-ion batteries

In sodium-ion batteries, lithium is replaced by sodium, which is more than 400 times more abundant in the earth's crust and therefore extremely cheap. Due to the heavier sodium and the cathode materials used, the energy density is about 2/3 of the values of today's best NMC lithium-ion battery and thus in the range of LFP batteries. However, since sodium-ion batteries do not need to contain nickel or cobalt, and in addition cheap sodium instead of lithium, there are estimates of the cost of these batteries in the range of 25 to 40 €/kWh. Since the "hard carbon" used on the anode has no potential thresholds due to different lithiation days, some characteristic potential points that are now intensively used for aging and performance diagnostics are omitted.

However, sodium-ion batteries have so far only been announced for the automotive market and are not yet on the market. However, CATL, by far the largest Chinese cell manufacturer, has announced a sodium-ion battery for 2023. So the technology seems to have the potential of further cost reduction and a reduction of scarce lithium, but at the expense of maximum energy densities and therefore rather for the compact and mid-range car segment. Since sodium-ion batteries can probably be built to a large extent on the same production lines as lithium-ion batteries, a market introduction could be relatively quick. Vehicle users, when the time comes, will be able to feel the new technology primarily through low costs. From a technical point of view, the vehicles will hardly come up with any new features.

Chapter 6 Buildings

Take-away Messages (Dirk Müller, Reinhard Madlener)

- The sustainable energy transition (Energiewende) requires significant reductions in energy demand, which can only be realized by fast serial retrofitting and prefabricated components
- Electricity-based heating/cooling supply is a main trend in the coming years in line with the increased share of renewable electricity
- Heat pump-only solutions will not be the optimal solution for building clusters when considering the needs for operating heat/cold distribution grids
- Today's heating grids have to be converted to low-temperature heating grids to also allow for the implementation of renewable energies
- The optimal level of insulation from a social welfare perspective needs to be determined for each type of building

Prof. Dirk Müller

Prof. Reinhard Madlener

Energy-related emissions account for around 85% of German greenhouse gas emissions. A large proportion of these emissions (around 50%) are attributable to the heating sector. To limit global warming, CO_2 emissions in the heating sector must be reduced rapidly and climate neutrality achieved in the medium term. To achieve this, the heating demand for all types of buildings must be consistently reduced and the remaining demand for heat must be met primarily on the basis of renewable energies (RE).

Existing buildings are among the major consumers in the heating sector. Due to the regulations in force, new buildings have had a high construction standard for years and emit little CO_2 quantities compared to the existing building stock. Efficient energy systems and renewable energies as roof-mounted solar photovoltaic systems as well as very high insulation standards can be implemented for new buildings with technology available today. The existing challenges appear in the existing building stock. To offer adequate solutions here, the following questions must be answered: What is the appropriate civil engineering and architectural solution for the existing building stock? What is the best fitting technical solution for existing buildings and what energy demand to be met? What CO_2 avoidance costs may be called for to achieve acceptance among the population or the building owners?

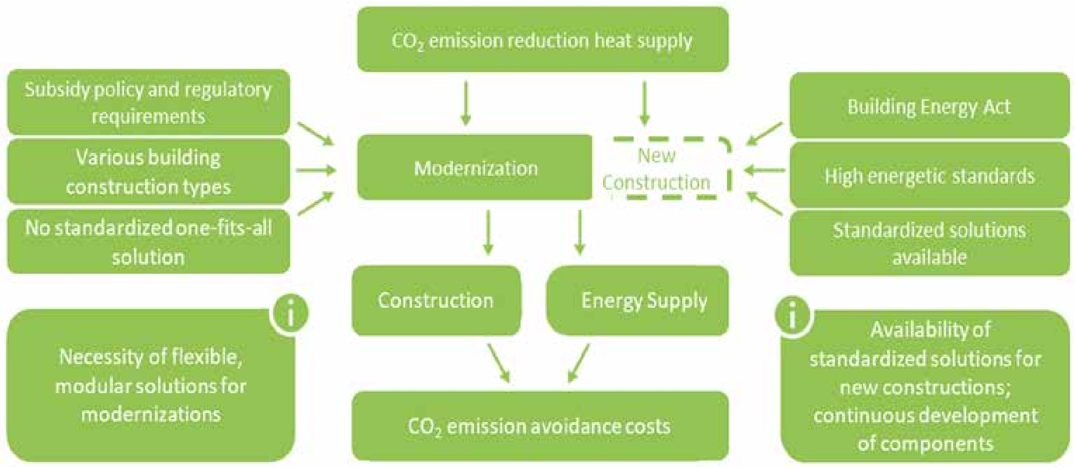

Figure 6.1 General conditions for the emission reduction of building's heat supply.

A successful energy transition requires three cornerstones: (1) increasing energy efficiency, (2) on-site renewable energy generation and use, and (3) grid-scale renewable energy generation and subsequent use for building operation. An innovative overall concept is based on consumption reductions and combined use of renewable energies in the direct environment of the building and via the final energies used. In addition to "green" electricity, renewable gases can also play a role here in the future.

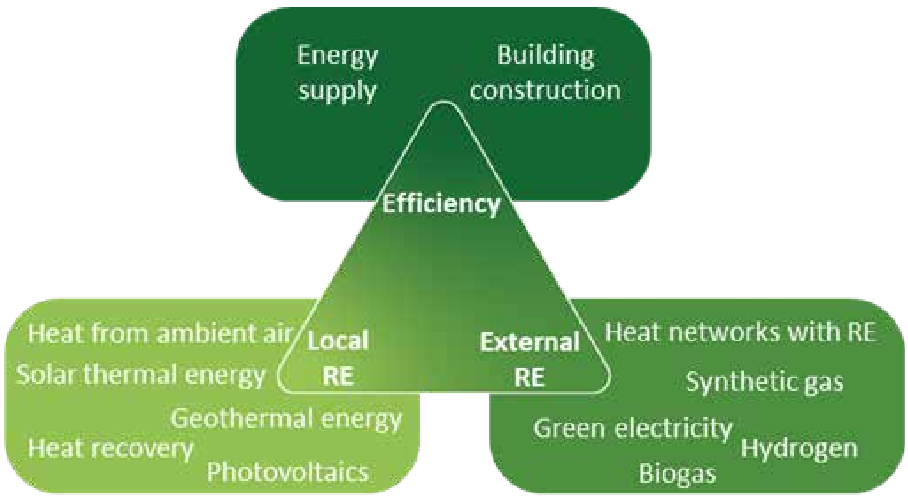

Figure 6.2 Cornerstones for the decarbonization of the building stock.

In terms of reducing consumption, the focus must be on existing buildings which are dominating the building stock and where there is a substantial remaining potential. Regarding technical systems operation and control lead to a fast reduction of technical losses. The integration of waste energy is simplified if all supply temperature can be reduced using a so-called LowEx approach. In addition to these measures, the new construction and expansion of heating networks is of great importance, as this approach can rapidly reduce CO_2 emissions, especially in

densely populated areas. The economic efficiency of new networks can be increased by a connection obligation. In Denmark, for example, compulsory connections mean that 63% of residents have a heating network connection today. Heating grids make it possible to use large-scale installations for renewable energies, highly efficient cogeneration, and waste heat integration. Additionally, the 5th generation heating grids with supply temperatures between 10 and 30 °C can provide heat transfer between buildings. If heating and cooling demands are sufficiently simultaneous in a district, the central plant needs to provide the differential load only, as shown for instance by the TransUrban. NRW project.
According to a study by the German Federal Environment Agency (UBA), 18 million residential buildings and about 1.5 million non-residential buildings had been built before 1977 in Germany. About 70% have either not yet been renovated for energy efficiency or have only been partially renovated. While energy consumption decreased by 31% between 1990 and 2010, it has stagnated persistently since then. According to surveys by the German Federal Ministry of Economics and the German Institute for Economic Research (DIW), private households consumed an average of 130 kilowatt-hours of thermal energy per square meter per year in 2010. Eight years later, this number has not been changed. And from 2018 to 2019, the consumption of heating energy increased again, even though 385 billion Euros were invested in energy modernizations in the ten years prior to that. The "rebound effect" (see Chapter 4) is often cited by the housing industry as one reason for this contradiction [4]. Over the next 30 years, additional investment of 10 billion Euros per year in rental housing - or 25 billion euros for the entire residential building sector - will be necessary to meet the immense challenges [6].

What is needed from an energy policy evaluation perspective, but what is still very rare, are thorough (i.e. ideally scientifically guided) ex-post evaluations of the influence of public information and program design regarding energy retrofits of buildings on the participation and decision-making of building owners. In a recent Canadian study [2] this has been done thoroughly. The analysis was done in a way that the energy program's database was analyzed which comprised data from evaluations by certified home energy advisors. For each house, initial performance, recommended performance as specified by the energy advisor, and a follow-up (achieved) performance, if applicable, were recorded. The greenhouse gas emissions were calculated based on estimated fuel use. The participation and socio-demographic and some other characteristics of the participants were compared across the different programs and program stages. The study team finds that strong partnerships between university, local energy utilities and municipalities that greatly contributed to the success of the program. The authors find further that (i) higher incentives result in higher participation and verified improvements; (ii) performance-based incentives attracted houses with the highest potential for improvement; (iii) houses that returned for follow-up evaluations had, on average, been recommended greater improvements to energy performance; (iv) higher participation occurred in the follow-up evaluation among houses with low-efficiency natural gas furnaces; and (v) successful community engagement and social marketing initiatives resulted in high levels of initial participation.

As a pathfinder method for these upcoming investments the use of optimization models is one of the central methods of current energy research. Economic, ecological, and technical relationships are mathematically described in these models by so-called constraints. In addition, by setting up objective functions, parameters are defined to calculate annual CO_2 emissions of a building or the net present value of a building energy system. Given constraints, these models can calculate optimal decisions based on the logic of a rational acting investor. These models can provide inside to optimal technology mix for a new or existing building energy system that results in minimal CO_2 emissions. Using simplifications and additional model assumptions this allows the design and extraction of technical operation rules for city districts.

In national and international literature, optimization models are mostly used as one stage models. However, recent approaches show that more realistic results can be obtained when decisions are considered at multiple points in time since investments in a building or city district will not be processed at once. Such a "multi-year" optimization model has also been developed at EBC, which has already been published in an international peer-reviewed journal [5]. This model is under continuous development and calculates modernization schedules for different buildings, using the CO_2 footprint as well as the net present value of the building energy system as objective functions and making decisions about the optimal heating, cooling and electricity plants.

Modernization measures need to address both, investments regarding the building envelope and energy supply system. Insulation measures on the building envelope offer the potential to reduce the heat demand of a building. In residential buildings, insulation thicknesses between 10 and 24 cm can significantly reduce the final energy demand. In non-residential buildings, internal heat sources (e.g., from equipment use) are significantly higher than in residential buildings, which is why these buildings often need to be cooled even at lower ambient temperatures. The proportion of window area and the geographic orientation of the building have an analogous effect, since the solar gains of the building depend on this. Since insulating the building envelope may increase the cooling demand, a trade-off between heat energy savings and increased cooling demand must be defined. Roof insulation can reduce both, the heating and the cooling load. Studies also showed that if outdoor air temperatures rise in the future due to climate change and heat islands in cities, there may be losses in thermal comfort in summer even in residential buildings without cooling.

Modernization of supply systems can be divided into improving the control of energy systems, which makes building operation more energy-efficient, and by replacing existing systems. Most buildings in Germany are still supplied with gas and oil boilers. In the residential sector, pellet boilers offer a good opportunity for low-emission heat supply, although it should be noted that, viewed over Germany as a whole, only a limited amount of wood can be provided sustainably.

Heat pumps, in contrast, can be used nationwide and are therefore a key technology in the building energy transition. By using environmental heat (e.g. outside air, geothermal heat, groundwater), low-emission heat can be provided in the building. In residential buildings, the additional use of PV electricity makes sense to come as close as possible to a CO_2-free heat supply. When using heat pumps in existing buildings, the temperature level of the heat transfer system (e.g. radiators or floor heating) must be taken into account. In addition, in multi-family dwellings, emission savings from biogas-fueled CHP systems are economically attractive and a means of relieving pressure on the electrical distribution networks. In summer, the electricity needed for the heat pumps can be provided by photovoltaic systems on the buildings. However, in winter, especially on very cold days, the power grids will experience significantly higher loads than today. This aspect is not adressed in many current studies. In the residential sector, it must be noted that the share of domestic hot water production in energy demand is increasing due to the insulation of the building envelope and is therefore becoming more relevant. Lower drinking water temperatures lead to a better heat pump efficiency but increase the hygienic problem of legionella.

