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Flexibility from Energy Systems Integration

1. Introduction

"Energy systems integration", or "sector coupling", has several drivers spanning climate impact mitigation and economics, through to social and regulatory considerations. A key question is "What is sector coupling and how does it impact the flexibility of the energy system?" Here, the 'energy system' includes several sectors: electricity, gas, heat and transportation, which have in most countries been independent for decades – except for their coupling via combined heat and power units. In energy systems integration, some sectors may provide flexibility to other sectors, while others will demand flexibility when interlinking. To support these synergies among sectors, it is important to explore and quantify mutual interactions, as well as seek examples of how these integrations can provide flexibility and other benefits. Specifically from the perspective of the electricity sector, it is important to ensure enough flexibility in the interconnected systems to support decarbonization goals, such as those set in the Paris Agreement, while ensuring operational reliability.

In this article we consider two primary types of flexibility. First is the flexibility between sectors and resources, which is subsequently referred to as *resource flexibility* and includes shifting between different fuel types. This can be on the generation or demand side and is typically done for the purpose of decarbonization (Figure 1). The second type of flexibility is within a sector, and refers to *operational flexibility*, such as provision of reserves or ancillary services, achieved through resource sharing, operational control, and diversification.

For energy services such as light, heating, cooling, and transportation, a transition from one supplying sector to another - or even to multiple options- is expected. Thus, resource flexibility will increase.

