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Review and assessment of decarbonized future electricity markets

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Review and Assessment of Decarbonized Future Electricity Markets

June 2024

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Abstract

The electricity sector plays a key role in achieving zero-emission targets. The required transition will lead to substantial changes in the supply, demand, and distribution of electricity but also in stakeholder roles. Future market designs may change substantially to accommodate these changes, address challenges, and take advantage of new opportunities. This paper reviews the characteristics of future carbon-neutral electricity systems and electricity market design options. To provide a guiding framework for the literature review, we transfer the complexity of electricity systems into a three-layer structure: firstly, we analyze the papers that rely on techno-economic modeling of the *physical* electricity system. As a case study, we analyze various studies focusing on a decarbonized European electricity system in 2050. Secondly, we review papers that investigate the economic behavior and effects of self-interest-seeking *stakeholders* such as producers, network operators, and consumers. Finally, we review papers focusing on *policy and market design* questions that guide policymakers to achieve a target physical asset combination while considering the behavior of stakeholders. We highlight common trends and disagreements in the literature, review the main drivers of future markets, and finally provide a mapping between those drivers, challenges, and opportunities. The review concludes that the most promising next step toward a fully comprehensive assessment approach is to combine the existing approaches across topical and disciplinary boundaries.

Keywords: renewable energy, electricity market, investment, renewable support

JEL Classification: L94, Q4

1 Introduction

The whole energy sector is transitioning towards net zero greenhouse gas emissions. Several countries have announced pledges to achieve net-zero emissions. As of January 2024, 97 countries have communicated a net-zero target (see Figure 1). Even though more than 100 parties worldwide are yet to announce neutrality pledges, the parties with pledges represent 80.7% of global GHG emissions. Net-zero emissions pledges differ considerably in their timescale and scope. For instance, concerning sectoral boundaries, the Netherlands aims to achieve net-zero GHG emissions only in its electricity sector, and France, Portugal, and Sweden exclude international aviation and shipping. Concerning time scope, the majority of pledges target net-zero emissions by 2050. Companies have also announced net-neutrality pledges. For instance, 60-70% of global production of heating and cooling equipment, road vehicles, electricity, and cement are from companies that have announced net-zero emissions targets [1]. The energy sector is the source of around 75% of greenhouse gas emissions today; therefore, its decarbonization plays a key role in achieving zero-emission targets.

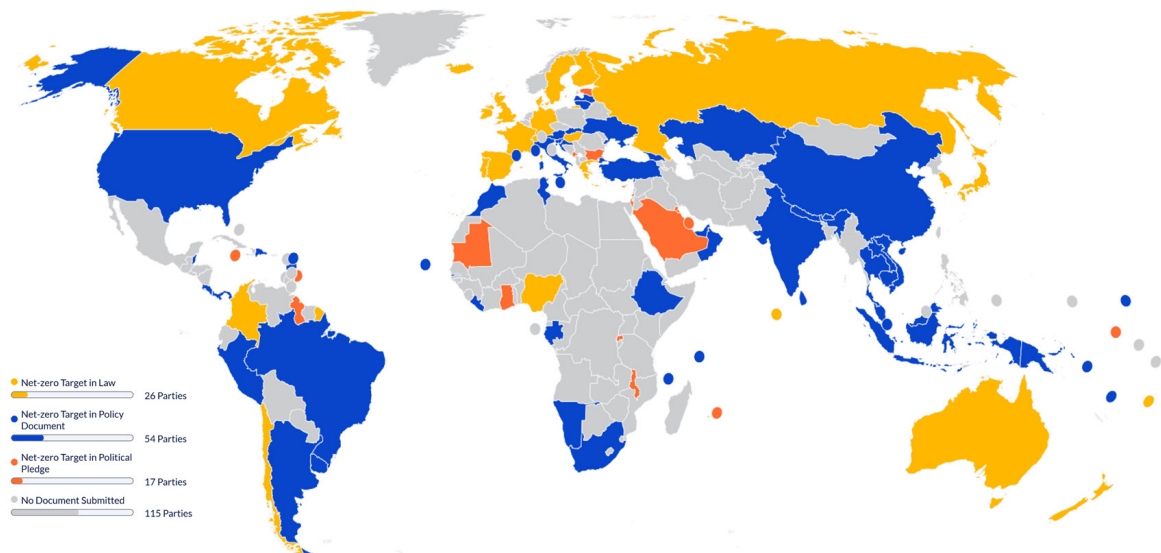


Figure 1. Countries with adopted net-zero target: (source: Net-Zero Tracker, World Resources Institute, at www.climatewatchdata.org/net-zero-tracker, status: January 2024)

Electricity markets play a crucial role in the future of the energy system. On the one hand, a large share of global electricity demand is traded via electricity markets or some competitive process. Currently, 40% of the global electricity demand is traded in fully competitive markets, while an additional 47% is being exchanged in a hybrid form of competition. On the other hand, electricity demand is going to increase in the future as decarbonization of energy subsectors is mostly envisioned via electrification. Not only the total energy consumption will increase by 2050 (mainly due to growth in non-OECD countries) but also the share of electricity in meeting total energy consumption may increase from 20% in 2022 to around 52% in 2050 in a net zero emission scenario [2].

Designing the future electricity market faces specific attention as it needs to address new challenges and can benefit from new opportunities. Future markets will experience substantial changes in supply, demand, and distribution structures as well as stakeholder relations. On the supply side, the share of renewable energy sources (RES) will increase considerably, which reduces the share of (fully) dispatchable plants. Moreover, while marginal costs mainly drive current markets, opportunity cost bidding may be the main driver of market outcomes in the future as the share of storage facilities and demand-side management increases. The supply (and storage) side may be considerably more decentralized if consumers become a major investor in RES capacities such as PV. Digitalization of the system (particularly the distribution grid and consumer side) allows for a more efficient supply decentralization and visibility for end-consumers. Accordingly, in future markets, the underlying challenge evolves from matching a few large power plants with a largely inflexible demand to effective coordination of intermittent RES with storage and demand-side flexibility options. Making all these changes work needs policy interventions; therefore, future market designs may differ substantially from current designs.

Even today it is already crucial to design electricity markets that are compatible with a decarbonized electricity system. On the one hand, investments today may have long-lasting effects due to their long lifetime. For example, coal power plants and transformers have a lifetime of between 30 to 50 years. Therefore, market designs for a decarbonized system should be explored in a forward-looking manner. On the other hand, to achieve net zero emissions by 2050, decarbonization of the electricity sector may need to be realized as early as 2035 in advanced economies and 2040 globally [1]. Indeed in 2022, the G7 group of most industrialized nations agreed to predominantly decarbonize their electricity generation by 2035 [3]. Moreover, in the EU, policymakers, practitioners, and academics are intensely discussing reforms in the electricity market to address the 2022 energy crisis challenges partially caused by the Russian invasion of Ukraine and high gas prices. The reforms address short-term challenges particularly because gas scarcity challenges may continue to arise in the coming years [4]. However, potential elements of such a reform should not be counterproductive to long-term decarbonization plans of the power sector and the required future market design adjustments [5].

Given this background, this paper reviews the characteristics of future carbon-neutral electricity markets and their design options. The aim is to not only facilitate the design of future carbon-neutral markets but also provide forward-looking guidelines for currently discussed market design adjustments. To provide a guiding framework for the literature review, we transfer the complexity of electricity systems into a simplified three-layer structure: the *physical* layer focus on physical assets and their technical aspects, the *stakeholder* layer represents the role of various actors in the system, and *policy and market* layer that captures regulatory, policy, and market design elements affecting the system. Firstly, we review techno-economic studies that focus on modeling characteristics of *physical* assets in the future electricity system, assuming a central benevolent planner optimally combines physical assets to minimize system costs. As a case study, we compare modeling approaches and findings in various studies focusing on a decarbonized electricity system for Europe in 2050. Secondly, we review papers that diverge from a

central planner perspective and investigate the economic behavior, role, and effects of different self-interest-seeking *stakeholders* such as producers, network operators, and consumers. Particularly, we review papers analyzing changes in stakeholders' landscape and roles. Finally, we focus on the *policy and market* design literature that guides policymakers to achieve a desired carbon-neutral combination of physical assets while ideally considering the behavior of stakeholders. We highlight common trends and disagreements in the literature, review the main identified drivers of future markets, and finally provide a mapping between those drivers and future challenges and opportunities. Finally, we provide areas of research that require further analysis.

The remainder of the paper is organized as follows: Section 2 explains the three-layer representation of the electricity market. Section 3 presents a review of the literature according to the three layers. In section 4, common trends and insights of the literature are summarized, and research gaps are identified. Section 5 summarizes and concludes the paper. The Appendix provides a short overview of the reviewed papers in section 3.1.

2 Structure and Determinants of the Electricity Sector

To provide a guiding framework for the literature review, we transfer the complexity of electricity systems into a simplified three-layer structure, as shown in Figure 2:

- The physical layer includes the technical aspects of electricity systems on the supply, transport, and demand side.
- The stakeholder layer captures the role and relation of the different actors in the system.
- And finally, the policy and market layer captures the wide range of regulatory, policy, and market design concepts and adjustments prevalent in electricity systems.

Naturally, the three layers are highly interlinked with policies and markets shaping actor behavior and investment and usage patterns of the system's underlying technology.

The purpose of this structure is twofold. On the one hand, it captures the intricate interactions within an electricity system and allows identifying how those are expected to change while moving toward a decarbonized future. On the other hand, the structure will shape the review process. By clustering the existing research insights along the layers, we will identify where common insights have already been derived, where diverging viewpoints are prevailing, and where research gaps still exist. We will define the three layers and elaborate on the interaction within and between the layers.

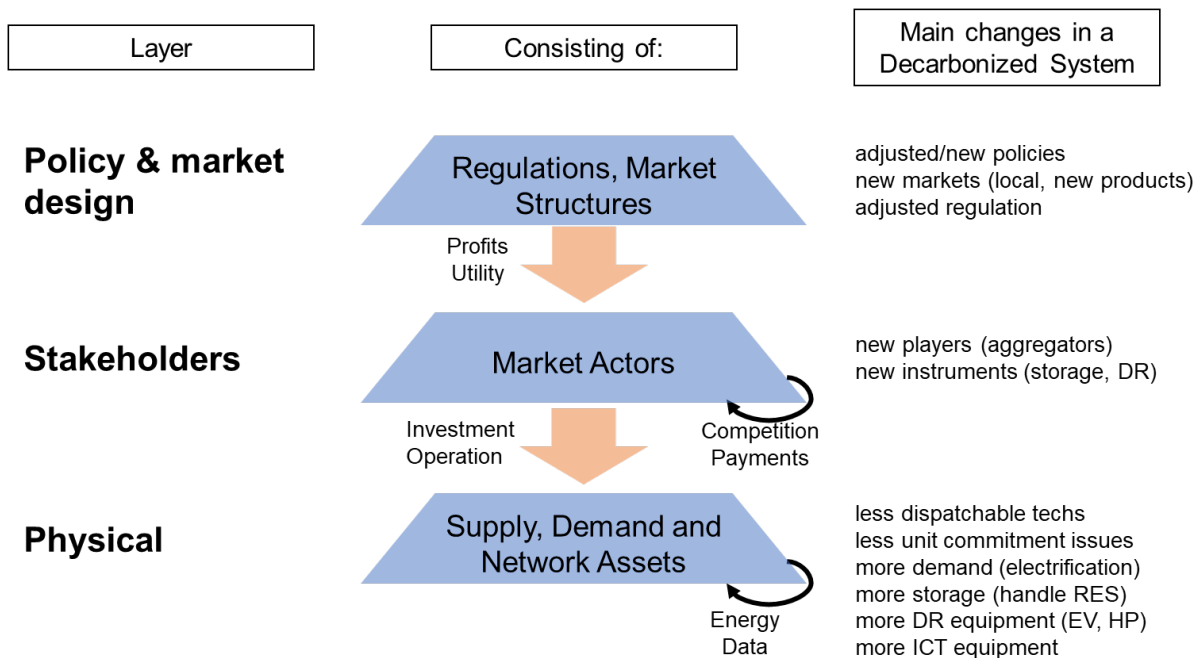


Figure 2. Three-layer representation of the electricity sector

2.1 Physical Electricity System Layer

Physical and engineering aspects play a crucial role in electricity markets as maintaining a balance between supply and demand requires a specific set of physical assets, which are usually categorized into the supply side, demand side, and network assets.