In the non-residential sector, heat pumps also offer a high potential, as reversible designs can provide heating and cooling. Switching between heating and cooling operation is already possible on an hourly basis with current systems. New four-pipe heat pumps offer simultaneously heating and cooling. In the case of geothermal-based heat pumps, it is also possible to use passive cooling, for which only a very small amount of electricity is required. If a sufficient area of land is available to install a geothermal field, these systems are preferable to outdoor air-source heat pumps based on many known field tests in non-residential applications. Depending on the ratio of heat to electricity demand, the non-residential sector will need to investigate in detail whether solar thermal, solar photovoltaics, or a combination of the two is beneficial for emissions savings.

Using forecasted boundary conditions, such as energy and technology prices, the CO_2 factor of the public power grid, and others, statements about the relevance of different technologies over time are possible. Until Ukraine was attacked by Russia, gas-based systems were an economical choice for many building types in Germany. The current gas shortage and high gas prices are accelerating the shift to heat pumps. Combined head and power (CHP) systems offer a good transitional solution towards electricity-based heat pump systems and, as an interconnected system in a distribution network, can avoid high peak electricity loads. Heat-led CHP systems generate electricity when the heat pumps‘ electricity demand is high.

One of the most important limits for the acceleration of our energy transition is the capacity of craftsman workforce to implement all the desired modernization measures. According to Öko-Institut e.V., 100,000 additional skilled workers are needed in the relevant trades in Germany [3]. The European Union assumes 160,000 additional jobs in the European construction industry [1]. In addition to the shortage of skilled workers, it should be noted that the distribution of costs between landlords and tenants can inhibit investments in energy efficiency. The tenant-landlord dilemma also reduces the effectiveness of incentive-based policy instruments such as a carbon tax. The amount of the actual rent increase after energy efficiency retrofits depends on the structure of the regional rental market. Possible solutions to this problem are offered by contracting, tenant electricity models, housing cooperatives and warm rent models. The new options of the Energy Communities promoted by the EU also offer new opportunities for a broader participation of a large share of our population.

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Chapter 7

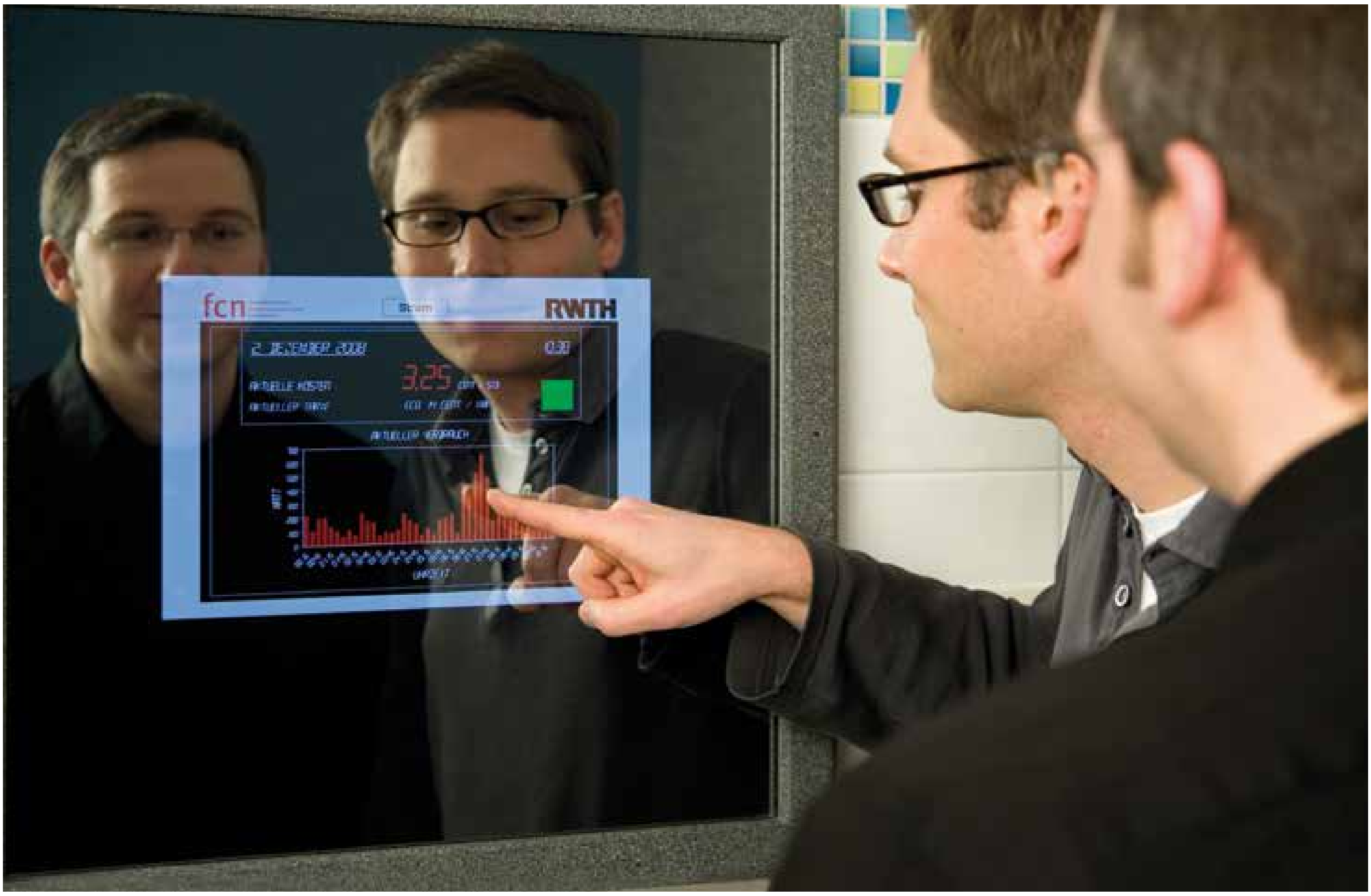
Digitalization and Decentralization

Take-away Messages (Antonello Monti, Ferdinanda Ponci)

- Whereas in the past the focus was on smart grids, more recently the trend is clearly digitalization, implying an increased level of complexity, and an acknowledgement that the energy customer / consumer is key
- Energy customers / consumers are the more relevant asset holders in a more decentralized system
- High shares of renewable energy challenge traditional grid automation, leading to a more complex and more decentralized system, but also a more controllable one
- Energy system transformation by digitalization requires a complete redefinition of the principle of grid operation (new role of power electronics to fine-tune power flows everywhere in the grid; safe grid operation by automation in all branches of the grid; enabling and adopting new business models reflecting the new role of customers / consumers)
- System operation as a fully software-defined process (multi-layer software architecture), the goal is to abstract the complexity of reality
- Growing role of DSOs (key intermediary, masking complexity of customer interactions) and open source software (e.g., Linux Foundation Energy)

Prof. Antonello Monti

Prof. Ferdinanda Ponci



From Smart Grid to Grid Digitalization

The Smartgrid has been a research topic for quite some time now both in Europe and the United States. While in the United States this was mostly connected to the idea of grid modernization, the European approach has been mostly related to supporting the increasing penetration of renewable energy sources.

Having a look at the literature in the field, it's anyway possible to assess a recent shift from smart grid to grid digitalization. The main question is then what is the reason for this shift. And analysis of this shift can be found in a recent report from the ETIP-SNET [3]. One of the main conclusions of this report is that the focus on digitalization represents a real change regarding the direction of evolution of the grid transformation process.

To understand the meaning of this change it is necessary to start from the definition of digitalization. For this reason, it is important, first, to put some clarity on the terminology.Also reported in [4] there are three terms that are easy to confuse:

- Digitization
- Digitalization
- Digital transformation

Digitization essentially refers to the process of transforming the information in digital format to be used for computer processing. Digitalization is often confused with Digitization but it has a much broader meaning. Digitalization regards using digital technologies to transform business operation. Finally, the digital transformation is a cross-cutting process that, by using digital technology, transforms an enterprise to make it practically and timely possible to operate in a customer-driven end-to-end mode. So how can we relate these three terms to the energy systems?

According to the already mentioned ETIP-SNET report, the new trend in the energy system is the changing role of the customers that is driving a complete reconsideration of the operation of the infrastructure. In a nutshell, we may say that the digital transformation, driven by the growing role of the customers, is pushing the need for several projects of digitalization that require as a starting point a complete digitization of the infrastructure.

According to data collected by Agentur für erneuerbare Energien back in 2017, in Germany private citizens owned 31.5% of the installation capacity [3]. By adding farmers, the percentage reached 42%. Classical utilities represent in this scenario 15.8%. These numbers are a clear call to completely rethink the energy system coming to create the conditions for a customer-centric grid. An important point for technology deployment, policy and regulation decisions though is to understand the implications of this transformation and how this is going to significantly affect grid operations.

A short history to better understand the present

The structure of the power system didn't change much for a long time. The key principles of operations were defined at the end of the 19th cent as result of the famous “War of current” and the results have been driving the structure and the direction of growth of the electrical system for more than 100 years [5].

While the most famous topic was DC versus AC, the selection of AC as the winning technology brought also some fundamental structural decisions, which have also been the main drivers of the automation principles. In a nutshell, Edison believed in a decentralized energy system while Westinghouse envisioned a centralized view. Thanks to the transformer technology, it was possible to create a clear separation between Transmission and Distribution, and to concentrate the generation in large power plants.

This appeared to be also a good decision because, after the first experience at Niagara Falls, generation started being based on combustion processes and then it was convenient to separate it from the city location. The system then developed in the direction of interconnecting and building ever larger systems, bringing networks together and making the system more and more robust to perturbations. Europe is the best case of this kind with the efficient and robust interconnection of 28 countries, all operating in synchronism and supported by a large mechanical inertia given by the rotating masses of the large synchronous generators. The network itself doesn't need to store energy and imbalances are reflected in the way frequency deviates from the standard 50 Hertz. This is a very nice concept because this signal can be monitored everywhere and becomes a communication channel which can be shared without the need of the second infrastructure. The control room does not need in principle to communicate to the power plant and identify in every moment intime if the network is in a very stable and in equilibrium point strictly looking at the deviations from 50 Hertz. That is, with a single signal, it is possible to understand if there is a need for changing the operating points for the power plant so to keep the energy balance under control. The large inertia of the system allows the operator to take the decisions with a reasonable window of time making the dynamics reasonably easy to manage.

This solution is really simple, reliable and allowed developing the infrastructure we have today. A key part of this solution is also the division of the network in two sections: one dedicated to balancing which is the transmission network (where also all the power plants are located) and a distribution network which is where the loads are connected. The energy goes from transmission to distribution and is delivered to the load: the distribution network, in this vision, is very simple, passive and doesn't need much intelligence. The intelligence is concentrated at the transmission network which is a small part. To give some numbers: in Italy, for example, the transmission network is about 30,000 kilometers whereas the distribution network of one of the larger distributors (but not the only one) is 1.3 million.

This separation of responsibility brought the system to a level of complexity very manageable. Thanks to few control points at the transmission level, it is possible to safely feed millions of customers. The key assumption again is that “down at the bottom” everything is passive. All those hypotheses are now under discussion because the changes we are introducing to the network are questioning the validity of all these basic principles.

First of all, we are progressively removing the large generation units and correspondingly the mechanical inertia related to them: we are making everything electronic. This is in principle also an advantage because components become programmable and we have the possibility to do things that were not possible before. Power electronics makes now available components that can operate at basically every power level going from the small 100 watts at home to the MW level, from distribution to transmission. Basically, we can also completely rethink the principle of operations and we are not anymore linked to the necessity to operate in AC and synchronizing these systems around a single frequency. This is an interesting change because at the same time if we analyze the network with high penetration or renewables, the concept of frequency as a system level quantity is anyway challenged by the fast dynamics created by the low inertia of the system. The more we move to an electronic network the more the concept of frequency as a communication signal is challenged by the fact that we don‘t have any more the large mechanical systems rotating basically at constant speed through time so all the basic concepts we had before are now under discussion. The value is that now from the very bottom of the system, so where the electrons are really controlled, we have programmability thanks to power electronics.