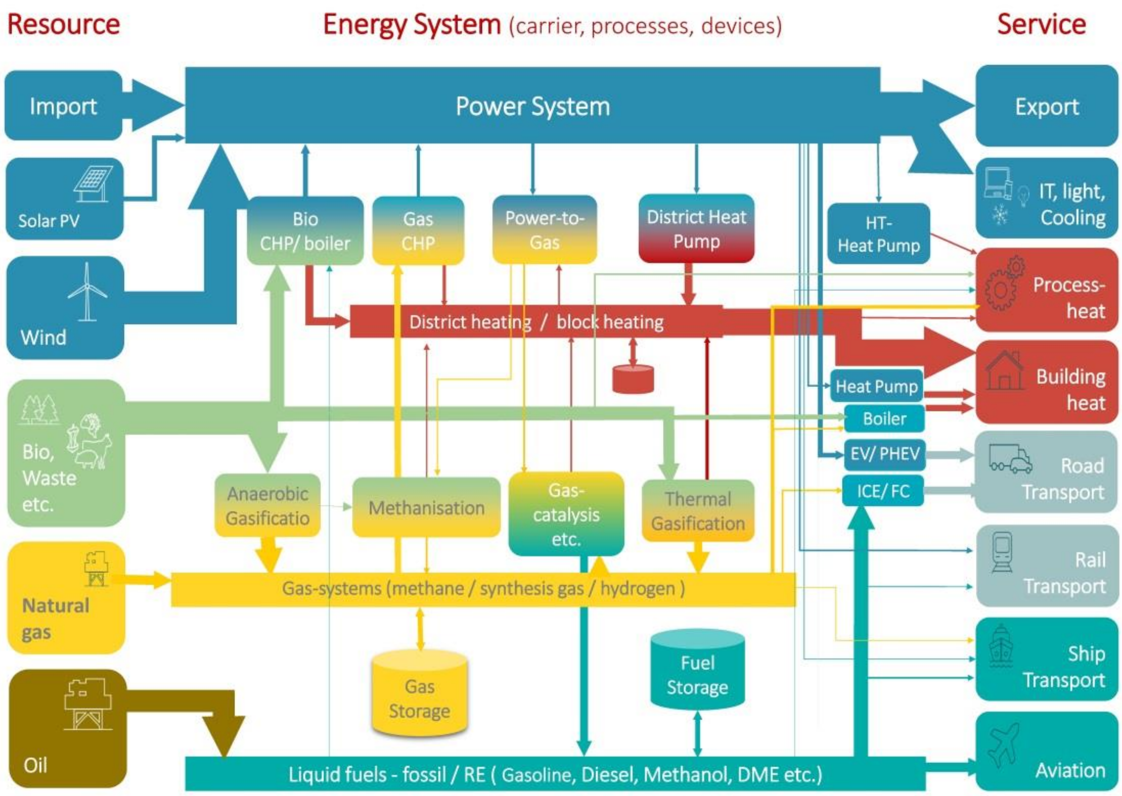

Figure 1 Simulated Energy Flow in Denmark 2035 (source: Energinet)

CHP	*Combined Heat and Power*
EV	*Electric Vehicle*
PHEV	*Plug-in Hybrid Electric Vehicle*
HT Heat Pump	*High temperature Heat Pump*
ICE / FC	*Internal Combustion Engine / Fuel Cell*
IT	*Information Technology*
RE	*Renewable Energy*
DME	*DeMethylEther*

The coupling of the gas and electricity systems has received significant attention in recent years. In Europe, a European regulation (EU No 347/2013), adopted by the European Parliament and the European Council requires the interlinked modeling of the electricity and gas sectors for purposes of planning infrastructures at the Pan-European level. Focusing more on operational issues, in the United States the Federal Energy Regulatory Commission (FERC) issued Order No. 809 in 2015, “to better coordinate the scheduling of wholesale natural gas and electricity markets in light of increased reliance on natural gas for electric generation.”

What is driving sector-coupling? In isolated cases, like combined heat and power generation (CHP), it is simple cost-benefit considerations, but the major impetus today is decarbonization. Since sustainable biomass resources are limited and carbon capture and sequestration (CCS) is constrained by cost, limited opportunities for sequestration, and regulatory considerations, in many sectors the main decarbonization option is electrification, with wind and solar dominating electricity generation. Sector-coupling is then also necessary to provide resource flexibility to integrate variable renewable energy resources (VRES), especially where large scale transmission projects are not possible. It is likely that in the future, economics will be sufficient to drive electrification across sectors. A good example is the transportation sector, given the continuing decline in the costs of battery electric vehicles (BEVs) and carbon policies which lead to higher costs for traditional liquid fuels. However, when considering the climate change mitigation options, electrification of many more sectors will be critical in order to reduce emissions.

2. Translating Paris across borders and sectors

The main goal of the 2015 Paris agreement is to limit "the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C". In order to compare the costs and benefits of different ways of achieving the Paris agreement, engineers, scientists and economists have developed Integrated Assessment Models (IAMs) that allow exploration of the interactions between the physical climate, land usage, energy system, and economy. Scenarios differ based on the speed of change they assume is plausible, the choice and development rates of technologies, efficiency measures, the distribution of greenhouse gas reduction among regions and sectors, lifestyle changes, economic development, and the possibility to remove carbon dioxide from the air in large quantities, among other factors. A set of possible scenarios that would limit global average temperature rise to 1.5°C are shown in Figure 2.