The *supply side* consists of diverse power plant technologies that significantly influence the system's overall affordability, adequacy, and stability. Across technologies, the plants' characteristics, such as investment/operational cost, GHG intensity, operational constraints, availability, dispatchability, capability to provide ancillary services (e.g., reactive power and inertia), and location in the network, differ greatly. With the transition towards a decarbonized electricity system, the existing fossil fuel and nuclear-based systems will be restructured, and new carbon-free technologies will need to enter the system; new renewables (wind, solar, biomass) are the most prominent new entrants. This will have important implications for managing system stability, as wind and solar generation is weather dependent and must be combined with other technologies. The altered mix on the supply side will also significantly impact the other physical dimensions of the system.

The *demand side* consists of a diverse set of consumers who gain utility from electricity and pay a price in exchange. Electricity consumption (in the short term) can roughly be categorized into inelastic/inflexible and elastic/flexible parts. Inelastic electricity demand is usually defined by external factors, e.g., production needs in a factory, opening times of stores, household activities, etc. On the other hand, flexible demand may partially reduce or shift its consumption subject to some constraints. With the expected emergence of new electricity demand due to a transfer of mobility and heating demand into the electricity sector – i.e., the electrification of energy demand – new flexibility options

could also enter the market. Similarly, a share of the currently inelastic demand might turn into flexible loads if regulations create incentives for the consumers.

Related to this flexibility development on the demand side are *storage assets* like pump hydro and batteries. They also represent an emerging technology placed in-between supply and demand. They can provide flexibility for the system by storing energy in times of surplus (i.e., when new renewable availability exceeds consumer demand) and releasing it in times of shortages. Consequently, they are similar to flexible shiftable loads in their system effect. However, storage technologies differ from flexible demand (and each other) in their short- and long-term efficiency. Moreover, while other supply technologies operate based on operational costs, storage technologies operate based on opportunity costs.

Finally, *electricity networks* in the form of transmission and distribution networks allow the transfer of energy from the supply to the demand side. Consequently, they will be impacted by changes on the supply and demand side, respectively. In addition, emerging digitalization (i.e., smart meters and smart grids) could also impact the planning and operation of network assets.

2.2 Stakeholder Layer

Stakeholders invest and operate the assets of the physical layer based on their respective individual incentive structures. Stakeholders try to achieve a goal (e.g., maximizing profits or utility) given a set of available instruments (e.g., the supply and flexibility technologies). Thereby they shape the composition of the physical layer while the policy and market layer shapes their incentives space and the interactions between the different actors in the system. Generally speaking, interactions of stakeholders owning the same type of assets (supply, demand, or networking) is usually more competitive. In contrast, interactions with other types of assets can be competitive as well as complementary in nature.

In the electricity system of the last century, the main actors have been energy utilities, regulators, and consumers. With the restructuring and liberalization of the electricity market, new actors emerged, especially on the supply and retail side. Concerns about market power abuse led to the split up of the regulated network assets from generation assets (i.e., unbundling). With the transition towards a decarbonized system and the expected electrification on the mobility and heating side, new actors will likely enter the system.

The resulting interaction of that new stakeholder mix will have significant implications for the overall system. The same physical assets can be operated differently if owned by different stakeholders. For example, a storage asset owned by an independent producer aiming for profit maximization will try to use the asset to shift its generation to the hours with the highest prices in the market and assign charging periods to the hours with the lowest prices. The same storage owned by a local household with its own PV generation aiming for an overall energy cost minimization will try to shift the potential supply surplus in sunny hours to any hours with a high demand surplus; none of those hours necessarily need to correspond to the high/low price hours on the market. Similarly, different operational incentives and

profits lead to different investment incentives for different stakeholders and will impact the ownership distribution of assets.

Consequently, not only will understanding the individual role of the respective system actors be crucial for assessing future electricity systems, but also their interaction and the bi-directional relation with the physical layer.

2.3 Policy and Market Layer

Electricity systems have always been subject to policy and regulatory interventions. Before the restructuring wave in the late 90s and early 2000s, most electricity markets in Europe and the US have been fully regulated. The restructuring process introduced more market-driven aspects, but an underlying regulatory framework (especially for the network) needs to be kept in place. In addition, renewable energy, energy efficiency, and environmental policies have been implemented in the last decades, leading to profound changes in the respective electricity systems. The desired decarbonization is expected to increase this development.

Policymakers can alter regulations and existing policies and introduce new policies to obtain specific political goals and steer (or at least influence) the behavior of stakeholders. Even when a policy's eventual goal is to influence investment or operation of certain physical assets, the policy needs to make effects through incentivizing stakeholders given that stakeholders are the entities investing and operating assets. In addition, the restructuring introduced a market dynamic that can, in theory, evolve itself through stakeholder activities (e.g., many wholesale markets in Europe have emerged as private trading platforms). However, policymakers still set general regulations and standards for market activities and define the conditions for the trade of energy and services.

Similar to the other two layers, there is a high level of interaction between the different elements within the policy and market layers. Given the multitude of political objectives besides decarbonization, the electricity system will likely remain subject to a diverging set of (potentially even conflicting) policies and regulations.

As the policy layer defines the maneuverable space for stakeholders, which, as described above, defines the composition of the physical layer, the interaction between all three spheres is important to assess the overall future system aspects properly. For example, given the respective technology options, consumers may choose between investing in storage assets and/or activating load flexibility. On the one hand, the technology costs given by the physical layer will be an important driver for the respective consumer decision. On the other hand, the implemented policies (e.g., specific subsidies) and market and tariff design (e.g., flat or variable household tariffs) can influence the cost-benefit assessment.

3 Review of Future Electricity Assessments

Given the overarching electricity system structure described in Section 2, we will review the scientific literature along those three layers and their interrelation. Following, we will provide an overview of 1) the different technology options, system combinations, and challenges researchers have identified on the physical layer, 2) if and how the role of existing actors will be altered, which new actors are expected to enter the system, and how those actors of the stakeholder layer are expected to influence the physical layer, and 3) which policies and market design options are investigated, and how they impact the overall system development.

3.1 Physical Electricity System Layer

In this section, we mostly focus on the modeling literature that aims to represent the physical state of highly decarbonized electricity systems. The technical physical feasibility of a highly or fully decarbonized energy system has been discussed extensively in the literature. Since 2004 more than 200 papers have analyzed the possibility of 100% renewable power systems. Studies in this field differ substantially in their geographical scope, investigated time horizon, the definition of allowed technologies on the supply side, and the included sectors modeled. Studies focusing on a single country are more common than global- or region-focused studies. Europe is the only region for which several transnational studies have been carried out on a broader and regular base. Several of the Europe-focused studies also model complementarities of renewable sources in North Africa. Studies may only focus on the power sector, consider the electrification of the transport and heating sector, or model the entire energy system. Some studies set a certain target time horizon. In contrast, others only show the feasibility of a 100% renewable power system for a given past weather year (e.g., [6] and [7]). To limit the extend, we mostly focus on studies analyzing the feasibility of at least 95% reduction of CO₂ emissions in Europe in 2050 to enable a rough comparability between the numerical results. However, we also complement the analysis of the results from those European studies with studies from other regions to highlight specific developments. A summary of the covered studies is presented in Appendix; please refer to [8] for a broader literature.

3.1.1 Electricity generation

On the supply side, the studies differ substantially on both modeled technologies and their shares (Figure 3). However, as one common exterminator, all decarbonized scenarios rely on a mix of *PV and wind* on their supply side. Across the investigated studies, those two technologies cover a share of 70% or more on average. In the most optimistic case, their share goes up to 92% of the total generation [9]. Nevertheless, the distribution of generation between PV and wind sources can differ drastically from one scenario to the other: ranging from settings with almost three times more annual wind energy than PV (PyPSA– heating scenario in [9]) to settings with almost 50% more PV generation (Regions scenario in [10]). In most scenarios, wind turbines have a higher share than PVs. Some studies exclude offshore wind from their analysis as their cost projections seemed uneconomical (at the time of running the

respective studies). Some of the studies also report aggregate values for onshore and offshore generations. Among those with separate reports, offshore wind is in on average in the range of 33% of onshore wind generation. The most optimistic scenario for offshore wind depicts around 70% higher generation from offshore wind compared to onshore wind (PLEXOS- High demand scenario in [11]).

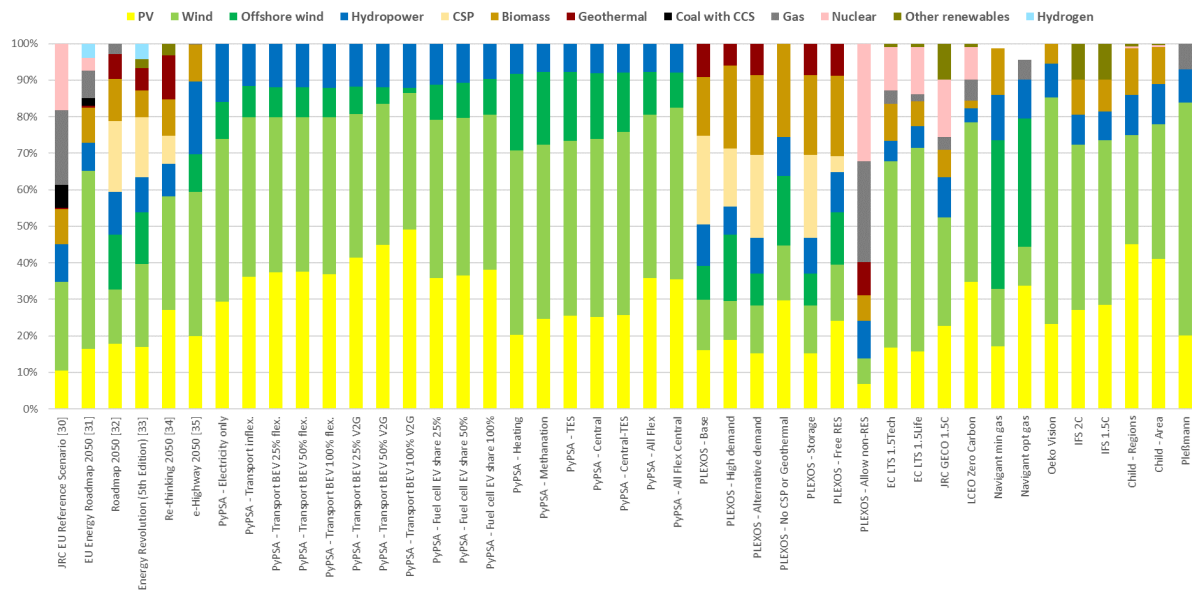


Figure 3. Technology generation shares of the European decarbonization studies.

In a decarbonized power system, the residual demand not supplied by variable RES must be met by other carbon-neutral technologies (e.g., hydro, biomass, nuclear, etc.) or storage assets (e.g., hydro-pumped storage). **Hydropower** is the other renewable technology available in all considered scenarios. Even though hydro's share technically varies between 4% to 19%, in absolute terms, hydro generation in 2050 is around 470 TWh per year in most scenarios, indicating limited growth compared to current values. In fact, several scenarios exogenously set the hydro capacity of 2050 equal to their latest actual values arguing that limited untapped dam hydro potential remains in Europe. As a result, other complementary technologies should be invested in by 2050.

Biomass is treated very differently in the studies. For instance, [9] do not consider biomass, given concerns about the sustainability of fuel crops. In contrast, [11] consider biomass as the only remaining dispatchable RES technology that can be installed in significant quantities. On average, the biomass share is around 6% but can go as high as a quarter of generation (PLEXOS - No CSP or Geothermal scenario in [11]). In scenarios with a high share of biomass, other dispatchable renewable technologies (geothermal or concentrating solar power, CSP) are rarely used as biomass can provide peak capacity. **Geothermal and CSP** deployment for electricity supply is limited in many scenarios. The highest share of CSP (24% of total generation) is provided by a scenario with an exogenously given CSP capacity (PLEXOS - Base scenario in [11]). Geothermal is excluded in many scenarios due to its assumed low

potential and/or cost-effectiveness for electricity generation. The highest share of 9% is assumed in the scenario Re-thinking 2050 in [12].