This is not just futuristic but we can look at some numbers to understand that it is already happening today: using Germany as an example the total contribution of renewable energy was more than 40% last year but during the day (that's what counts from the automation stability control point of view) we already had moments in which the intake was over 100%, which means Germany was exporting energy to neighboring countries. We had moments in which, particularly in summer, simply the energy from solar photovoltaic was more than 50% of the total load of that moment: this means that we have significant moments in time in which we are already experiencing conditions in which the majority of the devices driving the network and injecting energy are fully electronic and so fully programmable. The question arises how to substitute the mechanical inertia so to be really system-supportive. Efforts in this direction are already active with the whole effort of research related to the Grid-Forming Converter, i.e. making the renewable energy sources able to provide a complete set of grid services including inertia provision.

On the other hand, this is an indication that we are already in a completely new scenario. The transmission is in the middle for the long distance and basically, it's also, so to speak, an insurance supporting smaller systems that are more local. Those local systems, still thanks to the transmission, can help each other: that's the value of the interconnection but we have much more going on at the low and medium voltage level which means that the system with which we are dealing now is an active distribution network. Renewables are mostly connected at the medium and low voltage level, creating a completely new scenario in which instead of having few large power plants, we have a huge number of small but highly controllable systems that are all located in the section of the network that was considere passive as before. Going back to the buzzword “smart grid”: this terminology is quite misleading because the grid was smart and fit from the beginning. The point is that it was only needed to be smart in a small section, while now we need to involve infrastructure and make it intelligent because now, we need to reach out to devices that are spread in a completely different way. This is basically the challenge which means we have programmability, but we have complexity deriving from the huge number of devices. The advantage is that we can think or rethink the principle of operation and understand also how to organize such a complex system with millions of actors: they now can play a role by assisting. The old-fashioned view was to estimate the load and to balance the load with the generation: this was the game of frequency stabilization explained before. Now the question is what we do in this situation given that we have electronics, and we can control every single device. At the same time, we don't have this same capability of ramping up and down freely the generation any more because we try to capture as much as we can from renewables whenever they are available.

Basically, the system used to be totally load-driven but it is becoming more and more generation-driven. To rethink the new principle and to fully exploit the new level of programmability of the system it is critical to properly address the digitalization process to really achieve a digital transformation which brings the customers at the center which will facilitate the involvement of the main asset owners in this new constellation. The programmability of the system makes also sure that we will have enough flexibility to adapt the principles while the system evolves through this comprehensive transformation.

The different layers of digitalization

Following this short review of the pre-conditions, we can approach the process of digitalization. As a first glance, we can still refer to the ETIP-SNET report and identify that there are different layers in this process which implies also different approaches to the digitalization process.

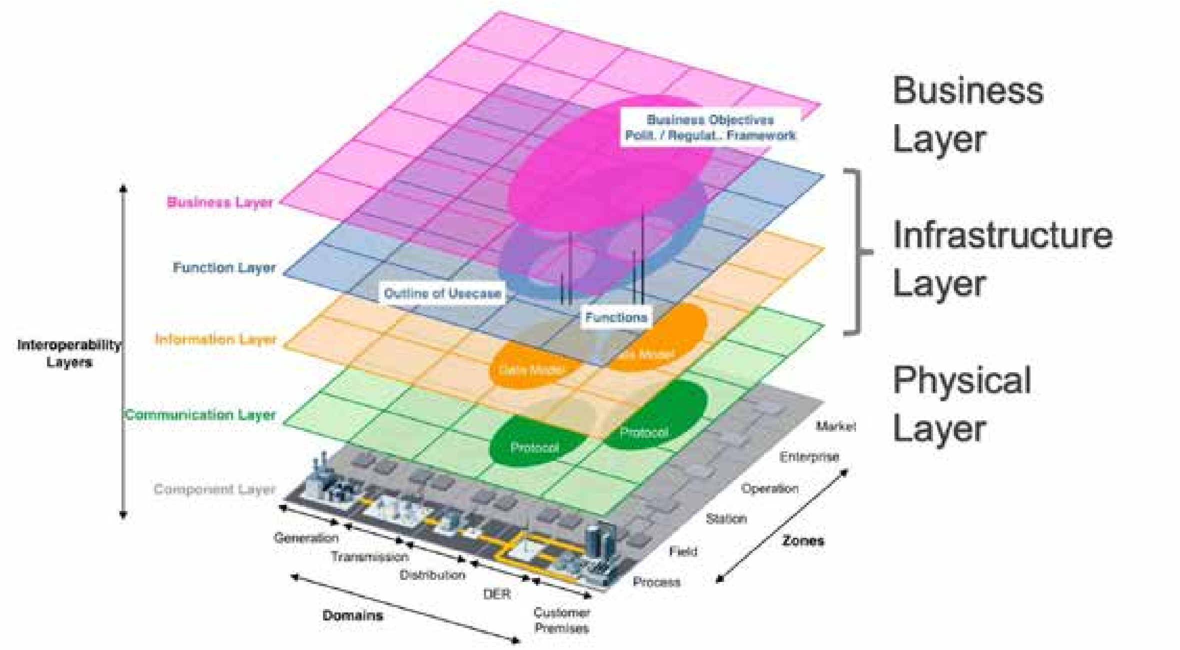


Figure 7.1 Mapping the digitalization of energy to the SGAM architecture [1].

This report, as summarized in Figure 7.1, maps the digitalization process to three different layers with different characteristics:

- Physical layer
- Infrastructure layer
- Business layer

The physical layer has mostly to do with the power electronics. As mentioned in the previous section, the power electronics is making the grid intrinsically digital and, correspondingly, fully controllable. A lot of innovation can still emerge in the coming years from the way we are going to exploit this level. For the moment, the trend has been to use the programmability of power electronics simply to emulate the characteristics of the legacy systems. This is a typical approach for a transition phase but not the most likely approach in the long term. The infrastructure layer refers really to how to steer the grid. This is where classical grid automation plays a role. Given what it was previously reported here the challenge is to understand how to address the complexity of bringing intelligence to the distribution network on the one hand, and how to build a new a more integrated way of working in cooperation with the transmission network on the other hand. While the separation of roles was the key element of the classical system, the interaction and the cooperation are the key elements for the future network. The business level is where the digitalization meets the digital transformation.

Digital transformation means changing the way energy companies interact with customers, which in this context means changing what the element of the trading is. In the old view, the concept was very simple and the relation buyer-vendor was really clear. In the new scenario, this last separation is disappearing because the same actor may play both roles but there is the more fundamental question of what is sold. Currently, we talk about energy, i.e. €/kWh so you buy energy because in a fuel-driven economy there is a clear non-zero marginal cost. In a futuristic system, maybe 20 years from now, the marginal cost of energy will be close to zero and thus you have completely different scenarios.

Rethinking automation: a software defined energy system

Given the previous categories, let us now focus on the infrastructure layer, which is the most important from an automation perspective. As already mentioned, we are dealing with defining the solution for a system that is extremely complex with the potential involvement of millions of players and devices. One way to approach this complexity is to define a scalable and flexible architecture which is open enough to accommodate new ideas and innovation but structured enough to define a way to organize the complexity.

Lending terminology from the communications sector, we could say that restructuring grid automation means defining a Software-Defined Energy Network. The basic idea behind the software-defined approach is a mechanism of abstraction that allows layers to think independently from the technology underpinning the implementation. In a nutshell, it is an approach aimed at exploiting the maximum of the flexibility from an infrastructure minimizing the hardware intervention. This is possible as long as the system is equipped with enough programmable devices to facilitate such flexibility. As mentioned in the brief historical review, this is the main ingredient of the transformation and so the hypothesis holds.

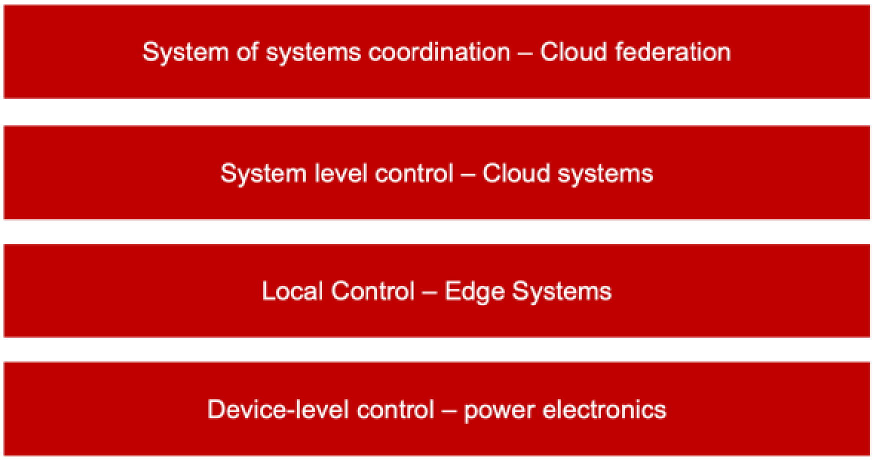


Figure 7.2 A multi-layer architecture for the full digital automation of the energy system.

As reported in Figure 7.2, thinking in software terms, the new automation system can be organized as a multilayer architecture in which at every level we have a different type of software with a different type of requirement.

As already discussed, we have at the device level the power electronics, which means controllable interconnection between energy sources or energy users. Think about electromobility but also basically every device we have at home right now is connected to the AC grid through some power electronics. Best examples are the washing machines or refrigerators: they normally have now, for efficiency reasons, power electronics inside and they fully control the power flow: this means we have this device-level control everywhere and then there is the chance to build the network from the bottom up. The first level of local control coordinates and harmonizes for the purpose of the system. This type of coordination needs an edge architecture and makes the link to a higher-level control.

This higher level, from a software perspective, can be considered as a cloud deployment that clusters the information from the edge systems on a higher level. Finally, a system level view can be something like a cloud federation view, also representing the possibility of interconnecting country by country.

What we want to achieve in building such a software system is a democratization of the energy system with the idea to create a real open European energy system in which the barrier of our countries do not play a role so that also the classical separations are removed. The role of the different operators, let us say in France versus Germany, are not a barrier from the business point of view so that wherever a customer sitting in Europe, she/he can participate to this system offering or requesting energy services. Independently from the location wherever somebody services are accessible and marketable, and the same applies to data in a vision of creating a European Data Space. This software-driven view of the power system has huge implications on the hardware level. While we build a pyramid of abstraction that facilitates, on the business level, a fully transparency of the energy system, on the other hand, the same process facilitates, at the hardware side, a better use of resources.

A very simple example is given by the role of data versus instruments. The classical view of the power engineer is: one box, one function. A full virtualization of the infrastructure that starts from the lower layer, as suggested in this view, means that equipment is immediately transformed in data. What matters is how the data are generated and how they are transferred. The processing of these data is then a separate software component. Devices can play a different role in the system depending on the conditions. In the IT domain this is quite obvious: let us simply think about the endless functionality a smart phone can have.

In energy systems, this is not the case because there is not a culture yet to think in terms of software-defined equipment. Even in a modern grid, the current version of digital substations is equipped with “boxes” giving “specific services”. Thinking more in a software-defined way, it means to focus on the process of digitalization of the information close to the source of information and then to virtualize the processing with the support of edge-cloud technology.

This view of flexibility can be reflected in every component of the system. We do not have any longer a clear separation between sources and sinks of energy. Let us consider a modern home equipped with PV on the roof and battery storage. A house is in some moment using energy and, in some moment, generating energy. It is basically a software decision what is the behavior of that node on a network: if it's a source or a sink is data-driven.

At the same time, the huge amount of data and the complexity of the infrastructure are also challenging classical physics-based modeling approaches: equations become more and more unmanageable so we have to tackle the complexity using data-driven approaches. This process of data abstraction is also relevant in another direction. We have more and more connections of the electricity infrastructure to other infrastructures, which means, first of all, linking to mobility but also to heating and cooling grids.

So what is interesting is that while we are transforming internally the electrical system, the electrical system itself is also becoming more important than it used to be because the amount of primary energy that goes through the electricity grid is supposed to more than double in the future systems. Imagining in the future all the cars to be charged through the electric grid and all the heating systems to be based on something like heat pumps, a huge amount of energy has to go through the infrastructure which makes the intelligence of this infrastructure even more critical to avoid a complete redesign of the system.

The changing role of the distribution grid operator

Assuming to adopt the previous vision, the next question is how this vision reflects on a possible structure for a modern Distribution System Operator (DSO). The DSO is the main actor linking a large number of customers and the Transmission System Operator. The challenge of DSO digitalization can then be split in three different parts:

- Interaction with the customers
- Internal organization
- Link to the TSO and markets in general.

Interaction with the customers

There has been in the past a lot of discussion on the definition of the interaction of the customers. There has been also a time in which many experts identified the transition to the Smart Grid with the adoption of a Smart Metering infrastructure. The current reality is that in many countries, including Germany, we are still at what we can call the Customer 1.0. The Customer 1.0 does not have any way of communicating or exchanging data with the grid operator. The majority of households is still equipped with an electromechanical meter which can only be read manually and does not provide any kind of connection.

In the best scenario, we have right now some customers that we can define as Customer 2.0. These are the customers equipped with the first generation of meters, which are not particularly smart but mostly electronic. A main limitation of the first generation has been to focus exclusively on the simple use case of flexible tariff and automatic reading. While this can be considered as a significant evolution, still it does not create the conditions for the interaction that can be envisioned for the future. Following the previous consideration on a customer-centric grid, what is critical is the definition of a standard data gateway which supports the definition of new service exchanges. Such an infrastructure will free the interaction from the classical kWh-based billing and open the way for a real service-based approach which is the overarching goal of the digital transformation.

One of the main concerns that have been slowing down the process is related to cybersecurity but, as it will be better introduced in a later section, solutions are currently available that are able to offer the proper flexibility without compromising on security. Creating an interaction based on service is a key step to involve customers. Right now, there is a huge gap between the definition of services as performed by sector experts and the need for service as perceived by customers.

A good example in this direction is given by the discussion about the flexibility market. While flexibility markets make a lot of sense for grid experts, they have no meaning from a customer perspective because it is hard for the average person why he or she should become “flexible”. Here again the digitalization can play a key role, masking the complexity of the concept of energy flexibility behind ideas that are way more understandable for the final user.

The average person has no interest to understand the complexity of electrical systems: to create customer activation it is critical that domain experts change the way they talk to the customers and not to make things too complicated but talking to their needs. Typical examples in this direction are given by the possibility to interact with the customers in terms of easy services such as warm home vs selling energy for heating. People care about their comfort but they do not care about the way it is achieved as long as the cost is considered as acceptable. Decoupling consumption from comfort means activating flexibility.

Internal Organization

The next step is then how to make use of this newly available customer interface. Here it becomes important to define an architecture for the network operation which fits in the overarching picture already introduced. A relevant effort in this direction is given by the work performed within the Horizon 2020 project Platone, coordinated by RWTH Aachen university/ACS with Avacon Netz as a partner [1]. The focus is really on how to deal with this amount of data that can be locally processed by the distribution system operator while at the same time also acting as a bridge to market and services. The goal is to position the DSO and also to facilitate customer participation so that they can be connected. This solution is currently tested in three real fields with three relevant grid operators:

- ARETI, Italy
- Avacon, Germany
- HEDNO, Greece.

A large demonstrator in the city of Rome in Italy is testing the multilayer architecture and the customers are connected to the grid operator through a blockchain access layer [8]. This is used to build trust between the operator and the customer. At the core of the solution there is a technical platform, which is the one dealing with the technical grid automation. The last role of the architecture is the interface to markets.

As a result, customer data are available for dual use thanks to the blockchain interface and can be used for grid operation functions but also as a link to flexibility markets (including the TSO level). This multilayer architecture is summarized in Figure 3, showing all the components of this system which realized a central data-driven role for the Distribution System Operator while creating the best conditions for customer inclusion [9]. All the components have been developed and released as open source solutions making the adoption for different implementations possible and also the further development with a cooperative approach. This is also a very recent and relevant trend in system automation that has been proved to be extremely successful in other sectors and that is only recently emerging also in the energy sector.

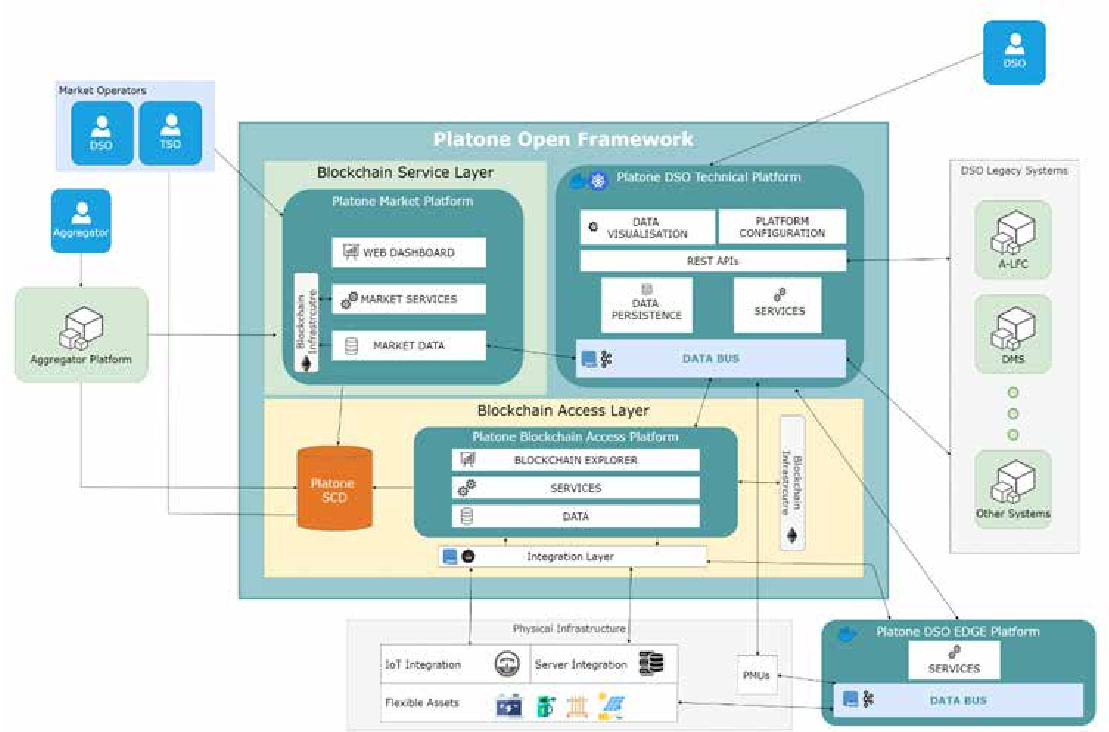


Figure 7.3 The Platone framework architecture.

RWTH/ACS is focusing on the technical platform which is a revolution in a revolution. The DSO technical platform adopted in this project is the result of a previous H2020 project called SOGNO where the idea was first introduced [10]. The main innovation is to approach the automation, completely removing the monolithic approach used by major vendors and to create an open architecture that is based on IoT technology. The core is to integrate the different automation functions in the platform based on microservices architecture so that the automation can be developed modularly, and different players can be integrated in a single platform. This means for the grid operator to avoid a single provider solution creating an open ecosystem where innovative ideas can also be easily integrated.

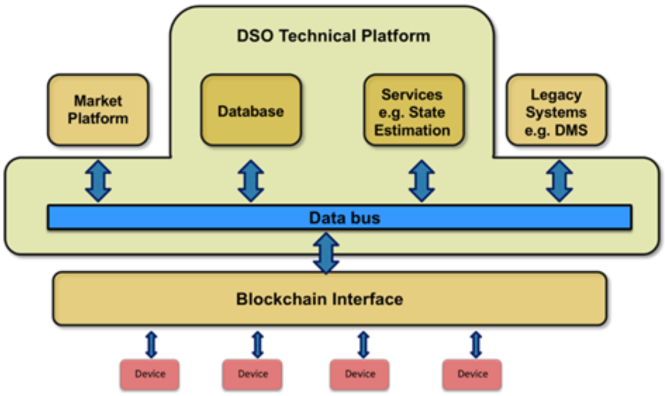


Figure 7.4 The role of the DSO Technical Platform in the Platone framework.

The DSO Technical platform is in the middle of the Platone architecture and equipped with three main interfaces (see Figure 7.4):

- Customer level interface, in this case based on a blockchain solution
- Link to the legacy system: adopting this solution does not mean canceling the previous experience. Traditional SCADA/DMS can be integrated with a special connector so that the adoption of the new solution is not a complete revolution but a process of integration of innovation
- A link to the market.

The core of the platform is based on the SOGNO architecture developed by RWTH/ACS and now selected by the Linux Foundation Energy as the reference architecture for distribution grid automation. A view of the architecture of this platform is reported in Figure 7.5.

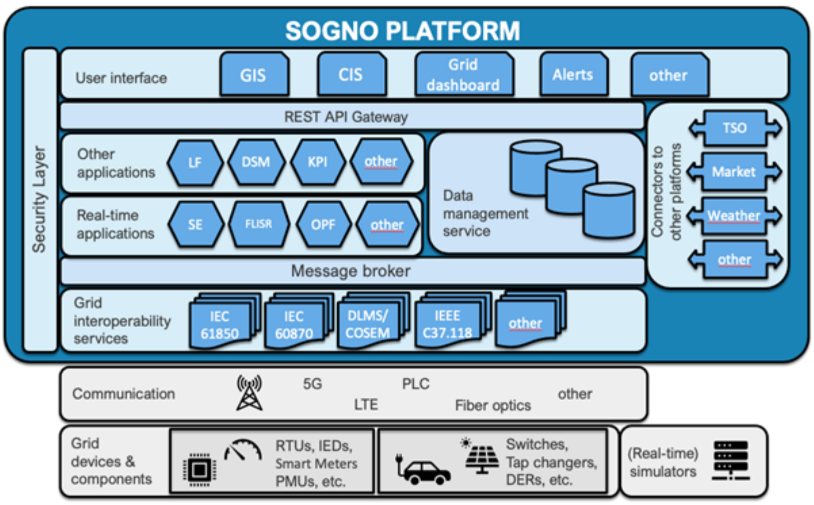


Figure 7.5 The architecture of the SOGNO platform.

Following the experience of the city of Rome gained in this project, ARETI, the city-level grid operator decided to adopt this solution for their next generation ADMS. The call for tender was in 2022 and it will represent the first commercial implementation of this solution developed at RWTH.

Building the big picture

The last piece of the puzzle is how to create the big picture. As mentioned before, the overarching goal is the creation of an open European-level market for energy. This means that we need to create another level of integration, which is the one in the original architecture reported as cloud federation. This activity is the core of the project OneNet coordinated in cooperation by RWTH/ACS and Fraunhofer FIT, the latter of which is working at delivering this last but critical component of the digital transformation. The goal is to create a real system of system is thanks to which different grid operators also from different countries can cooperate so to have a European approach to flexibility management. The goal is to make it possible for customers to have access to the energy market at the European level and participate to service provision independently from the physical location. The idea is to develop an appropriate middleware that is allowing the coordination among the different networks. Each grid operator can be connected via suitable data connectors so to create a single system, exactly One Network (One Net) for Europe.

This vision requires creating a standard way for the data to travel among platforms and a standard way of defining also energy services so that one can build a system of systems. These so-called "connectors" that will be installed in the different grid operators, making data exchange and service exchange possible with a single view. Interesting here is that instead of creating a single solution for Europe, different EU Member States can adopt different models of the market and data management without limiting the possibility of energy exchange with other Member States. A pictorial representation of this middleware is reported in Figure 7.6.