The power sector does not necessarily phase out all *fossil-fuel*-based plants from its mix. Even though coal is phased out in all decarbonized scenarios, gas plants are still active in nine scenarios. In a scenario with cost-competitive CCS with a 100% capture rate (PLEXOS - Allow non-RES in [11]), gas power plants are supplying 28% of total generation in Europe. However, many studies explicitly rule out the usage of CCS technologies by arguing that CCS is not a sustainable solution as it represents a high-cost, high-risk option on economic, environmental, and social grounds (e.g., see [8]).

Most studies explicitly removed *nuclear* generation from the generation mix, arguing that their social acceptance issues and cost structures would not allow for new investments. Of the highly decarbonized scenarios, only four include nuclear with a share of 10% and up to ca. 32% (namely, PLEXOS - Allow non-RES, EC LTS 1.5Tech, EC LTS 1.5Life, and JRC GECCO 1.5C).

Beside the specific technology shares, the studies also differ in the overall assumed generation level. The modeled generation varies substantially from 3'000 TWh up to 10'000 TWh, with the majority being in the 4'000 to 6'000 TWh range. In comparison, the total net electricity generation in the EU was around 2 800 TWh in 2018. Given that the geographical scopes of the modeled countries are relatively comparable across the studies, the variation stems mainly from the modeled sectors, i.e., electrification, the extent of electrification, and storage options. For instance, while PyPSA's "electricity only scenario" requires a total generation of around 3'000 TWh, including electric vehicles increases the generation to around 4'000 TWh, assuming fuel cell vehicles using electricity-based fuels, the total required generation increases to around 5'000 TWh [9]. Furthermore, and finally including the electrification of the heating sector increases total generation to 6'000 TWh. The amount of energy storage also affects the total generation. For instance, Navigant's optimal gas scenario relies on around 2'500 TWh of generation from PV and wind to be exclusively used for green hydrogen generation (as storage), which contrasts with Navigant's minimal gas scenario assigning only around 500 TWh to green hydrogen generation [13].

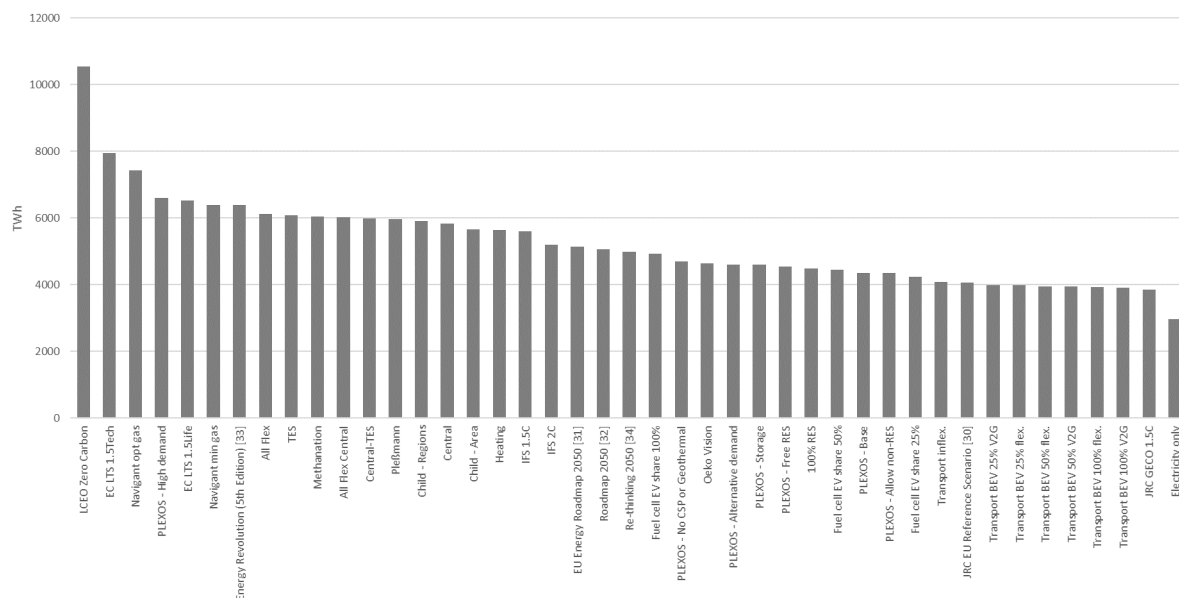


Figure 4. Total generation of the European decarbonization studies

3.1.2 Storage technologies

Storage plays a role in all scenarios, but capacity developments differ by technology. For pumped storage hydro, most studies explicitly assume that the existing capacities in Europe remain constant over time because power plant potentials are exhausted. The other storage technologies show a wide range. For example, [9] model battery storage technologies in several scenarios, which leads to installed capacity varying from 15 to 1340 GW. [13] finds seasonal battery storage an unrealistic option even at strongly reduced investment costs for batteries. Instead, they suggest using a higher production of green hydrogen and gas power plants to lower system costs. [11] include 80 GW of compressed air energy storage in one of its scenarios.

[14] review several earlier studies on energy storage requirements and concluded that battery requirements differ depending on whether the renewable generation is dominated by wind or solar energy; i.e., for Europe and the US, at variable RES shares of over 80%, the required battery capacities are 1.0–3.0 TWh for PV-dominated grids and 0.2–1.0 TWh for wind-dominated grids. Readers are referred to [15] to review approaches for representing energy storage in long-term electric sector models.

3.1.3 Electricity Demand

On the demand side, the analyzed scenarios differ on total demand, modeled sectors, the approach of electrification, and flexibility. Several studies focus only on the conventional electricity demand. However, decarbonizing the whole economy most likely involves *coupling the transport, heating, and electricity sector*. As a result, total electricity consumption may double compared to current conventional demand levels.

The scenarios that include the *transport sector* differ mostly in the type of vehicles modeled (i.e., battery electric vehicles (BEV) and/or fuel cell vehicles (FCEV)) and the level of flexibility added to the electric

system. While transport itself is mostly assumed to be independent of power system conditions, BEV's electric consumptions follow different patterns depending on the charging behavior modeled by the scenario. Some of the studies assume that transport-related electricity consumption is fixed and treat it as another inflexible demand (e.g., [11]), while other studies take into account the charging behavior of BEV (e.g., [9]). In an inflexible or instant charging approach, the BEV owner charges the vehicle regardless of the power system conditions, potentially instantly after making a journey and getting access to a charging station. Consequently, the charging pattern looks like a lagged transportation profile (an example of which is shown in Figure 5). This can lead to a significant increase in peak demand (e.g., as reported by [9], from 459 GW to 659 GW).

Taking advantage of the flexibility provided by batteries in BEV can significantly reduce overall system costs. Figure 5 illustrates that smart charging allows shifting at least part of the demand from peak hours to off-peak hours, such as late-night hours or weekend days with lower consumption. In the assessment of [9], allowing for a 25% flexibility BEV level reduces system costs by 10% compared to an inflexible setting. However, the marginal benefits of increasing the flexibility decrease with a higher level of flexibility, leading to only a 14% cost reduction in a 100% flexibility scenario. Some scenarios consider the possibility of cars charging back to the grid, known as vehicle to grid or V2G, which provides extra flexibility for the system by providing huge amounts of extra batteries to the grid. In the case of having 100% V2G BEV, the power system may need no battery storage capacities in 2050, and investments in PV can increase as the large battery capacities help shift noon PV generations to peak hours [9].

In scenarios with FCEV, a part of the transport fleet is substituted with vehicles based on fuel cells consuming hydrogen, which provides a different layer of flexibility to the system. In addition, hydrogen may be used as seasonal storage to handle seasonal PV and wind generation fluctuations. However, the total electricity demand increases since the required energy conversion processes required for FCEVs (electrolysis process with an efficiency of around 80% and fuel cell conversion of hydrogen to electricity with an efficiency of around 60%) is higher than that of more efficient BEVs (with battery charging and discharging efficiency of around 85%). [16] analyze the effect of parked and grid-connected hydrogen-fueled FCEV on balancing the system in 100% renewable electricity energy systems of five European countries for the year 2050. Their results show that only in a few hours of the year, 26 to 43 percent of FCEVs are required, particularly in energy systems with high shares of solar energy.

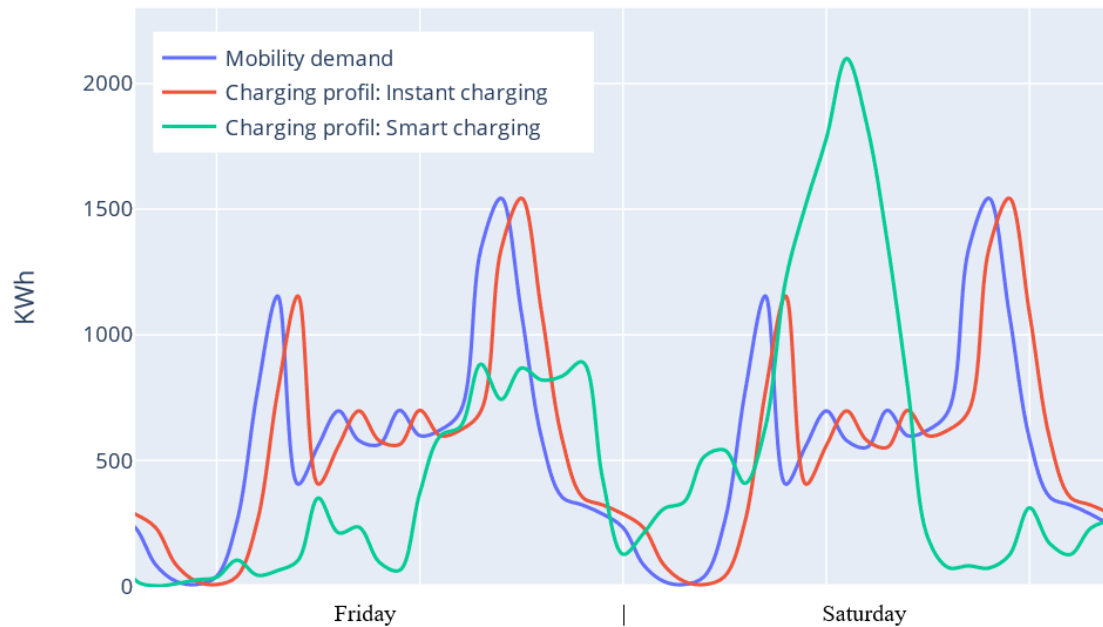


Figure 5. Transport demand of electric vehicles in a working day (Friday) and a weekend (Saturday) for a week in 2040 from [17] and derived BEV charging profile in instant charging and smart charging approaches

The scenarios that model the *heating sector* differ mostly in the amount of consumption needed and the flexibility added to the electric system. Similar to the transport section, some studies simply assume a fixed total electric heating demand and treat it as other inflexible electricity consumptions (e.g., [11]). On the other hand, some scenarios consider a more detailed model of the heating sector accounting for different heating technologies and flexibilities. For example, [9] assume heat demand is driven by temperature (space heating) or rather constant over the year (hot water) and consequently independent of the electricity system. However, the total level of electricity depends on the respective heating technology. In addition, [9] also model thermal energy storage.

Given that heating demand peaks in winter, electrification of the heating sector typically favors wind generation compared to PV generation due to wind's higher winter availability. However, the effect may fade away if long-term thermal energy storage becomes economic because the summer PV surplus may be transferred to winter [9].

3.1.4 Network

Most of the studies neglect distribution networks, account for transmission networks in a simplified manner, and assume the existence of data networks. Most studies model transmission networks via externally defined net transfer capacities (NTCs) between countries or regions. For example, [18] assume NTCs between regions equal to a fixed percentage (15% or 40%) of the overall installed capacity of the corresponding region. EU Reference Scenario 2016 [19] assumes NTCs will increase in the future due to planned grid reinforcements and improved market coupling that leads to NTCs being close to the physical capabilities of cross-border lines.

On the other hand, [10] also allow for network capacities to be optimized. They analyze two scenarios: no interconnection between countries and optimal interconnection capacities; leading to almost four times higher capacities than today. [9] also include a scenario with optimal increased interconnection capacities using an NTC approach.