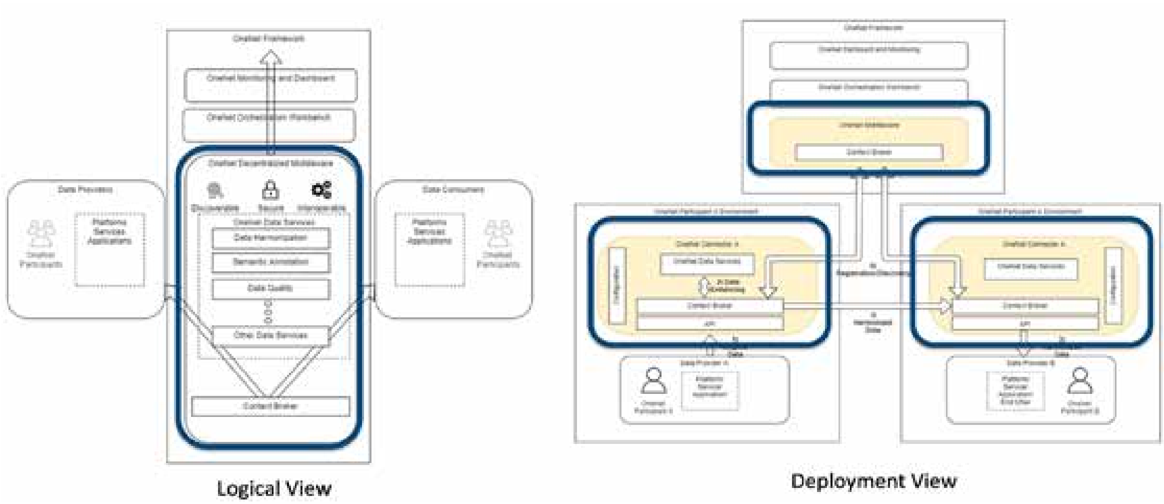


Figure 7.6 The architecture of the OneNet middleware for data connectors.

This is not just a theoretical exercise but it is currently under test in a long list of grids across Europe thanks to four large demo clusters involving the majority of the European Countries. A map showing the involved countries is reported in Figure 7.7.

Figure 7.7 The location of the OneNet demonstrato.

Also in this case all the software developed in the project will be released as open source, following not only the more recent trend but also the requirement of the European Commission with the purpose to very quickly push the adoption of the innovative solution.

The emerging concept of energy data space

In November 2022 the European Commission published the Digitalization of Energy Action Plan [6]. A key element of this document is the definition of six pillars that are identified to drive the transformation. These are:

- Connectivity, interoperability and seamless exchange of data between different actors while respecting privacy and data protection;
- Coordinated investments in the electricity grid supporting an accelerated deployment of the necessary digital solutions;
- Customer empowerment;
- Cyber-security;
- Green ICT; and
- Effective governance.

Focusing on the first point, a main priority emerging from the report is the creation of an EU Framework for sharing data to support innovative energy services. In a nutshell, the European Commission is envisioning the creation of a single European Data Space. The concept has been already analyzed in on-going research activities and some of the key conclusions are reported in a report of the EU project OpenDEI [7].

Data Spaces are a prerequisite for the creation of a data economy. The effort to create a European approach is active also in other business sectors such as, for example, health. The key element is to create software instruments facilitating data exchange while fully supporting data sovereignty. Here with data sovereignty, we do not refer to the simple case of managing the data within a specific geographical region, but the most relevant and complex case of providing the data owner with full data access control. The data owner should be able to define who can access the data, how many times and for which purpose.

The advantage is twofold: on the one hand, with clear mechanisms of data access the trust of the final users is expected to grow and, on the other hand, the higher level of trust will foster a greater activity. The final goal is to unlock customer action and make customers an active part of the future energy system while enabling cross-sectorial use cases currently not possible because of a lack of data regulation. Solutions in this direction have been already developed and have already been adopted by several service providers. The most relevant case is the IDSA (International Data Space Association) Connector, originally developed in the framework of Industry 4.0 and now adopted also in other fields. Given the aspiration of a single European solution, the aspect of interoperability is central.

The European Commission has started in the second part of 2022 a set of projects that are going to develop a long list of use case applications for data space in energy. Among these projects, ENERSHARE is an activity technically coordinated by Fraunhofer FIT Center for Digital Energy in cooperation with RWTH/ACS. Furthermore, to make sure that the full set of projects reach an interoperable solution, the Horizon Europe project Int:net is overseeing the coordination of all the five projects in this area while working at the more general challenge of interoperability in a digitalized energy world. This project, too, is led by a joint team at Fraunhofer FIT and RWTH/ACS.

In parallel, at the industrial level, the main challenge is the alignment of many relevant initiatives such as GAIA-X, FIWARE, Big Data Value Association, and Industrial Data Space Association.

The role of open source in this process

Previous examples showed the growing role of open source in energy systems. We are moving away from the classical proprietary principles. A main reason is that the full implementation of the digital transformation is too complex and expansive for a single actor. It is not possible for a single company to produce such a solution so that cooperation is a must.

This process of cooperation happened already in other sectors and the best example comes from the communications sector. Each new generation of wireless communication system is developed as a cooperation exercise and developed by using an open source approach. When deployment comes, the different vendors dress the solution appropriately to create the branding. The idea is to make the same in the energy sector.

It is a win-win situation for both sides: vendors save on development costs and can focus on what the customer can really appreciate, grid operators are freer in selecting solutions and can be more directly be involved in the development process. This is only possible if on the top of the open source there is governance. Linux Foundation Energy is the best example in this direction. Created originally by two large grid operators (RTE and Alliander) it has been growing in the two years to involve a large set of major players with different backgrounds: large vendors but also large IT players such as Google and Microsoft. The example of the city of Rome shows how this approach can rapidly transform the business. At the moment, the foundation is managing a quite relevant portfolio of projects, as summarized also in Figure 7.8. Among others, the already mentioned SOGNO project, led by RWTH, is one moving at the faster pace. Other such projects are already in production for both RTE and Alliander who have been the first mover in this business.

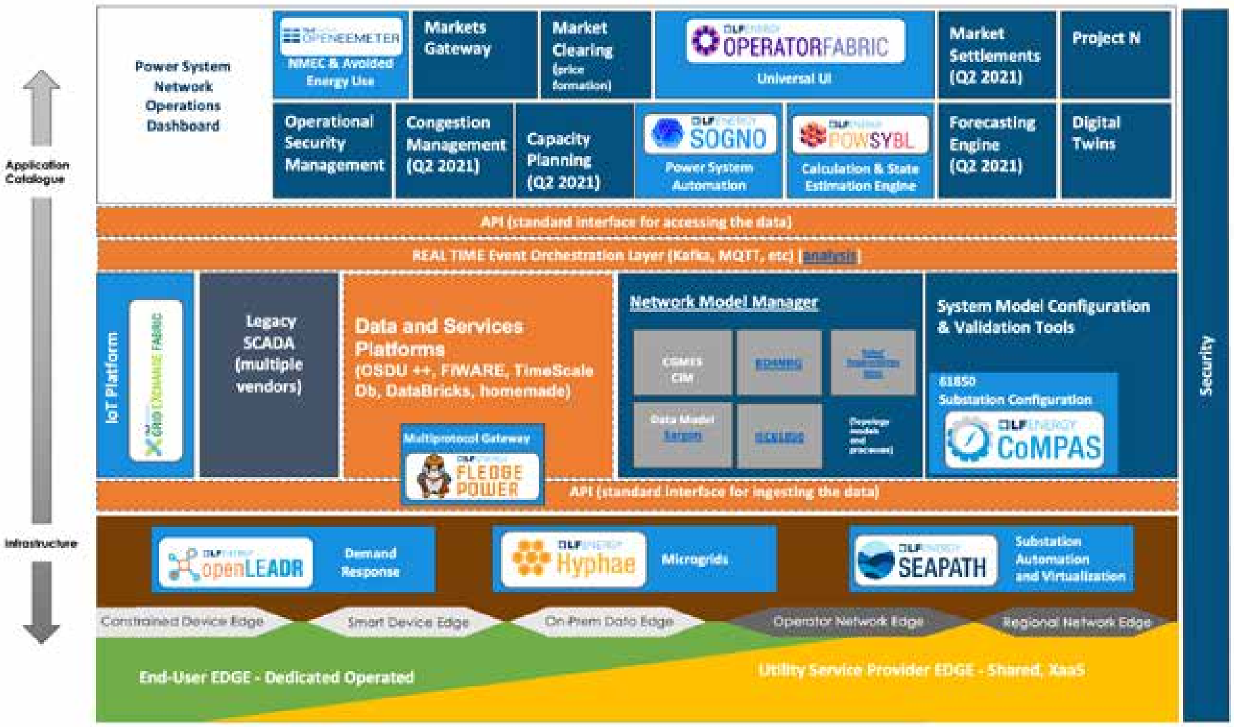


Figure 7.8 The software stack according to the Linux Foundation Energy.

Conclusions

The digital transformation is a very complex process but it is also a necessary step towards the decarbonization of the energy system. It requires complex and innovative architectures able to scale and to facilitate the creation of a brand-new energy ecosystem built around the customers. The digital transformation corresponds also to a tremendous effort of software development. Only open source can make it possible at the right pace and at the right cost.

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Chapter 8

Flexibilization, Infrastructures, and Path Dependence

Take-away Messages (Rik De Doncker)

- The EU Green Deal encourages sector coupling. Strong increase noticeable of demonstration and development projects for DC Factories, large-scale electrolyzers (GW, coupling to HVDC) and reconversion of (CO_2 neutral) city quarters using DC technology.
- There are technical (e.g. power electronic) solutions with enormous efficiency potentials and material savings for flexible smart grids of the future
- Technical change (e.g. regarding multi-terminal MV/LV grids) is slowed down by lack of standards, lack of models, inexperience of planners/installers, and lack of experts (well-trained electrical engineers)
- Path-dependencies (AC legacy) severely slows down the diffusion of DC systems
- Using classical 50 Hz AC technology to electrify all sectors will increase copper demand significantly. This bears the risk of high copper prices even shortages, that could prevent timely transition towards a CO_2 neutral energy supply system.

Prof. Rik De Doncker

Background

Awareness of global climate change, due to the high consumption of fossil fuels, has stimulated worldwide over the past 20 years research and development (R&D) towards a CO_2-free energy supply. In 2019, the European Commission approved the EU Green Deal, which casts in concrete CO_2 reduction targets to achieve the climate goals by 2050 (see Fig. 1). No doubt, the EU Green Deal is accelerating the need for innovation, i.e. bringing products and solutions to the market. In Germany, this drive for innovation, can be seen by the fact that the funding for the Sustainable Energy Transition is shifting from R&D, primarily supported by the Federal Government Ministry of Research and Education (BMBF), towards demonstration projects supported primarily by the Ministry of Economics and Climate (BMWK, formerly BMWI). This can be exemplified by the €1 Billion R&D initiatives of BMBF spent between 2010 and 2020 to develop latter electric vehicles. A National Platform eMobility (NPE) was established to guide these R&D projects. Currently, funding for the electrification of the mobility sector has shifted towards BMWK demonstration projects that focus increasingly, for instance, on charging infrastructure.

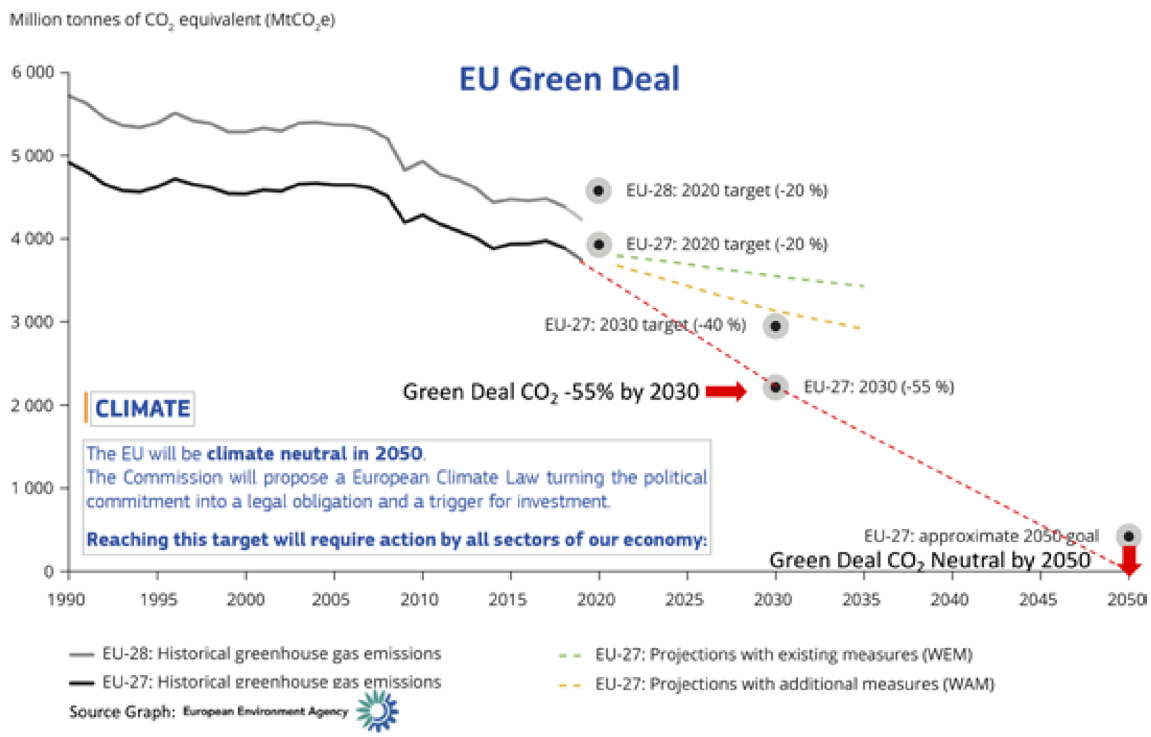

Figure 8.1 European Union Green Deal. The European Commission passed an EU climate law turning the political commitment into a legal obligation [1].

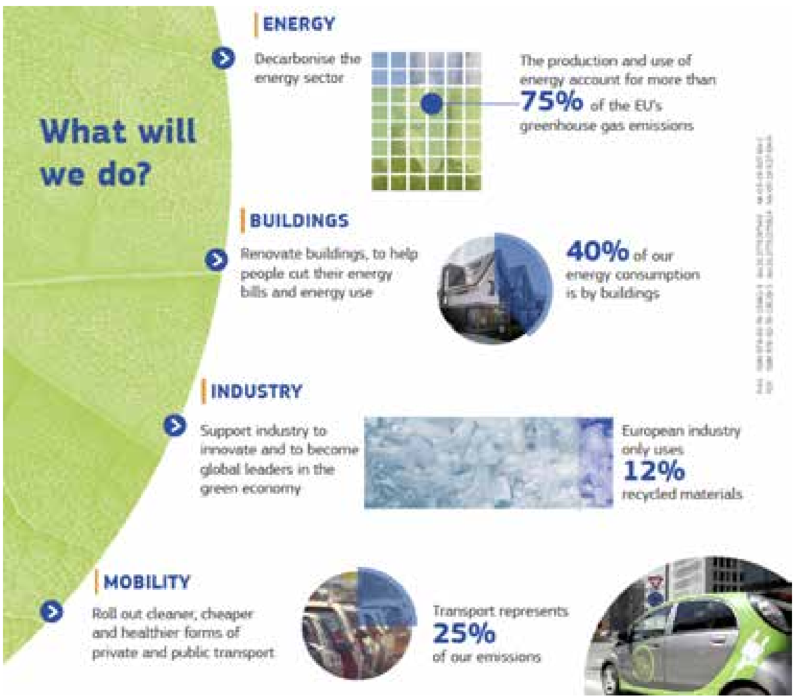

Figure 8.2 The EU Green Deal affects all sectors. All sectors need to decarbonize [1].

As illustrated in the EU brochure on the Green Deal (see Figure 8. 2), the EU Green Deal is based on full electrification of all sectors, which de facto means sector coupling. In our opinion, this is not just a challenge, but more so an opportunity to realize massive electrification of all sectors. Indeed, sector coupling provides some options for low-cost energy storage. For example, heat pumps coupled to heat storages in boilers or the building stock, can provide low temperature energy storages that, depending on their thermal capacity, can span days, weeks and even seasons. Dual use of batteries of electric vehicles, using bidirectional chargers, can provide fast response to stabilize the electrical grid. The study of the ACATECH ESYS project calculated that when 80% of all electrical energy is generated from wind and PV, electrolyzers will become relevant from a commercial viewpoint [2]. Chemical energy storages, in the form of gas (hydrogen or methane) or synthetic fuels, provide long-term strategic storages and can make the EU independent of fossil fuel imports, in particular Russian gas. The current war in Ukraine has made it clear that our dependency essentially on one dominant energy supplier is a major risk that can neither be ignored nor tolerated.

In all these sectors, direct current (DC) technology comes to the foreground. Nature gave us only DC electro-physical and electro-chemical galvanic (voltage) elements. Hence, batteries, PV, even the conversion systems inside wind turbines, are all DC power sources. Today, at the consumer side, most industrial equipment and household appliances, are connected to the alternating current (AC) grid via rectifiers that provide DC power. Hence, most industrial and consumer products operate intrinsically on DC power. DC converters provide power to electronic circuitry, such as computers, audio-visual apparatus, communication and automation systems. Inverters convert DC power to variable frequency AC. Nowadays, almost all electrical drives are inverter-driven, controlling speed of motors to improve efficiency, increase their speed range or reduce noise. Such drives are essential in traction and propulsion systems, such as in ships, railways, light rail, electric vehicles, electric bikes, etc. Even common household appliances, such as vacuum cleaners, use high-speed, light-weight turbine motors with speeds of up to 100,000 rpm, replacing universal, commutator DC machines [3].

These inverter-fed brushless motor drives have much longer lifetimes (> 10,000 operating hours) than DC commutator machines (800 hours). In addition, high-speed machines have higher power densities; in other words, they are lighter and use considerably less materials. Dishwashers and washing machines (spinning up to 1,800 rpm) use variable-speed inverter-driven drive systems to save energy and water consumption. Furthermore, considering the fact that the rectifiers in electronics and appliances count for about 50% of the conversion losses and 60% of the power electronic costs, eliminating them improves reliability, and provides major cost and material savings. This can be realized when connecting all major appliances to a DC network. Note that material savings and extending the lifetime of components can also reduce in a major way the ecological footprint to produce all these apparatus and appliances. One can conclude that power electronic energy conversion systems are needed, not only to improve efficiency, but also to save materials, thereby reducing the ecological footprint. In this regard, one can ask the hypothetical question whether we would have sufficient resources to implement a 100% electrified world. Most discussions focus on the supply chain of rare earth materials, which are not rare on this planet, but are currently being supplied primarily from China, which leads to a single-source supplier. Rare earth materials are used to produce strong permanent magnets that are used, for example, in electric vehicle (EV) motors and wind turbine generators. However, based on our research, it is perfectly doable, without any loss of efficiency at the system level, to manufacture propulsion systems for electric vehicles and generators for wind turbines using electrical machines that do not use permanent magnets at all. In some drive applications induction machines, synchronous and switched reluctance machines are better suited than permanent magnet synchronous machines, because these machines can operate at higher speeds [4].

Already more than 20 years ago, falling prices of inverters have enabled manufacturers of large, multi-megawatt industrial drives to market effectively synchronous reluctance machine drives instead of induction or synchronous machine drives [5]. Today, for cost reasons, several EV car manufacturers are switching back to high-speed induction machines or switched reluctance machines, without any penalty on range. On the contrary, depending on the driving cycle, especially at high-speed driving, the more expensive permanent magnet machine requires reactive power, which consumes more energy. Hence, as a mass product, we anticipate that more drive systems in EVs will move to higher speed switched reluctance machines (above 30,000 rpm), thereby reducing mass and volume of the electric motor, which positively influences the range and reduces the power and material consumption for EVs. Last but not least, our research has proven that torque pulsations and noise issues of this machine type can be avoided simply by implementing proper inverter control algorithms [6].

This illustrates that power electronics is a key enabling technology that enables a major reduction of the ecological footprint of modern electrical drive systems. Hence, we are convinced that good engineering practice and proper design can cope with a dependency on rare earth materials. Looking at the mobility sector, we often get the question whether we can find enough lithium for the much-needed Lithium-ion (Li-ion) batteries for the transportation sector, in particular EVs. R&D over the past decades has led to Li-ion batteries that use less than 10% of the lithium as compared to first generation Li-ion batteries. Also, the amount of expensive materials, such as nickel and cobalt, which are needed in the production of some Li-ion batteries has been reduced and, in some cases, entirely eliminated. Tesla foresees another 50% cost reduction (down to 50 us$/kWh), not just by scaling up production, but mostly by continuously improving the entire battery pack production chain. With the currently high fuel prices and lower maintenance costs of EVs, total cost of ownership of EVs is already at par and even lower that of internal combustion engine vehicles. No doubt, this trend will continue and we can anticipate that within this decade prices of battery electric vehicles and trucks will become even lower than equivalent internal combustion engine vehicles.

In conclusion, worrying too much about rare earth materials, nickel, cobalt or lithium to electrify all sectors seems to be a diversion. What should worry us more is the price and availability of the best conductor material nature has provided to us, namely copper. In its 2019 report, the US Geological Survey predicted that, at the 2019 use and production of copper, we will run out of copper altogether by the year 2065 [7]. Already, despite a short fallback due to the war in Ukraine, we can see that the copper prices have practically doubled over the past five years (see Figure 8. 3). In its May 2021 edition on booming copper prices, The Economist declared that futures in copper would yield a higher return on investment than gold or platinum [8]. These are all signs that the world is using copper at an increasing rate, while its resource is limited.

Figure 8.3 LME copper prices, showing the steadily increasing stock price of copper [9].

Keeping in mind that the 2019 US Geological Survey report was based on copper usage that did not yet include the massive scaling up of EVs and heat pumps, the world will run out of affordable copper much sooner than the report predicted. Indeed, despite recycling ever more newly mined copper is needed to cover demand (18 Mt in 2019, 21 Mt in 2021). Actually, till 2019, only about 30% of the worldwide copper use was for electrical equipment. When we electrify all sectors, the use of copper will increase manyfold. Statistics show that 1,446 billion passenger cars are globally on the road. On average a battery electric vehicle uses about 90 kg of copper. Hence, electrification of all these vehicles, will require about 130 million tons of copper. Compared to the 2019 estimated global reserve of 830 million metric tons (Mt), this would indicate that by 2052 we run out of copper, assuming that copper use in all other sectors remains constant (at about 21 Mt per year in 2021).

However, we should be concerned also about the fact that about 1 billion people have little or no access to electricity, let alone the same mobility as we have in developed nations. If we are serious about reaching the climate goals globally, and prevent social unrest and massive migration, we have no choice but to electrify the entire world. In our opinion, this leads to some shocking conclusions with respect to the use of copper, both for the mobility sector and the global electrical grid infrastructure. In Europe, we have about 520 vehicles per 1,000 inhabitants. If the entire world, with about 8 billion people, would move towards the same mobility comfort, we need more than 360 million tons of copper. Assuming that this transition to EVs can be accomplished in 20 years, this could lead to a major copper shortage by 2042. Clearly, the electrification of individual mobility on a global scale as we know it is not a sustainable solution and alternative mobility solutions need to be found and implemented.