In contrast, [11] use a ‘center-of-gravity’ approach to model transmission flows between countries, with the urban-area-weighted centers of each country serving as nodes. They allow for new transmission capacity investments. They also include extra grid reinforcement costs in the case of investment in wind and PV technologies, which are estimated by calculating the shortest transmission distance (across either land or sea) to the nominal load center. The optimized additional transmission grid reinforcements (on top of the reference capacity of 60 GW) range between 2 GW to 416 GW. In the scenarios with *exogenous CSP capacity* in the Iberian Peninsula, reinforcements range from 321 GW to 416 GW, as the transmission corridors must be significantly reinforced to bring CSP generation to the rest of Europe. Only 2 GW of reinforcement is built in the *Allow non-RES* scenario due to the lower variable RES capacity. Allowing cheap storage in the *Storage* scenario leads to 10 GW (3%) less transmission reinforcement.

Studies on distribution grid aspects are usually limited in their geographical scope and do not provide a full electricity system assessment. However, [20] show that spatial representation of transmission is crucial while assessing the ability of energy storage to defer transmission investments. Moreover, networks dominated by photovoltaic energy call for more storage, while large shares of wind rely more on transmission capacity [14]. It should be noted that grid interconnection alongside storage systems can play an important role in stabilizing power systems [21]. Overall, long-term planning models typically have a limited representation of interregional transmission and distribution systems.

3.2 Stakeholder Layer

The large-scale optimization models of the previous section basically neglect stakeholders. They are designed as cost-optimal problems akin to a benevolent central planner [22], representing the “what could optimally be achieved with a given technology set” logic. In this section, we focus on papers investigating the role and behavior of the different actors in electricity systems. Those studies usually focus on one or a few stakeholders and do not cover a full system perspective. They can be both conceptual in nature (i.e., understanding the general behavior of an actor) or qualitative (e.g., modeling the future investment/usage pathway of an actor). To maintain comparability with the insights on the physical layer, we will structure this section along the same supply, storage, demand, and network value chain pattern and complement this structure by including insights on the role of exiting and the emergence of new actors.

3.2.1 Actor representation on the supply side

On the supply side, the stakeholder literature mainly focuses on investment-related aspects. To understand the role of different stakeholders, the following questions are of particular relevance: i) what

decision-making criteria or objective functions are accounted for, ii) how risk and uncertainty are accounted for, and iii) what choice variables and overall system environment and developments are assumed. In addition, also the respective modeling and assessment tools are of relevance.

Many studies model the investment behavior of investors based on the classical *net present value* (NPV) approach. NPV quantifies the current value of an investment considering the investment costs and future profits of an investment option discounted with the interest rate (e.g., the weighted average cost of capital). The approach may be suited to for-profit-oriented companies as well as cost-minimizing actors. This approach can take the form that only the technology with the highest NPV is constructed based on the NPVs for various potential available technologies [23,24] or that investment into all technologies with a positive NPV is possible [22]. The expected future profits of an investment or a firm can be based on the historical returns of the same (asset) type. Instead, it may also account for the new investments' impact on the resulting market prices and quantities [24]. On the discount rate, the studies differ not only on their average discount rate (e.g., 5% in [24] and 8% in [23]) but also on whether investors have equal discount rates and if discount rates vary over time. For instance, [22] compare a case with starting 10% interest rate for all investors versus a case with a heterogeneous discount rate with a uniform distribution between 4% and 20%; plus, investors' discount rates may vary over time based on the investor's average profitability of their asset portfolio.

Although most studies use a deterministic setting or imply risk-neutral behavior, several studies investigate *decision-making under uncertainties* and risk aversion of investors. One approach to account for risk aspects is to use risk-adjusted discount factors while calculating the NPV of different firms; i.e., firms that find the future less risky use a lower discount rate than firms with a higher risk perception. Another approach is to assume that investors make their decisions based on a concave utility function to represent that risk-averse firms gain a higher utility from taking the expected value of a "lottery" than from taking the risky lottery. A third approach is to use mean-variance (or modern portfolio theory) to model diversified investment behavior; i.e., investors aim to maximize their expected (mean) returns while maintaining a maximum level of risk (e.g., the variance of returns) [23]. Regarding the importance of risk, [23] compare investment behavior in electricity markets with and without risk aversion. They show that investments in peaking technologies decrease with increasing risk aversions, affecting the system's capacity adequacy.

Regarding the respective choice variables of investors, the *available technology set* is one of the most important ones. Several studies assume firms specialize in one specific technology, e.g., conventional technologies, peak technologies, a certain type of renewable energy sources, or storage. In contrast, others allow firms to invest in multiple technologies, which enables firms to use complementarities of several technologies.

Another distinction in the studies is the level of market *competitiveness*. Many studies assume a perfectly competitive market setting with firms as price takers. Other studies assume that some firms can exercise market power and affect market prices by withholding capacity investments and/or withholding generation. For example, [25] shows that the existence of market power distorts market

outcomes in systems with conventional and storage technologies. Storage firms overinvest if conventional firms exercise market power because the higher market prices in peak hours (due to withholding generation) increase the profitability of arbitrage for storage. In contrast, the storage firm underinvests if it has market power because then the storage owner smooths its storage decisions over time to avoid a strong price reduction when it sells and a strong price increase when it buys. [26] show that if an incumbent with dispatchable technologies invests in RES, it substantially reduces generation from its dispatchable technology to keep the market price high for both its conventional and RES generations.

Regarding the mathematical *model approaches* used for investigating investment decisions, most studies apply optimization, equilibrium, and simulation approaches [27]. Optimization models are well suited if one entity, e.g., a firm, tries to optimize a desired value, e.g., profit. The large-scale system models of the previous section are usually designed as cost minimization or welfare maximization of a social planner. However, such a central planner system outcome may also be “decentralized” to profit-maximizing firms; e.g., [28] shows that in a market economy with free entry and price-taking actors, the socially efficient decarbonization plan of a social planner can be implemented by profit-maximizing firms using environmental taxes. Equilibrium and simulation models explicitly consider independent profit maximization firms with the distinction that equilibrium approaches use traditional mathematical programming frameworks (i.e., Cournot [29], Stackelberg [30], or supply function equilibria [31], while simulation approaches are suitable if the considered problem is too complex to be solved via equilibrium models. Simulation models generally rely on solving for the behavior of actors sequentially (e.g., one by one), which simplifies solving the problem and allows for more detailed modeling of actors’ behavior and relations (e.g., [32] assume that investors make investment decisions in a randomly determined sequence). Simulation models that allow for a more dynamic behavior can be categorized as agent-based models, allowing agents to learn from past behavior. Readers are referred to [24] for a more detailed review of agent-based modeling approaches.

3.2.2 Representation of storage actors

Even though storage is expected to play a crucial role in future decarbonized electric systems (see Section 3.1.2), the literature on the economics of electricity storage and the assessment of storage actors is relatively sparse [33]. [33] consider the case of a profit-maximizing speculative investor in grid-scale battery storage using a dynamic general equilibrium framework. They show that grid-scale storage can smooth out market prices if the supply is volatile enough to generate incentives for storage speculators to invest in storage capacity in the first place. [34] consider the interactions between Lithium-ion batteries and power-to-hydrogen-to-power (noted as “H2”). They first show that in a perfectly competitive setting, the social optimal system result can be obtained via profit-maximizing suppliers for each technology, even when accounting for the limited energy capacity of energy storage and ramping constraints for dispatchable generations. Secondly, they show that for the case of a deeply decarbonized “Texas-like” power system, going from a looser to a tighter emission constraint leads to a 5-fold increase

in the optimal energy storage capacity of H₂. [35] use a stylized open-source model to show the role of electricity storage and other flexibility options for integrating variable RES. They show that relatively high shares of variable RES are achievable with moderate amounts of electricity storage. However, the role of long-term storage increases significantly as the variable RES share approaches 100%.

As with the supply side, market power can also play a crucial role in storage investments. As mentioned above, [25] analyze firms' incentives in the presence of market power, allowing for strategic behavior in storage and/or production. They also highlight the role vertically integrated firms with market power in storage and generation can play in future systems. [36] use Cournot-type competition with varying levels of market power to study a 100% renewable market with elastic demand and storage. They argue that in the absence of storage, the price would be determined completely by the demand side, as renewables have zero marginal cost. In contrast, in the presence of storage, prices are determined dynamically by demand and intertemporal storage decisions, breaking the static logic of "merit order" with dispatchable generation. Using numerical simulations, they show that such dynamics lead to "price plateaus," as it is optimal for the storage operators to adjust their rate of charging or discharging so that the price remains constant for some time.

3.2.3 Actor representation on the demand side

Compared to traditional consumers, the future electricity system is expected to have a more active demand side. With the emergence of new technologies, consumers can more easily adjust their load levels and invest in local supply options and storage technologies. Consequently, consumers in a decarbonized system will have more freedom in choosing their respective objectives, ranging from economic to environmental interests and social concerns.

Consequently, the representation of electricity consumers has also become a growing field for researchers. Roughly speaking, future consumers in a decarbonized electricity system can take one of the following forms: i) inflexible consumers (like traditional consumers), ii) flexible consumers, iii) prosumers, or iv) prosumagers. While the traditional demand assessment was mostly focused on estimating load levels given a set of external drivers (i.e., season, daytime, temperature, etc.), the latter three types all require a more economic-oriented analysis to translate technical potential and options into specific consumer behavior.

Flexible consumers use smart management systems to adjust the amount and/or timing of their flexible loads, such as electric vehicles and heating systems. The potential for demand-side flexibility is thought to be significant [37]. For instance, according to the International Energy Agency [38], the global flexibility potential in 2040 can be around 9'276 TWh (with building, transport, and industry/agriculture sectors covering 6'221, 1'551, and 1'504 TWh, respectively). Most of the flexibility literature focuses on residential and tertiary buildings, as they represent about 40% of global energy consumption [39]. Furthermore, buildings have several energy systems that can be controlled to provide demand-side flexibility services, namely heating, ventilating, and air conditioning [31].

Prosumers (*producer and consumer*) are grid-connected energy users that have invested in distributed renewable generation units (most likely PV) in their domestic environment whose surplus generation may be traded with the grid or interested energy customers [40]. Therefore, they represent a direct linkage between the supply and demand sides and one central aspect of the potential for decentralization that comes with the emergence of small-scale renewable energy options. Finally, *prosumagers* (*producer, consumer, and storage*) also own storage assets that can increase self-consumption or provide an additional source of demand flexibility [41]. Besides the network dimensions, those consumers link all relevant value chain elements into one deciding entity.

Instead of maximizing their utility (or minimizing their energy costs), consumers may seek several objectives when becoming a prosumer or prosumager. With the recent decrease in the leveled cost of PV and storage and the expected further decline in the coming years, the question of investing in those technologies naturally has a strong economic dimension. Depending on the electricity tariffs consumers face and support policies in place, investing in PV or storage assets can lead to lower and/or less volatile electricity costs compared to grid-based consumptions [42]. In addition, consumers may invest in renewable energy to address environmental concerns or as a climate change mitigation measure [43]. For example, a consumer may invest in PV and batteries to reduce generation from other sources that they find environmentally unfriendly, e.g., nuclear or fossil-fuel plants. Consumers may also invest in PV and storage because they are partially driven by their preferences for locally produced energy and for being at least partially self-sufficient [44].

In addition to the individual consumer perspective, their potential cooperation has become a research focus. A group of consumers, prosumers, and prosumagers may create a cooperative to maximize total self-consumption, reduce energy bills, optimize community welfare [45], increase comfort and environmental benefits, or extend the chance for electricity market participation [46]. This is not just a theoretical concept, as evident by the increasing number of local energy cooperatives; for instance, since 2006, 835 local energy cooperatives with 200,000 private members have been founded in Germany [47]. In the academic literature, consumer cooperatives are analyzed under different terminologies such as “citizen energy,” “community energy,” “energy communities” [48], and “prosumer community groups.” Also, microgrids usually link strongly to such cooperation [49].