As we pointed out in the previous E.ON ERC Festschrift [10], the classical AC grid is constructed based on bulky 50/60 Hz AC transformers, which were invented and developed using knowledge and technologies that were available already more than 120 years ago. As shown in Figure 4. a classical 50 Hz distribution transformer uses approximately 2.5 kg of copper and Si-steel per kVA. Not including reactive power and the redundancy that is required in classical radial distribution grids, we use approximately 25,000 tons of copper and Si-Steel in transformers per GigaWatt (a GW equals one million kW) to bring the electricity from central power stations to end-users. About half of the weight of 50 or 60 Hz transformers is copper, which at present is also about 8 to 10 times more expensive than the Si-Steel. In developing countries, one can estimate that the peak installed capacity of power stations is on average approximately 1 kW-peak per person. For example, Germany has 80 GW of peak installed power capacity for about 80 million inhabitants. This number would increase at least two-fold if we depended on volatile renewable power sources and fully electrified all sectors, especially when heat pumps are installed for heating and cooling. Scaling up the installed capacity of developed nations and providing the same classical AC grid infrastructure to all people, including those that are still deprived of electricity, simple calculation shows that we require about 110 million tons of copper just for transformers only. Although this amount is of the same order of magnitude of a global five-year annual copper mining production output, combined with other sectors, such as the mobility sector shown above, scarcity of copper will occur well before the EU Green Deal is realized. At least, when we keep classical infrastructure solutions and markets as they are. Under these circumstances, even developing countries will not be able to afford the increasing cost of classical transformers and electrical equipment long before 2050. Even when we switch to aluminum as a conductor, which reduces the efficiency of transformers, the cost of 50/60 Hz transformers and operating them will increase significantly.

Figure 8.4 Dr. P.Joebges standing next to a 4,5 MVA, 50 Hz dry-type distribution transformer. With a total weight of 11.5 tons, 2.5 kg per kVA is needed (with permission).

Figure 8.5 E.ON ERC|PGS assistants preparing a 5 MW DAB for testing. A 5.0 MVA, 1,000 Hz dry-type transformer is used for galvanic isolation. With a total weight of 675 kg, 0.140 kg per kVA is needed (with permission).

Clearly, from a technical viewpoint, innovation is required not only for the distributed, volatile power generation plants, which are based primarily on wind and photovoltaic (PV), the energy storage systems and the automation (digitalization) at the consumption side, but also, more importantly, for the energy distribution infrastructure. At E.ON ERC and with our industry and academic partners of the Research Campus Flexible Electrical Networks (FEN), we have developed solutions, based on power electronics, that overcome these rising cost issues and material scarcity. At the same time, combined with digital control and low-cost communication systems (Internet of Things), the proposed solutions create more flexibility in the distribution grid, which enables more use of renewable power sources, increases capacity for charging infrastructure and electricity consumption.

In particular, with increasing use of power electronics in all sectors, we see the enormous potentials of DC technology in the transmission and even more so in the distribution grid. Over the past decades, we developed and demonstrated high-power density DC-to-DC converters for flexible DC electrical grid infrastructure in wind farms, PV systems, factories, building heating and cooling systems and fast charging infrastructure in the urban environment. What we learned is that at the same cost of power electronics, wind farms and PV parks can be linked to medium- and high-voltage DC grids, with smaller transformers, which at 1 kHz use about 15 to 20 times less copper and Si-Steel, as illustrated in Figure 8.5.

As shown in the previous Festschrift [10] and other publications [11], the capacity of DC transmission lines and distribution cables can be at least twice as high as those of AC lines and cables. DC distribution grids have the potential of dynamically rerouting power from and between low-voltage levels (e.g. charging stations) to the medium-voltage distribution grid, even the high-voltage transmission grid. Last but not least, DC grids favor underground DC cables, which require less space, can be integrated in or along existing infrastructure (highways, tunnels, pipelines, riverbeds, etc.). Therefore, we are convinced that the expansion of the electrical grid ultimately is not only more economic, but also socially more acceptable. Hence, in developed countries, with high population densities, DC transmission and distribution seems to be the only way to implement the EU Green Deal by 2050.

As mentioned, DC converters, i.e. so-called DC transformers, are the key component to realize flexible distribution grids in which the DSO can instantaneously store and route electricity to the points of consumption. DC converters can be seen as Edison's missing link to realize large-scale distribution of electrical energy. The invention of the AC voltage transformer back in the 1880s tipped the design of grids towards AC grids. Note, however, that large DC grids are still in use, predominantly in railways. However, DC power electronic converters can do more than just converting DC voltages. Indeed, topologies are available that are bi-directional in power flow, others provide galvanic isulation, and some can buck (decrease) and boost (increase) the output voltage with respect to the input voltage. One such circuit that combines all these properties is the so-called dual active bridge (DAB) DC converter, which was proposed in 1988 for the NASA space station project [12]. In particular, the three-phase variant of the DAB is proven to be most suitable for high-power applications, ranging from few kW to hundreds of MW. With the galvanic isulation, a modular design can be realized that extends further the voltage and power capacity of such DC converters, which is now being considered as the main building block of DC substations.

Over the past decade we continued the development of DAB-based DC converters and added many features that make the DAB converter suitable for grid applications. At E.ON ERC|PGS and ISEA, we developed model-based predictive control algorithms that provide dynamic stability under transient conditions, while maintaining zero-voltage switching (low switching losses) and precise voltage control. Furthermore, algorithms preventing saturation of three-phase transformers while compensating transformer asymmetries demonstrated and tested on 5 and 7 MW, 5 kV DC converters. In addition, recent work provided and demonstrated the fault-ride-through (FRT) capability of the DAB converter. FRT capability allows multi-terminal DC grids to be protected using DAB controls and low-cost disconnect switches [13]. This approach avoids expensive hybrid circuit brakers. Combining the multi-level modular high-voltage converter (MMC) with the DAB control concept led to the invention of a compact HVDC to MVDC converter for high-power DC substations. With today's power electronic semiconductors this substation could operate with 200 to 400 Hz transformers, which are 5 to 8 times smaller than their 50 Hz counterparts. As all three-phase DAB converters demonstrated with existing power electronics hardware, and since the medium-frequency three-phase transformer is commercially available, one can state that from a technology development viewpoint, the medium-voltage DAB DC converter for grid applications has reached a technology readiness level (TRL) between 7 to 8. In low-voltage applications, such as charging stations, DAB converters are already qualified and commercially in use (TRL 9).

Another aspect that supports the idea of DC distribution systems is the fact that such DC grids can be built as a private grid, i.e. outside the regulatory public grid. As the EU is supporting energy communities, DC private grids can be implemented between several prosumers, sharing the energy without feeding this energy (at low prices) in the public grid. Already in private homes, a so-called DC nano-grid is implemented when PV panels are linked via DC converters directly to a battery and heat pump. From here onwards, it is a small step to use DAB DC converters, which have galvanic isulation, to exchange DC energy to other users. A study at RWTH showed that the 5 kV/5 MW DC Research Campus Grid, designed and built by FEN partners (see Figure 8.6), can save energy costs to the amount that the infrastructure cost can be paid back in about three years [14]. Indeed, this Research Campus Grid effectively connects two AC substations of the local utility, i.e. forming a multi-terminal DC grid. Hence, it provides a path for a horizontal power flow in the distribution grid. As such, it has the capability to avoid peak loads at the individual substation. In addition, it provides a means to increase self-consumption and can feed, via the grid-side AC-to-DC inverters, much more power back into the AC grid when testing, for example, large engines, fuel cells and gas turbines. Energy that otherwise would be dissipated in resistive braking systems. Studies show that computer and data centers fed from DC grids need less cooling power (up to 30%) as the losses of grid-side power supplies can be avoided. Also, the multi-terminal DC substation concept provides a much higher electrical supply reliability.

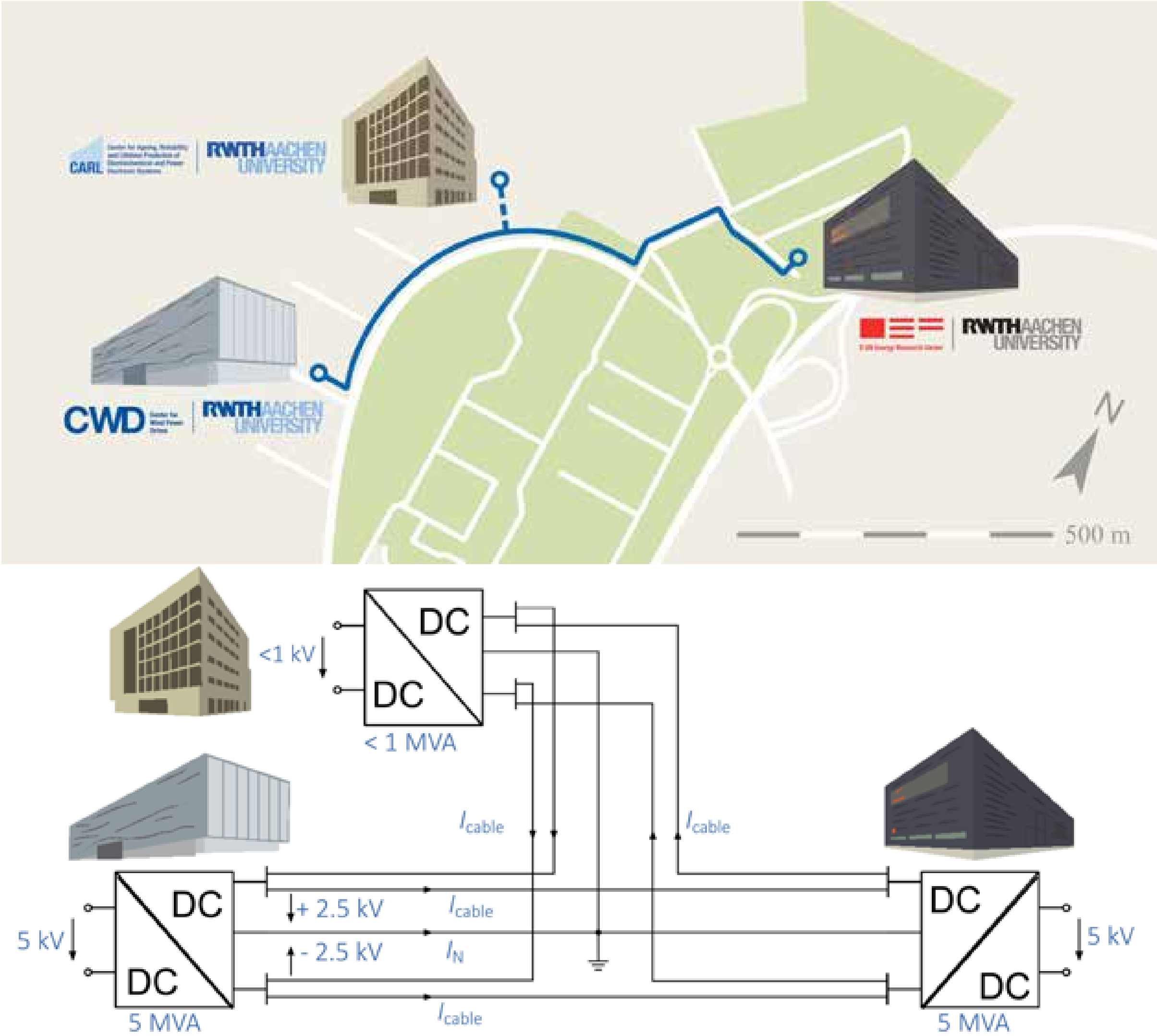

Figure 8.6 The RWTH 5 kV MVDC Campus grid connects the 4 MW Center for Wind Power Drives (CWD) with the 5 MW test hall of E.ON ERC|PGS. The bottom picture shows an elementary schematic. A low-voltage connection to the Center for Aging, Reliability and lifetime Prediction of Electrochemical and Power Electronic Systems (CARL), which has a 100 kW photovoltaic system and large battery test infrastructure, is planned. The MVDC can exchange energy between the centers, avoiding peak loads and decreasing the cost of operating them [14].

So, one can ask, why don't we have DC apparatus and a DC distribution grid already? What stands in the way to switch from AC distribution all the way to DC distribution? The answer is mixed. We see DC technology in several existing applications, some date back to the early 1900's. Among these are the aforementioned railway applications at 3 kVdc in Belgium, Spain, Italy and Russia. Also, the regional trains in France and the Netherlands use 1.5 kVdc overhead lines, while most metro systems, trams and trolley buses in the EU are at 750 Vdc.

What stood in its way in the past was the high cost of power electronic converters. However, over the past 25 years the cost of power electronics has dropped at least by a factor of 25. Thanks to the massive production of converters for wind turbines (estimated installed capacity more than 1.000 GVA) and PV inverters (estimated at about 750 GVA), already in 2015 the cost of a medium-voltage converter for wind turbines had dropped below the cost of a 50 Hz transformer. No doubt, looking at the materials used, the levelized cost of electricity (LCO) of the classical grid using 50 Hz transformers will increase due to increasing copper prices. In the long run, the LCO of wind turbines will continue to increase as next to copper large amounts of concrete and steel are used. On the other hand, the LCO of PV systems will continue to decrease as the base material it needs is sand, which is abundantly available, and electrical energy. The latter could ultimately come from PV. However, as wind and PV tend to balance to some extent their volatility, the amount of installed capacity of wind and PV must be carefully planned taking the cost of transmission, distribution and storage systems into account. Especially off-shore wind farms can benefit from innovations in the area of HVDC transmission and MVDC networks. Studies at RWTH show that off-shore wind farms using MVDC collector fields can substantially reduce their LCO as compared to the 50 Hz, 33 kV collector fields that are used today [15,16]. Also, newly developed HVDC to MVDC converter systems are promising to reduce substantially the cost of off-shore platforms that connect the wind farm to the HVDC cables.

These observations are confirmed in several recent publications and reports [17,18,19]. In [20| Hyosung presented its medium-voltage DC link for the South Korean Utility Company KEPCO in the Jeon-Nam province, which we were able to visit in December 2022. What we learned was that the main reasons why a +/- 35 kV, 30 MW MVDC was installed were not only lower cost and stability issues of the grid, but also the fact that the Korean AC distribution grid has a limited connecting power of 20 MW, which makes further expansion of renewable power sources (wind and PV) impractical.

Furthermore, novel niche applications are popping up. For example, individual home heat pump systems with PV and/or battery storage. DC charging stations that use a common DC bus. The project ALIgN in Aachen demonstrates a DC connection between two low-voltage transformers to provide fast-charging capacity to electric vehicles. Some car manufacturers already use DC distribution in their production facilities to charge batteries from large rooftop PV systems and recuperate the kinetic energy of robots and material transport systems. Hence, as more and more battery Giga-factories are being built, the so-called DC-factory is becoming a reality as they are economically and ecologically justifiable.

DC buildings are daily in operation at the campus of TU Delft and in Amsterdam (CIRCL building of ABN Amro Bank) [20]. To my knowledge, the Engineering Building of Seoul National University, South Korea was the earliest adopter to implement a full DC building (see pictures, Figure 8.7). These DC buildings are fully operational, using 350 to 380 Vdc protection circuitry and low-voltage USB or USB-c plugs throughout the building. From an energy viewpoint, these buildings are quasi-autonomous and show that present-day technology can provide self-sustainable energy solutions.

Figure 8.7 The 1970 Engineering Building at Seoul National University (top left), was completely remodeled in 2012 to become energy-efficient. It is equipped with a 36 kW-peak PV system (top right). Prof. S. Sul explains the 380 Vdc power line to which EV chargers, all electronic loads and the AC distribution system are coupled (bottom left). The 380 Vdc system is electronically protected and also has 380 DC circuit breakers (bottom right) (pictures taken by Prof. De Doncker, with permission of Prof. Sul).

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Chapter 9

Chapter 9 – Synthesis –The Way Forward at E.ON ERC and beyond

(all ERC professors)

Introduction

In the following, based on the preceding chapters, we offer several insights and conclusions from those as further 'food for thought' for the readers. Obviously, there are few easy fixes or strategies, but an overarching insight seems to be that interdisciplinary and integrated research – as it has been practiced at E.ON ERC already for the last sixteen years – is indeed a recipe for success in terms of a more holistic understanding of the issues at hand and possible solutions, but also to avoid single-sided and biased policy recommendations.

Chapter 2

- It is still a very long way to go towards (energy) sustainability, many trends are still pointing in the wrong direction (i.e. growth or stagnation instead of decline of non-sustainable energy supply and use).
- The energy trilemma needs to be revisited in light of digitalization and new issues emerging such as social justice and poverty.
- The diffusion of innovations in general, and innovative energy technology with new infrastructure in particular, tends to be a very time-intensive process that is slowed down by "exnovation" (i.e. getting rid of the legacy of existing technical systems and related infrastructure).
- The steeper the gradients for the energy transition and achieving net zero in 2050 become, the harder and risky it becomes to achieve the goals.
- Shocks (Covid-19, Ukrainian war, …) might, on the one hand, make it easier to unleash change but, on the other hand, priorities of policy-makers and society might change a lot as well.

Chapter 3

- In the second half, the costs of the energy turnaround will increase sharply for new generators but especially for infrastructure.
- Making energy demand more flexible is therefore becoming the key to the second half of the energy turnaround.
- A climate-friendly, but fair and technology-open market design is important for fair cost allocation, high cost efficiency and thus broad acceptance of the energy transition.

Chapter 4

- Large energy efficiency potentials still remain but are not always easy to exploit.
- Exergy considerations are paramount.
- Energy efficiency policies should be guided by social welfare considerations.
- Appropriate metrics for understanding the level of efficiency at larger system levels is still lacking (e.g., homes, factories, city quarters, regions) and uncertainties are particularly high. ERC has built up considerable knowledge on assessing energy efficiency potentials from different angles, and is in a unique position to advance the state-of-the-art in this field especially related to more sophisticated energy systems and extended system boundaries.
- The complexity of energy efficiency dynamics requires multidisciplinary approaches and research efforts, employing a mix of advanced methodologies and empirical analysis.

Chapter 5

- The transportation sector requires a significant transformation, prioritizing alternatives such as cycling and public transport, to meet climate policy goals. Even if the goal of 15 million e-cars on German roads by 2030 were reached, conventional vehicles would still make up two-thirds of the total.
- Hydrogen in fuel cell electric cars will play only a minor role in 2030. If we are using e-fuels and hydrogen, they should be used primarily in areas where each unit of electricity can efficiently be translated into CO_2 savings.
- In the realm of heavy goods transport, the crucial factors of range and fuel costs necessitate the consideration of both fuel cell and battery drives. Especially battery drivetrains are able to efficiently convert electricity into mechanical energy, but require charging hubs along motorways.
- Green fuels emerge as pivotal for both long-haul aircraft and large maritime vessels. In the case of coastal and inland shipping, including ferries, the feasibility of battery-electric vessels is already evident, contingent on the establishment of an effective charging infrastructure.
- The establishment of an adequate e-vehicle charging infrastructure, both public and private, is of utmost importance. Implementing cost-reflective pricing mechanisms can help alleviate congestion issues, while subsidies will remain necessary, especially in rural or remote regions and for fast-charging facilities.
- Anticipating 'miracle battery technologies' in the foreseeable future is not realistic.

Chapter 6

- The rapid addition of heat pumps and electric vehicles creates high consumption peaks in the electrical grid during cold winter days. These load peaks can only be covered by coordinating all consumers and a suitable design of all heat pumps and and storage systems. The Center is already working on advanced and fully dynamic bottom-up studies of local distribution grids. In addition, new simulation-based design methods for heat pumps and storage units are being developed. Improving the coefficient of performance at low temperatures also contributes to solving these high peak loads during cold winter days.
- Combined heat and power (CHP) will become more important in the future, especially in multi-family houses and in the commercial, trade and service sectors. The use of regenerative gases will increase continuously. Due to the outdoor temperature, the operation of these plants will be synchronized with the operation of many distributed heat pumps creating a more cellular energy system. By analyzing quatier concepts, the E.ON ERC can develop procedures for the optimal allocation and operation of these plants.
- Cold heat networks can make a significant contribution to the energy transition in metropolitan areas. To date, there is much uncertainty in the planning and operation of these networks, which prevents their rapid development. The E.ON ERC is working on computer-aided design methods and developing procedures for predictive operation of these cold heat networks. The procedures are also being extended to include new approaches taking hydraulic limitations in existing networks into account.

Chapter 7

- Open source is going to disrupt software development in the energy sector. Open source approaches are already a widely adopted solution in other sectors, while for energy we are in an early stage. At the same time, the growth of foundations such as the Linux Foundation Energy shows that there is a trend towards a change also in the energy sector. A massive application of open source solutions has the potential to speed up the digitalization process but also to disrupt the classical value chain. New actors will emerge and possibly substitute large providers of automation solutions in the energy sectors creating a much more dynamic environment where also start-up can more easily emerge with innovative solutions.
- New operational principles for power grids. Flexibility on the demand side is currently seen as the main tool to keep the network stable when operating with high presence of renewables. However, flexibility has a limit and it does not address the dynamic issues of power electronics driven power grids. In a futuristic scenario with up to 100% power from renewables, we should consider completely new operating principles. Research has already demonstrated new principles of operation inspired by the internet that may revolutionise the way we use the grid achieving completely new levels of infrastructure exploitation.
- Computing everywhere. The modern trend to develop system on chip more than classical microprocessors is opening up completely new opportunities of distributed computing capabilities. A growing role of the edge has already emerged as a trend, but now the presence of High Performance Computing everywhere could completely transform the way we think data management and data processing. In this sense the dual use of infrastructures (such as in the case of 5G) is facilitating deployment reducing investment costs.
- Quantum technology for new computing solutions and also secure communication. Quantum Computing is rapidly evolving opening unprecedented opportunities in terms of computing capabilities, but even more disruptive is the idea of an end-to-end quantum automation system where also communications are based on quantum technology and the full process of control and automation, from sensing to actuation, takes place in the new domain. This would open up the opportunity of a cyber-physical infrastructure that is intrinsically secure and not vulnerable to cyber attacks.

Chapter 8

- Power electronics are a key enabler to realize the energy transition. Power electronic converters are essential, not only to couple renewable power sources (wind and PV) to the grid, but also to control power flow and convert electrical energy in a usable format for end users.
- Nowadays, new wide bandgap semiconductor materials (SiC, GaN) are commercially available, replacing silicon based power electronic converters. These next generation power semiconductor devices enable tenfold higher switching frequencies, which increases the power density of power electronic converters. In particular DC-DC converters benefit form these devices as power densities up to 50 kW/kg have been demonstrated, as compared to 5 kW/kg for silicon based DC-DC converters. Hence, next to improved efficiency, lots of materials can be saved, which reduces cost and the ecological footprint of power electronic converters.
- Prices of power electronics continue to fall. Over the past 25 years, the cost of power electronic converters has reduced by a factor of 25 (from 500 €/kVA down to 20 €/kVA), to the point that power electronic three-phase inverters are cheaper than 50 Hz distribution transformers, of which prices continue to increase Also, the reliability of power electronics has improved significantly, which improves acceptance. In adition, power electronic converters can be built modular, which reduces production costs but also enables design of systems that provide redundancy (as is done in HVDC, aerospace).
- Low cost power electronics enables a new thinking on how to design collector grids for large scale windfarms and PV systems will take place. Similarly, DC distribution in data centers, factories, commercial buildings, city quarters, university and industrial parks are becoming the norm creating energy communities, which are not in the regulated public grid.

- Classical 50/60 Hz AC distribution grids require complex control to guarantee power quality (frequency and voltage control). On top of that, the distribution grid has a radial structure with lots of redundancy using open ring bus structures. Transferring power from one substation to another can only happen at the next higher common voltage level. Often this requires feeding power in the transmission grid, which leads to extra costs and may cause locally overload of the transmission grid. Horizontal DC connection between DSO substations create a so-called underlay grid, enabling energy transfer between medium- and low-voltage substations. This creates flexibility to provide power quality in the AC grid. At the same time, more renewable power sources and storage systems can be installed in the distribution grid, especially when these are directly coupled to the intermediate DC link between these substations. Several medium-voltage DC connection have been demonstrated and are currently in operation, for example, the 30 MW MVDC connection installed by KEPCO, South Korea.
- Electrification of all sectors and electrifying the entire world with classical 50/60 Hz AC grids is not sustainable. Per Gigawatt of active power transmitted from central power stations to end users, 25,000 ton of copper and silicon steel is used on transformers alone. To avoid "peak copper" by 2045, alternative solutions need to be found that either minimize or replace copper use. As almost all electrical appliances, motor drives, propulsion systems, battery chargers, PV converters, wind turbine drives, lighting, etc. are intrinsically using DC power, a shift towards DC technology, not only in transmission(HVDC) but also in the distribution system is unavoidable. Clearly, power electronic based energy systems are controllable, more flexible and offer lower capex and opex costs.

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