Consumers can form cooperatives using legal frameworks that different regulators have recently proposed to account for cooperative actors. For example, on the European level, the ‘Clean energy for all Europeans’ legislative package defines two cooperative types: ‘renewable energy communities’ (REC) and ‘citizen energy communities’ (CEC) [50]. Both are legal and autonomous entities based on voluntary participation and are controlled by shareholders and members, which can be residential consumers, small and medium-sized enterprises, or local authorities. The primary purpose of these arrangements is to “provide environmental, economic or social benefits” for their members “rather than financial profits” [41]. They differ with respect to their technology set (REC only allows for renewable technologies) and geographical scope (REC requires members to be nearby the owned projects). Albeit

only a recent example, it nevertheless shows that the prospect of energy communities can play a significant role in decarbonized electricity systems.

The behavior of individual and collective actors has been extensively studied in the literature. For example, based on an experiment on prosumer with demand-side management [51] find that oversizing the storage hardly increases self-consumption while demand-side management becomes more important in settings with low storage capacity, and vice versa. [52] use a model-based analysis to show that combining 0.5–1.0 kWh of storage capacity per kW of installed PV capacity can increase self-consumption by around 13–24%. [53] simulate PV self-consumption for households in various EU countries and find that, without batteries, self-consumption varies between 30% and 37%. This rate increases with PV and battery sizes, but full autarky would require excessive oversizing of both the PV and the battery systems. Moreover, the profitability of prosumage heavily depends on the provided indirect subsidies of the regulatory environment via tariff design. Similarly, [54] argues that PV energy storage systems may, from a consumer perspective, continue to be economically inferior to PV systems without storage even in case of decreasing storage costs due to the comparative over-proportionally cost reduction of PV.

Most research on the new consumer types is focused on the respective actors. Studies investigating the interaction with the overall system while accounting for a more detailed stakeholder representation are scarce. For example, [10] integrate prosumers' behavior into a large-scale decarbonized sector analysis. For the sake of simplicity, they fix the share of prosumers' demand to be 20% of total demand and allow up to 50% of total excess generation to be fed to the grid, which is reimbursed at a fixed rate. They show that in the presence of prosumers, the remaining grid consumption and peak load are reduced by 17% and 6%, respectively. In contrast, [45] take into account that tariffs paid by consumers may be adjusted by the retailers. They use a game-theoretic approach to model the interaction between the retailer and households as a Stackelberg game. They show that under the considered regulatory framework, the deployment of community energy storage can increase the retailer's operational profits while improving the alignment of the community energy system with the signals from the electricity market.

Finally, the linkage between the often-more-technical-oriented microgrid literature and consumer representation is showcased by [55]. They demonstrate the performance of machine learning algorithms in managing the operation of a community battery storage system in a microgrid environment.

3.2.4 Network companies

While supply, storage, and demand side actors are mostly assumed to act in a (more or less) competitive environment, network operators will remain regulated. The modeling approaches in the physical layer section that account for network aspects assume an optimal system behavior on the network side. However, distribution system operators (DSOs) and transmission system operators (TSOs) are either profit-maximizing firms subject to state regulation or other forms of state-regulated entities (e.g., independent system operators in the US). Therefore, TSOs and DSOs' behavior depends directly on the corresponding regulatory constraints, which do not necessarily need to align with optimal system

structures. For example, [56] show that if incentive regulation provides network operators with strong incentives for cost efficiency, they could forgo network investments that have no immediate cost reduction effect. This naturally also links to the broader literature on regulatory economics and incentive regulation (e.g., see [57] and [58]).

The literature investigating electricity network actors more directly can roughly be structured in two blocks: i) the interactions between regulated entities (e.g., TSO and DSO) and ii) a regulated entity and a competitive entity (e.g., TSO and generation investor). Regarding the former, the role of future flexibility options is of concern. In future markets, the share of flexible resources that can actively be controlled in the distribution grid will increase. Given that both TSOs and DSOs can benefit from such flexible resources, they may compete for them. TSOs could use these resources for frequency control, voltage control, or congestion management, while DSOs could acquire flexible resources for local congestion management and voltage control [59]. Therefore, the need for increased cooperation between DSO and TSO is widely recognized in the literature [60–62].

For example, [63] analyze DSO-TSO interactions under three alternative coordination schemes: a) a co-optimization problem where an integrated market operator activates jointly resources connected at transmission and distribution levels, b) a shared balancing responsibility that assumes bounded rationality of TSO and DSOs which act simultaneously and is formulated as a non-cooperative game, and c) a decentralized leader-follower setup which considers a DSO that can anticipate the clearing of the transmission market by the TSO. They show that the decentralized coordination schemes are more profitable for the TSO and that rational expectations from the DSOs give rise to a last-mover advantage for the TSO. On a more method-related note, SmartNet [64] develops a simulator for TSO-DSO interactions over large-scale transmission and distribution networks allowing nodes to provide complex bids for their flexibility activations. For a broader review of TSO-DSO markets coordination mechanisms in a decarbonizing system, readers are referred to [65].

Regarding the interaction between regulated and competitive market aspects, the literature focuses on the interplay between network investments and market dynamics and the (partial) complementarity of transmission and generation assets. Even though the academic literature explored the option of allowing merchant investments that refinance via congestion rents [66,67], in practice, the increasingly important task of investment in transmission capacity has remained with regulated TSOs. Consequently, network investment plans and their underlying regulatory nature are crucial for detailed long-term scenarios (i.e., ENTSOE's Ten-Year Network Development Plan). On the strategic interplay between TSO and suppliers, [68] develop a theoretical Cournot game with strategic behavior of a generation company and a transmission company and apply it to a three-bus system. [69] analyze the interplay of transmission and storage investments in a multistage game. First, the TSO chooses optimal line investments and a corresponding optimal network fee. Afterwards, competitive firms trading energy on a zonal market with limited transmission capacities decide on their optimal storage facility investments. They show that such interactions may yield inefficient investments in storage, which may be accompanied by suboptimal network facility extensions compared to the nodal pricing benchmark. Readers are referred

to [70] for a recent review on the co-planning of transmission and generation expansion in a market environment.

3.2.5 Old actors, new actors, and aggregators

As is evident by the presented studies above, the supply side follows, by and large, the traditional assessment aspects focusing on investment. While the technology options are changed for a decarbonized electricity system and the role of uncertainty and risk increases, the main actor focus is still on companies carrying out those investments: incumbents and new entrants. Similarly, the emergence of storage alters the profit formulation, but for large-scale storage, the focus is still mostly on companies, either classical energy utilities or newly independent storage suppliers.

However, on the demand side, the existing actor setting is assumed to change significantly with the transformation toward a decarbonized system. The formerly passive demand side is seen as an important contributor to flexibility, and, as shown in Section 3.1.3, it will undergo significant changes due to the increased mobility and heating demand. Consequently, the role of consumers is seen quite differently compared to the old electricity system. The emergence of new types of consumers and their cooperation represents a significant development that needs to be accounted for in future assessments.

Related to this demand side development is the potential emergence of another class of actor: flexibility aggregators. Similar to retailers providing energy for several consumers by bundling their load and being active on the wholesale markets, aggregators could also bundle consumers' flexibility. An aggregator, in this sense, is a private company that connects consumers (prosumers and prosumagers) with power system participants who aim to supply these consumers or exploit services and flexibilities provided by the consumers [71]. Unlike consumer alliances, aggregators may be profit-maximizing entities. Demand aggregators are already active in several European countries, such as Belgium, Finland, France, the UK [39], and Germany [72]. The share and importance of aggregators could increase substantially as the share of distributed energy sources, batteries, and flexible demand will increase. Moreover, the European Clean Energy Package allows market participants such as "independent aggregators" to become more active in the markets in a non-discriminatory manner [73].

The business model of aggregators consists of trading their clients' flexibility to one or more actors through market mechanisms or bilateral contracts. The aggregator can participate in frequency regulation services, help solve grid congestions by selling flexibility to TSOs and DSOs or help balance the supply-demand portfolio of retailers or other balance responsible parties. The aggregator could operate outside the conventional chain of energy supply [39], or it can be integrated into a retailer/utility activity [71]. For example, in Europe, some retailers act as an aggregator since they offer special tariffs to consumers that can shift a part of their consumption when necessary [39].

Aggregators may outperform individual consumers/prosumers because they can benefit from economies of scale and manage risk better/differently. Economies of scale are well documented in the information and communication technologies industry, which are prerequisites for participation in market bidding and receiving control signals [74]. Moreover, fixed transaction costs may be associated with

participating in a market. Regarding risk management, larger aggregators usually have access to hedging products, e.g., contracts for difference [74].

[75] provide an overview of aggregators' role and modeling in electricity markets. Aggregators could interact with the market through bilateral transactions or participation in market bidding. The latter has been analyzed in the literature using mathematical methods such as stochastic optimization approaches [76–78], robust optimization approach [79,80], and information gap decision theory [81].

3.3 Policy and Market Layer

The stakeholder literature shows that self-interest-seeking entities can lead to system outcomes that differ from what is centrally optimal, which was the main focus of the models focusing on the physical layer. Stakeholders do not act in a vacuum but in a framework of markets, policies, and regulations. Those provide operational and investment incentives and shape the outcomes in both the stakeholder and physical layers. Therefore, in the following, we focus on the policy and market design literature that considers the behavior of stakeholders. Note that there will be a natural overlap with the previous sections. In particular, the policy-related literature has a lot in common methodologically with the stakeholder literature, as it usually also focuses on the policy impact on one or a few stakeholders and does not cover a full system perspective or, if so, only in rather general structures. We will again structure this section along the supply, storage, demand, and network pattern to maintain comparability across the layers.

One policy field strongly related to the literature described below is naturally the realm of climate policies. As the objective of this review paper is to focus on future decarbonized electricity markets, some form of climate policy is a given requirement. Most electricity related assessments assume some form of carbon price in the future. As such, we will not review this particular policy field in detail. Interested readers are referred to [82], [83], and [84].

3.3.1 Supply

Supply-side-oriented literature is mostly focused on market functionalities and focuses on investment aspects similar to the stakeholder literature. Following we will structure the literature along two main lines: short-term and long-term market adjustments. Short-term market policies target incremental changes to current short-term markets, such as spot markets, to handle the challenges of highly renewable systems. On the other hand, long-term policies aim to introduce side markets to face the challenges of future systems using RES auctions, capacity remuneration mechanisms, or other new long-term solutions.

3.3.1.1 Short-term market adjustments

Short-term market adjustment can address some of the challenges of future power systems with high shares of intermittent renewables. One aspect relevant for most European markets is the missing representation of *grid congestion* on the wholesale market layer; all producers and consumers of a certain geographical area see the same market price. As a result, later adjustments in the form of re-

dispatching are required. An increase in variable renewable production patterns can lead to significant shifts in the network load over time. Increasing the locational granularity of markets and adopting a locational marginal pricing (or nodal pricing) approach can help to address this challenge, as already widely applied in the US [85]. To avoid redistributive effects among consumers, nodal markets may limit the nodal component to the supply side while consumers still pay an average price. If full nodal structures are not feasible, policymakers can apply market coupling approaches such as flow-based market coupling to better represent network constraints in zonal-based markets. [86] compare nodal and zonal pricing production efficiency using numerical methods. They show that, compared to the nodal pricing approach, zonal pricing with available transfer capacity (ATC) results in large production inefficiencies due to the inc-dec game. However, a zonal market with flow-based market coupling (FBMC) improves the transmission network's representation and mitigates the inc-dec game.

Besides the locational resolution of markets, the *temporal resolution* can also become more impactful. Policymakers and market participants may want to increase the market's temporal resolution to handle RES fluctuations [87]. Even though RES generation can vary significantly in sub-hourly time scales, hourly clearing resolution is the most common time resolution in European day-ahead markets [88]. Energy markets that consist of short-dispatch intervals (e.g., 5-minute dispatch intervals) match variations in RES generation and demand more economically and reduce the required levels of regulating reserves needed [89,90].

The profitability of RES may also be increased by adjusting the *general market design* and providing more revenue options for renewable generation and flexibility providers; e.g., specific support measures for flexible resources, market coupling to increase participation in neighboring regions' markets, allowing one-sided energy bids in balancing markets, late gate closure time, frequent intraday markets, scarcity pricing, and increasing the price cap to the value of the lost load, VOLL [90,91]. Such measures can impact market prices as they increase residual demand or allow technologies with higher marginal/opportunity costs to be price setters, allow better management of uncertain production, and provide higher profits during shortages [90].

3.3.1.2 Long-term market adjustments

Long-term aspects are mostly concerned with investment incentives and whether a renewable dominated system will require continued support for renewable or back-up/storage capacities.

Given that renewable energies are expected to be the backbone of the future system, and current renewable shares are still rather low, *RES support policies* are a main theme in the scientific literature. Most of today's renewable capacities rely on some sort of support. Despite drastic cost decreases and occasional bids in auctions requiring no support (e.g., offshore wind in Germany [92]), the majority of researchers and policymakers are in favor of continuing support for RES in the next few years [93]. Feed-in tariff (FIT) and feed-in premium (FIP) policies have been prominent RES support mechanisms in the last two decades; currently, however, procurement auctions are the most rapidly spreading policy for supporting renewable energies [94]. *RES auctions* are expected to allow regulators to steer the renewable support policy more effectively because regulators can set the target renewable expansion

and the generation mix ex-ante [95]. Of course, this is contingent on the full realization of investments from the auction winners. However, one of the main acknowledged risks in auctions is the risk of non-realization, i.e., when awarded bidders do not realize their RES investment [96]. A rapidly growing literature analyzes the design of RES auctions as the success of auctions depends mainly on their design details [97]. For instance, the effects of first-price versus second-price auction designs [98], national versus regional auctions [99], and prequalification, penalties, and the grace period on realization rates [96,100] have been analyzed. The effects of the remuneration choice on risk exposure and bidding behavior have also been qualitatively analyzed [101,102]. [103] explore whether lessons learned in RES auctions may be applied to cost-effective energy storage procurement.

The future of RES auction support in a highly renewable and decarbonized market requires further research. The RES profits obtained in future decarbonized power systems depend on the overall market and policy framework, and whether auctions are required for support will need to be investigated by defining the remaining system conditions. [104] generate qualitative scenarios for future electricity systems to analyze renewables' future viability and how auctions might evolve over time. They argue that the status quo model of RES auctions is unlikely to be the dominant route after 2030. However, the RES auction could grow in importance in the form of private, municipal, or community tenders for power purchase agreements (PPAs). They argue that regulators will still need to play a role in the future, whether in the form of standardizing auction models and contracts or directing geographical density.

One of the main topics in research and policy debates is whether an energy-only-market (EOM) market design (i.e., only wholesale energy and balancing markets) is sufficient for long-term investment refinancing or whether *capacity remuneration mechanisms* need to be implemented in addition. Particularly, if markets have a price cap below the value of lost load (which is usually the case due to political reasons [23]), EOMs may suffer from a 'missing money' issue that reduces the potential earnings of peak load power plants. On a related note, the 'missing market' issue occurs when generators cannot hedge their investment risks through futures and contract markets [105]. Both missing money and missing market lead to underinvestment into generation capacities by stakeholders. Therefore, to improve generation adequacy, capacity remuneration mechanisms are designed to incentivize investments by offering capacity providers income on top of the energy markets [106].

Capacity remuneration mechanisms differ on the parameter fixed by the procurer (volume vs. price), the nature of the volume being procured (market-wide vs. targeted technologies), and the procurer (centralized procurement vs. bilateral arrangements with load-serving entities). The strategic reserve is the most common mechanism in the EU, in which a central entity procures a pre-determined capacity from plants. The capacity is only utilized in the case of shortages, and they are otherwise prohibited from participating in the energy market [107]. [108] use an agent-based model to analyze the effectiveness of a strategic reserve. They conclude that with high penetration of RES, the reserve design should be adjusted or replaced by an alternative mechanism. [109] use an experimental setup to show that markets with a high price cap as well as capacity markets effectively cure underinvestment by preventing load shedding. Unlike the majority of related analyses that assume risk-neutral investors for

the sake of simplicity [110], [111] use a real options approach to assess the effect of capacity payments on timing and the amount of investment in gas-fired power plants by risk-averse investors. Using a numerical study, they suggest that with a high share of RES, capacity payments are required to incentivize peak-load investments. [112] use a system dynamics simulation model to compare an EOM, a capacity market, and a strategic reserve mechanism. They show that risk aversion may reduce the reliability of an EOM, and the capacity market may lead to higher social welfare.

Nevertheless, [105] argues that if all the investment risks are transferred to consumers in capacity mechanisms, regulators and investors have lower incentives to manage and reduce the risk efficiently. [113] use an agent-based model to analyze the cross-border effects of capacity mechanisms, with Switzerland as the case study. They conclude that the planned market design changes in the neighboring countries of Switzerland may decrease investments in Switzerland. However, Switzerland requires no capacity mechanism as generation adequacy is still guaranteed due to the high Swiss hydropower storage capacity. The readers are referred to [110] for a review of capacity market design.

Some researchers explore options to design *long-term markets that work in parallel with short-term markets* (also called hybrid markets). Part of the market design literature suggest that current market designs, in form of EOM markets with various ad hoc policies, are not sufficient to ensure security of supply and deep decarbonisation of energy systems in the most cost-effective and timely way (see e.g. [114] and [115]). Instead, hybrid market designs should be used to partially disentangle long-term investment decisions from short-term operations using a balanced and differentiated use of competitive and regulatory design elements to coordinate and de-risk investment [116]. Such a mechanism may be implemented via various frameworks. For instance, [117] argue that complex sensitivities of market outcomes to RES quantities, locations, and mixes make it challenging for short-term market prices to alone promote an efficient decarbonized energy mix with RES and the required complementary technologies. [118] proposes a design in which a central planner runs targeted procurement auctions to determine the portfolio of local resources needed to assure resource adequacy by supporting the capacity of the right types and in the right places in the grid. The auction winners are those resources with the least-cost and best-fit portfolio. [119] proposes an approach in which a central planner minimizes the cost of the whole system (including transmission constraints and for several weather combinations) given bids from developers. The proposed market runs every 3 to 5 years and offers each cleared project a long-term hedging contract, structured as a swap with load, in which the project receives a performance-adjusted stream of fixed revenues based on its as-bid levelized cost.

[120] lays out principles for an electricity market cascade that relies on a derivative market design. In the long-term market, long-term energy schedules are bought, improving existing long-term bilateral contracts by increasing liquidity and transparency. The market aims to minimize the procurement cost through a “default dispatch,” which short-term markets take as a baseline for real-time operation.

[121] proposes two long-term markets based on long-term financial contracts imposing fixed prices for energy based on a specified fixed hourly production profile. In particular, a supplier submits an hourly profile (e.g., by the hour of day and month of the year) and the total annual production. A market clearing

mechanism connects bids with the highest system value to buyers in the long-term market. Accepted supply bids commit to providing payments to the buyer based on the real-time electricity price. If the supplier underproduces, it owes buyers more than it received from selling its production into the market. In contrast, if it overproduces, it can keep any additional revenue. None of the papers provide numerical simulations for their proposed market designs. Although these proposals have similarities with existing forward/capacity markets, they focus on incentivizing specific attributes needed in the future decarbonized, highly renewable resource mix.

3.3.2 Storage

Storage technologies are naturally impacted by both supply and demand side policies. Nevertheless, policymakers may design storage-specific policies. [25] argue that the positive externalities provided by storage, such as facilitating renewables integration, improving supply security, and reducing the need to invest in peak generation technologies, can justify specific policy intervention. Support policies could be in the form of procurement targets (to require utilities to acquire a specified quantity of energy storage), regulatory adaptation (to create opportunities for energy storage), demonstration programs, financial incentives in the form of subsidies or tax credits, and prosumer protection by establishing certain rights for customers who install energy storage [122].

Several studies have analyzed the economics of storage technologies from a system benefit or social welfare perspective. [123] and [124] show that in the absence of positive externalities, perfectly competitive markets induce the socially optimal investment in storage with no policy interventions. However, [25] show that the presence of market power distorts storage decisions (operation and investment), eventually increasing costs and consumer payments. [125] uses a stylized equilibrium model to analyze generation and energy storage interactions. He shows that adding perfectly competitive or strategic storage can reduce social welfare if the generation sector acts strategically.

3.3.3 Demand

Demand-side-oriented policies and regulations can roughly be structured along three lines: i) energy efficiency policies aiming at reducing the overall energy demand, ii) tariff design and the respective incentive structures for consumers as well as the linkage to DSOs and utilities, and iii) flexibility market-related policies. The latter also links to the broader relation of the demand side with system and network aspects. The emerging field of consumer cooperation adds to those three fields but remains limited in its extent so far.

3.3.3.1 Energy efficiency policies

Energy efficiency policies may lead to overall cost savings by reducing the energy efficiency gap, which is a deviation between the theoretical socio-economic level of energy efficiency and the existing level. Literature is rife with empirical studies that analyze the effects of previous and current energy efficiency interventions, including behavioral programs, subsidies for efficient appliances and energy savings, product standards, etc. [126]. Energy efficiency policies are expected to continue to play a role in

shaping future electricity demand. For example, the European Commission has published a proposal to adjust the ‘Directive on Energy Efficiency’ to introduce a binding target for reducing primary (39%) and final (36%) energy consumption by 2030 at the EU level; a part of which focuses on electricity consumption. [1] suggests that efforts to achieve climate goals should essentially include a push to increase energy efficiency. Furthermore, energy efficiency policies typically have more political support than policies that directly aim to limit emissions.

Many studies on interaction of electricity markets and future energy efficiency levels assume exogenously-determined energy efficiency progress. However, [127] include energy efficiency measures in an optimization model as investment options with several cost classes and potentials. Moreover, [128] develop a framework to implement short-term demand response and investments in energy efficiency in detailed partial equilibrium power market models. They show that in an 80% emission reduction target in the EU, energy efficiency contributes 11% of carbon emission reductions. They also measure the effect of such demand-side policies on supply-side investments. They show that compared to a scenario without short-term demand response and energy efficiency investments, 180 GW less gas capacity is needed in 2050.

3.3.3.2 Tariff design

Another set of regulations that directly target consumers are tariff designs. Tariffs play a central role in future electricity market policies since they affect consumers’ choices on investments and consumption usage, generation, and storage technologies. Tariff rates are designed to raise enough revenue (for financing grid and electricity-related support costs) and achieve economic efficiency (minimize deadweight loss) and equity as much as possible. Those principles of tariff design face challenges in the future electricity markets, particularly with possibly high penetration of distributed generation and prosumers [129]. For instance, traditional tariffs may not be equitable enough. Flat rate per KWh tariffs lead to transfers from the wealthy to the poor because the wealthy had to pay more, given that electricity consumption was correlated with wealth. However, prosumers have lower total consumption even though they are usually wealthier [130]. Therefore, [131] argue that tariffs based on volumetric charges and single metering are not cost-reflective and potentially lead to cross-subsidies and propose bi-directional metering as an alternative. Similarly, [132] compare net metering with dual metering (net-purchasing), advocating for the latter’s usage to create more accurate price signals to synchronize consumption and production and avoid cross-subsidization from consumers to prosumers.

[133] proposes that to support decarbonization tariffs should be a) mostly based on 3- or 4-season time-of-use rates (if possible real-time pricing) and b) be less dependent on demand charges applied during off-peak hours. [134] use a simulation-based methodology to analyze the effect of different tariff designs on system costs and the share of prosumers. They consider volumetric, capacity, connection point, and time-of-use (TOU) tariffs. Results indicate that volumetric tariffs lead to significant and rapid deployment of PV panels and batteries. However, they lead to substantial inequalities in the electricity costs as in these cases the economic burden of maintaining the network is mostly carried by remaining consumers. Moreover, if the tariff includes capacity fees, the deployment of PV panels and batteries

slows down and inclines the balance toward more batteries. [129] use per-minute data for 144 households in Austin to analyze the effect of increasing-block pricing, flat rate, TOU, real-time pricing, and capacity-based tariffs. Results show that traditional tariff designs allow for large wealth transfers to prosumers from consumers that may pay a median of 22% more than their fair share. On the other hand, TOU and real-time dynamic pricing lead to lower cross-subsidization and better economic efficiency. While demand elasticity does not significantly alter their conclusions for fairness, it significantly impacts those for economic efficiency.

3.3.3.3 Flexibility policies and markets

As already elaborated, flexibility will likely play a crucial role in future electricity systems. Policy interventions may be required to build up and maintain this flexibility. For instance, the EU's Clean Energy Package requires DSOs to take advantage of flexible resources by integrating them into both planning and operation tools using market mechanisms to select the most efficient resources. The main stakeholders involved in "flexibility markets" are TSOs, DSOs, balancing responsible parties (responsible for managing imbalances of a given entity), consumers and their aggregators, and retailers that buy electricity for their customers. Flexibility markets should be designed to facilitate TSO's balancing efforts, TSO and DSO's congestion and power quality management, and supply-demand balancing, among other things [62]. Even though there exist several flexibility market initiatives (e.g., in Europe, there are already at least 18 flexibility market initiatives such as ENRA¹, NODES², and GOPACS³), local procurement of flexibility is still a developing concept [135]. Several policy and regulatory barriers still need to be resolved to enable the full operability of flexibility markets. For example, market designers should clearly define who performs tasks such as prequalification, settlement, and market-clearing processes [136].

TSO-DSO coordination is one of the main prerequisites of a well-functioning flexibility market [62]. Therefore, policymakers' intervention is necessary as both TSO and DSO are regulated entities. Moreover, the provision of data networks (smart grids) and allowing participation of aggregating firms may also need policy interventions. Readers are referred to [137] and [62] for reviews on the design of flexibility markets and products.

3.3.3.4 Energy alliances

There is still a lack of studies focusing on the regulatory frameworks for cooperative consumers and prosumers [138]. The Council of European Energy Regulators [139] highlights that the regulatory framework should ensure that energy communities do not contradict existing market principles (e.g., unbundling and cost-sharing of the energy grids) or limit consumer rights (e.g., supplier switching). Regulatory frameworks should provide a level playing field for energy communities by removing their growth barriers and preventing them from causing undue market distortions. If energy communities are

¹ <https://projekt-enera.de/>

² <https://nodesmarket.com/>

³ <https://en.gopacs.eu>

allowed to own the grid, regulatory frameworks should prevent the duplication of assets, ensure economic efficiency, ensure customers receive an adequate service quality.

[138] provide a cross-country comparison between nine European countries and conclude that key barriers for energy communities are regulatory. [140] provide an overview of the current and emergent energy communities' business models and their key growth barriers. They conclude that to overcome the barriers and attract private funding, effective incentive policies and flexible regulatory frameworks should be designed to allow the pursuit of different business models. While most of the literature analyzes regulatory frameworks qualitatively, [141] provide a numerical model to study regulatory frameworks based on feed-in tariffs, net metering, and the self-consumption scheme.

3.3.4 Network regulation

As already presented in Section 3.2.4, most of the literature on network-related policy choices is embedded in the regulatory economics literature and investigates different incentive regulation approaches [142–145]. Similarly, the above-described tariff design questions and flexibility markets strongly relate to the DSO regulations.

One particular market aspect of electricity networks is the role of interconnections between different countries/zones and the related import/export aspects. Interconnections can increase the security of supply (due to the ability of the interconnected markets to share secure generation capacity) and reduce system costs (due to having access to more efficient sources and taking advantage of the geographical diversity of RES generation) [146]. Similarly, local renewable potentials and production patterns can be better utilized with sufficient exchange capacity [147]. Naturally, this extends the general regulatory nature of network investments with the coordination of investments across borders, which can involve different regulatory settings [148].

3.3.5 Policy Interaction

The effects of a policy may rely on its interactions with other policies. Due to the complexity of electricity markets, policies within the electricity sector interact with each other via several channels. Firstly, policies may affect each other as their goals directly overlap. For instance, policymakers' goals in climate change/environmental policies, energy efficiency improvement policies, and renewable energy support policies have overlapping goals and targets. Secondly, policies that focus on different targets may interact with each other because they target and affect the same stakeholder. When analyzing the effect of a certain policy, a stakeholder that faces only that specific policy may act differently compared to the same stakeholder facing several policies with various restrictions and incentives. Therefore, the stakeholder's behavior may diverge from the behavior expected by the policymaker of each individual policy [149]. Thirdly, policies that target different stakeholders may still affect each other because the targeted stakeholders interact with each via collaboration or competition [150]. For instance, policies that target RES investors affect policies targeting storage investors as they both participate and compete in the market.

There is an extensive literature on policy interactions within climate and energy policies. The most salient policy interaction in the policy mix is the interactions between the current renewable energy support schemes and climate policies (e.g., see [151–157]). However, the literature on the interactions between electricity market design and policies is still limited. [158] analyze the impact of storage and demand response on the need for capacity markets. They show that by allowing storage to participate in the capacity market, the cost of capacity markets reduces and profitability of storage increases. [159] reviews the impacts of combining capacity mechanisms and renewable energy support policies.

4 Common trends, insights, and research gaps

As presented in the previous section, a lot of research on electricity market aspects covers the range of the three layers developed in Section 2. In the following, we will summarize the findings so far and identify where potential avenues for future research lie ahead to obtain a full assessment of future decarbonized electricity systems.

4.1 Common drivers and insights

Given that *decarbonization* was a prerequisite for all studies included in this review, a shift away from fossil energies was a given. Consequently, the transition towards *renewable energies* plays a central role in all studies. Wind and solar are the main technologies of choice covering most electricity production. However, the studies vary in both absolute shares and the respective shares of the two technologies. Furthermore, there is a common agreement that *further supply* is needed from other sources to complement the weather-dependent wind and solar supply. However, there is no common agreement on how this residual supply is structured and which technologies will contribute to the system mix. Storage is expected to play an important role. Still, there is divergence across the research community along the questions such as how much storage is needed, whether and what seasonal storage options are needed, and whether and what power-to-X technologies enter the system.

A lot of the research on stakeholders, policies, and market designs for supply-side aspects builds upon the above common drivers. In particular, researchers investigate the impacts of intermittent renewable generation with high capital and zero marginal costs on the market, namely, their effects on risk and uncertainty for investors, renewable support requirements, and capacity support mechanisms. However, there is no common agreement on whether and what market adjustments are needed for an electricity system with a high renewable share. Furthermore, as there is no common structure for the residual generation part of the system, there is also no common agreement on whether and what the different potential technology mixes that complement wind and solar will imply for the stakeholder and policy aspects.

Beside the changes on the supply side, the transformation of the demand side is another common trend assumed in most studies. The demand transformation is shaped partially by a general *electrification* of energy demand. Although there is not yet a conclusion on how much electricity demand will increase due to coupling heat and mobility sectors with the electricity system, most studies assume there will be

a shift toward those sectors, which will open up new potential for flexibility on the demand side. Another generally accepted development is the increase in the importance of the demand side and its *flexibility potential* for managing the system. This also links to the interplay between the emergence of renewable energies and the increased importance of the demand side. Given the potential for a more decentralized generation structure and a more active consumer base, most studies see an uptake in the participation of different consumers on the market's supply side in the form of prosumers or even new forms of collective actors. But, again, there is significant variation on the scale of those developments in the existing studies and, consequently, their implication for the policy and market layer.

Finally, *digitalization* is a common trend underlying most studies in this review, despite mostly not being explicitly addressed in the studies. Most studies take a higher flexibility potential and ‘smart’ structures as a given. In particular, on the demand side, many of the investigated future possibilities require further technology adjustments to become a reality, i.e., by implementing wide-scale smart metering. However, the studies seldom deal with this dimension in detail. There is, of course, extensive literature on digitalization and electricity systems, particularly from a technical and engineering perspective [160]. Nevertheless, it has not yet entered most large-scale system studies or more focused stakeholder or policy studies.

Figure 6 summarizes the above-identified common drivers and resulting insights. Most of those commonalities are rather high-level and general in nature, which highlights that there is not yet any common agreement by the scientific community on how an overall future decarbonized system should look in more detail. Along those rather broad strokes, most studies focus on specific aspects and usually identify partial aspects of future systems. Moreover, across the studies, the underlying assumptions (e.g., on the role of nuclear in the residual supply mix or the importance of seasonal storage) are still so different that various resulting insights can be derived.

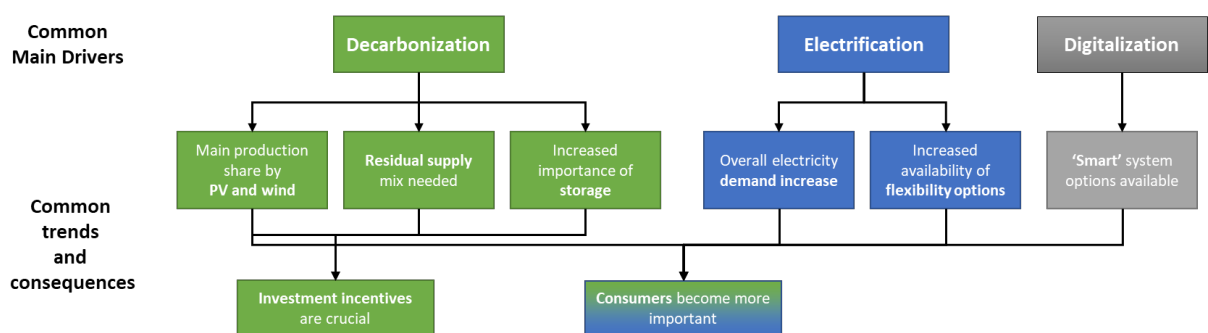


Figure 6: Common assumptions and insights of the investigated future electricity system literature

4.2 Identified challenges ahead

Although the real common denominators of the existing future electricity system literature are mostly on large-scale drivers and trends, they still allow the identification of resulting consequences and challenges that have significant coverage in the literature. Figure 7 provides an overview of those

relations. Most of the resulting challenges and changes are naturally linked to the increased renewable share, which impacts market dynamics, investments, and the overall system design. Most of the research on stakeholders, policies, and market design takes up specific elements and investigates those in more detail. For example, the altered investment risk aspects are analyzed from a stakeholder perspective via risk and uncertainty valuation approaches. They are taken up in the capacity mechanism literature as (potential) justification for those new market elements. Relatively speaking, the altered market price and investment aspects are covered by more studies than the other areas. On the other hand, in the consumer-centered literature, decentralization and altered local structures are a significant aspect. Network and balancing aspects are less prominent in stakeholder or policy studies.

The figure also highlights the high complexity and interrelation of the future electricity system. In particular, if the transition from today's system towards such a future system is to be accounted for, those dimensions increase in complexity as not only the new (potential) status quo needs to be assessed but also how to reach this new status given today's structures. The resulting recommended policy and market solutions addressing the challenges cover an equally large range. One of the most investigated policy areas is proper price signals and related market and policy design (e.g., wholesale prices, potential capacity or other support prices, and consumer tariffs). But again, no common agreement on the 'best way forward' has emerged so far.

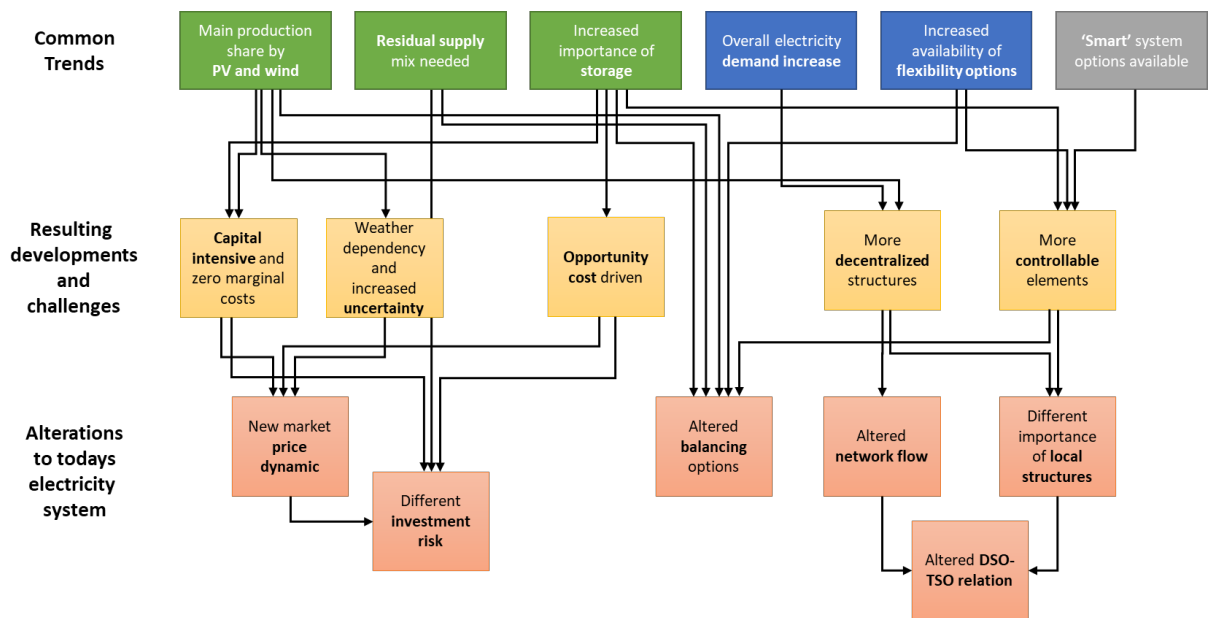


Figure 7: Relations between drivers, challenges, and alterations in future electricity systems

4.3 Research gaps and needed next steps

As the review pointed out, there is neither a holistic, all-encompassing system assessment approach in the literature nor a fully accepted future electricity system concept. This is most evident in the distinction between the large-scale numerical scenario studies and the stakeholder and policy-oriented literature:

most of the future quantification scenarios have limited or no stakeholder representation or market/system design perspective. They provide a theoretical first best technical solution given cost and technology assumptions but do not investigate how to reach or maintain such a system through proper policy and market designs [161]. On the other hand, many stakeholder and policy studies usually have a simplified technical representation, focus on only a part of the system, and neglect many important interactions. Thus, one central research challenge is the development of a combined assessment methodology that can account for relevant aspects across all three layers of Figure 2. In other words, combining the more socio-economic aspects of future markets with the techno-economic system modeling. This will also be needed to compare competing market design concepts under controlled conditions properly.

One important challenge along this way is the integration of demand and consumer-centered research approaches with supply-side-oriented assessments. As identified by most studies, the demand side will become a more active and increasingly important part of future electricity systems. While investigating different demand and consumer-related challenges is a large and growing research field, few studies still link those consumer aspects back to the national wholesale level in an integrated manner (i.e., allowing feedback in both directions). Given the emergence of a larger variety of consumer actors and cooperation among them, this also requires the extension of research approaches beyond pure cost minimization approaches (e.g., optimal household investment). For example, coordination among a cooperation can follow vastly different objectives, and coordinating such a cooperation with the remainder of the system is likely to follow other regulations. Accounting for the complexity of all those relations is definitely challenging. Still, if those actors are to shape the transition and our future system, we need to improve our understanding of their role. The linkage of consumer and system perspectives also calls for an extension of the debate on capacity markets to account for diverse actors on the lower voltage levels and their incentive structure, namely the interplay between tariff design and wholesale market dynamics. Concerning market dynamics, two aspects merit further focus: strategic behavior and storage impacts. The former is usually neglected for large-scale models (i.e., assuming a perfectly competitive system) and many stakeholder and policy assessments. Nevertheless, actors in the system do not necessarily have system interests in mind or even sufficient information to account for system aspects. With a new supply structure emerging, the question of market power abuse should also gain more attention. As electricity systems are characterized by regular scarcity conditions, the potential for market power abuse has already been a reoccurring issue in the existing system structure. How such conditions may change and what consequences they could and should have for market design are still relatively scarce in existing studies.

Related to this aspect is also the need to incorporate sufficient time details of storage options into the market assessment. As storage will be operated by an opportunity cost logic and could form a pivotal element of the overall system (compared to its rather minor role in today's system), accounting for its potential in shaping the system by strategic behavior is advised.

Due to its technical complexity, network aspects are often highly simplified or omitted altogether in more policy or market-oriented research. Given the increasing interaction between DSOs and TSOs and the increase in local supply, demand, and storage, the interplay between energy and network aspects will also need further investigation. As networks need to be designed for peak capacity usage, there is a huge interaction between demand and supply flexibility and the overall network investment needed. In other words, less flexibility will call for a higher level of generation capacity as well as sufficient network capacity to transport this energy to consumers. With the emergence of local generation and storage options, utilizing local opportunities could potentially be an important approach to reducing network capacity requirements. This challenge is increasingly complex as network aspects are part of a regulated environment, while energy-related aspects are usually assumed to be part of a more market-oriented environment. Identifying what trade-offs between energy and network assets are beneficial and how those benefits would be obtainable is, therefore, a highly complex research effort.

Summarizing, the current state of research on future decarbonized electricity systems does already provide some important insights and covers a wide range of aspects and methods. However, combining existing approaches across topical (and disciplinary) boundaries to obtain a more integrated assessment is likely the most promising next step toward a fully comprehensive assessment approach.

5 Summary and Conclusion

This paper provides a review on research of future electricity systems with the aim to identify common insights as well as challenges and research gaps. Structuring the review along three layers (the *physical* system layer representing the technical characteristics of the system, the *stakeholder* layer representing the role of various actors, and the *policy and market* layer capturing regulatory, policy, and market design aspects) we are able to highlight common trends and disagreements in the literature:

- i) Model based scenario assessments for a decarbonized European electricity system showcase that the shift will lead to a system in which wind and PV are the dominated generation sources backed up with other supply technologies and storage. However, the actual quantifications on the mix of wind and PV as well as the specific role of the other technologies are heterogeneous across studies.
- ii) There is a common agreement that electrification will lead to an increase in electricity demand, a general increase in importance of the demand side for the system, and an increase in the availability of flexibility assets. The actual extend and role of each of those developments is again heterogeneous across studies.
- iii) Network related aspects both on the TSO and DSO level and the need for smart systems is acknowledged in most studies or an implicitly assumed underlying trend. However, those aspects are seldom taken up in directly in system assessments.

The review highlights the need for further research across different aspects of the energy transition and consequently also across different disciplines. Especially with the increasing role of the demand side in our future electricity system, the growing importance of new stakeholders, altered market structures, as

well as regulatory and policy adjustments, an integration of those dimensions with the techno-economic model approaches providing large scale numerical assessments is still lacking. Consequently, from our perspective the central research challenge to be addressed is the development of a combined assessment methodology that can account for relevant aspects across all three layers; i.e., combining socio-economic energy research focused on stakeholders and overarching incentive frameworks with techno-economic system modeling.

6 Acknowledgment

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7 Appendix

Table 1 Studies analyzing the feasibility of at least 95% reduction of CO2 emissions in Europe by 2050

Reference	Model	Scenarios	Generation mix [TWh]									Flexibility [GW]				Demand [TWh]			Network
			PV + CSP	Wind (on)	Wind (off)	Hydro	Fossil	Nuclear	other RES	Hydrogen	Total	PHS	Battery+CAES	Power-2-X	Other	Total	Transport	Heating	
[172]	PRIMES	JRC EU Reference Scenario	429	980	0	421	1088	737	405	0	4060	0	0	0	0	3574	0	0	
[162]	PRIMES	EU Energy Roadmap 2050	843	2504	0	396	494	180	525	200	5142	0	0	0	0	3377	0	0	
[163]	Undisclosed	Roadmap 2050	1880	758	758	591	144	0	930	0	5061	AT	0	0	0	4385	0	0	
[164]	MESAP/Planet	Energy Revolution	1510	1450	901	620	0	0	1017	267	5765	0	0	0	0	3889	0	0	
[165]	Undisclosed	Re-thinking 2050	1732	1552	0	448	0	0	1255	0	4987	0	0	0	0	4987	0	0	
[166]	Antares	e-Highway 100% RES	892	1774	464	890	13	0	454	0	4488	114	0	0	0	4298	0	0	
[9]	PyPSA	Electricity only	871	1326	305	474	0	0	0	0	2976	47	57	107	-	2960	-	-	NTC
		Transport inflex.	1478	1779	352	474	0	0	0	0	4083	47	169	178	Y	3952	1102	-	NTC
		Transport BEV 25% flex.	1488	1691	327	474	0	0	0	0	3979	47	495	101	Y	3952	1102	-	NTC
		Transport BEV 50% flex.	1489	1668	325	473	0	0	0	0	3955	47	560	93	Y	3952	1102	-	NTC
		Transport BEV 100% flex.	1451	1688	317	474	0	0	0	0	3952	47	641	96	Y	3952	1102	-	NTC
		Transport BEV 25% V2G	1654	1570	298	473	0	0	0	0	3995	47	863	93	Y	3952	1102	-	NTC
		Transport BEV 50% V2G	1771	1531	175	474	0	0	0	0	3952	47	834	53	Y	3952	1102	-	NTC
		Transport BEV 100% V2G	1920	1464	56	474	0	0	0	0	3952	47	878	2	Y	3952	1102	-	NTC
		Fuel cell EV share 25%	1515	1835	409	474	0	0	0	0	4233	47	121	245	Y	4131	1102	-	NTC
		Fuel cell EV share 50%	1627	1920	431	474	0	0	0	0	4452	47	88	349	Y	4311	1102	-	NTC
		Fuel cell EV share 100%	1879	2090	488	474	0	0	0	0	4930	47	15	486	Y	4670	1102	-	NTC
		Heating	1145	2853	1176	471	0	0	0	0	5645	47	91	382	Y	-	1102	3585	NTC
		Methanation	1491	2890	1196	474	0	0	0	0	6050	47	141	404	Y	-	1102	3585	NTC
		TES	1548	2920	1145	473	0	0	0	0	6087	47	113	416	Y	-	1102	3585	NTC
		Central	1472	2839	1055	474	0	0	0	0	5839	47	99	305	Y	-	1102	3585	NTC
Central-TES	1538	2997	975	474	0	0	0	0	5983	47	88	258	Y	-	1102	3585	NTC		
All Flex	2190	2735	720	473	0	0	0	0	6117	47	1304	236	Y	-	1102	3585	NTC		
All Flex Central	2136	2825	583	474	0	0	0	0	6017	47	1153	99	Y	-	1102	3585	NTC		

[11]	PLEXOS	Base	1830	620	400	480	1055	0	350	0	4735	56	0	X	16 GW shedding	4409	800	500	Centre of gravity
		High demand	2300	620	1280	480	1455	0	420	0	6555	56	0	X		6020	800	500	
		Alternative demand	1840	520	510	480	898	0	400	0	4648	56	0	X		4409	800	500	
		No CSP or Geothermal	1390	720	900	480	1210	0	0	0	4700	56	0	X	4409	800	500		
		Storage	1834	580	416	480	1005	0	420	0	4735	56	80	X	82GW load shifting	4409	800	500	
		Free RES	1684	700	296	480	1061	0	410	0	4631	56	0	X		4409	800	500	
		Allow non-RES	290	390	0	480	1836	1127	387	0	4509	56	0	X		4409	800	500	
[167]	PRIMES	EC LTS 1.5Tech	1333	4060	0	439	298	941	878	0	7948	51	69	511	0	-	0	0	
		EC LTS 1.5Life	1029	3629	0	386	129	836	515	0	6524	53	54	403	0	-	0	0	
[168]	POLES	JRC GECO 1.5C	877	1144	0	419	137	602	671	0	3851	NR	0	NR	0	-	0	0	
[169]	EU-TIMES	JRC LCEO Zero Carbon	3663	4604	0	419	607	942	314	0	10548	NR	0	NR	0	-	0	0	
[13]	Navigant Energy System Model	Navigant min gas	1100	1000	2600	800	0	0	809	0	6309	NR/AT	0	NR	Y	5513	853	390	
		Navigant opt gas	2500	800	2600	800	400	0	0	0	7100	NR/AT	0	NR	Y	4461	772	399	
[170]	NR	Oeko Vision	1079	2878	0	432	0	0	252	0	4641	0	0	0	0	0	0	0	
[18]	interaction of seven models	IFS 2C	1405	2359	0	420	0	0	1015	0	5199	NR	NR	NR	0	0	0	0	NTC
		IFS 1.5C	1593	2526	0	439	0	0	1044	0	5602	NR	NR	NR	0	0	0	0	
[173]	LUT Energy System Transition	Regions	2655	1770	0	649	0	25	801	0	5900	AT	NR	37	-	5259	-	-	NTC
		Area	2317	2091	0	622	0	25	597	0	5650	AT	NR	4	-	5259	-	-	NTC
[171]	elesplan-m	Decarbonization pathway EU	1199	3805	0	539	426	0	0	0	5968	43	22	367	-	4448	-	-	CoG

NR/-: not reported, AT: as today,

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