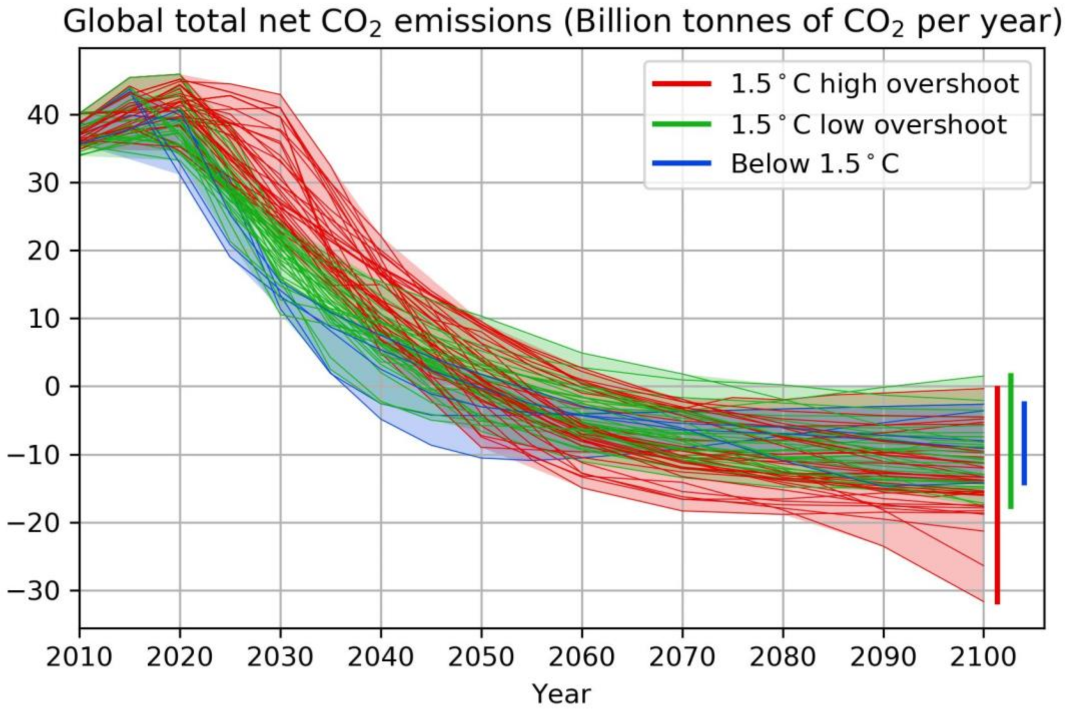

Figure 2 Different global scenarios for carbon dioxide emissions with global warming of 1.5 °C. Scenarios that delay emissions reductions tend to overshoot the temperature target and require more negative net emissions after 2050 (source: IPCC Special Report on Global Warming of 1.5°C, 2018, figure reproduced by authors using data from https://doi.org/10.22022/SR15/08-2018.15429 and the code from https://doi.org/10.22022/SR15/08-2018.15428)

Despite the large variations between 1.5°C target-scenarios (Figure 2), they all will require global net carbon dioxide emissions to reach zero by around 2050. Other greenhouse gases, such as methane and nitrous oxide, must also be reduced. The majority of carbon dioxide emissions come from the burning of fossil fuels for energy in electricity generation, heat provision, transport and industry, as well as from chemical processes in industry.

Countries implementing the Paris Agreement have therefore made specific commitments with regard to reducing carbon dioxide emissions in energy usage. For example, in 2016, 80% of Canada’s electricity was generated from zero-carbon sources, and the federal government has targeted increasing this to 90% by 2030. The German climate protection plan translates to an estimated share of 65% of gross electricity consumption covered by renewable energy sources (RES) by 2030, starting from a 31,6 % share in 2016. Denmark, covering 61% already today aims at 100% in 2030, triggering electrification of other sectors as well.

Individual states in the United States have made commitments aligned with the Paris Agreement. California passed a bill in 2018, SB 100, that committed California to a 60% share of renewables in yearly electricity generation by 2030 and 100% clean electricity by 2045 ("clean" includes low-emission renewables, nuclear and generators with CCS). In late 2018, New York State announced that a carbon-neutral electricity supply by 2040 is a legislative priority. In early 2019, U.S. public opinion is mounting toward extending the carbon-neutral targets to many other states.

In 2009, the European Union (EU), responsible for 10% of current global greenhouse gas emissions, set a goal to reduce greenhouse gas emissions by 80-95% by 2050. In 2018 the European Commission published modeling results for 1.5°C-compatible scenarios that reach greenhouse gas neutrality by 2050. The split of emissions among sectors in the 1.5°C scenario through 2050 in Figure 3 is typical for what is required in other regions of the world: emissions are reduced in power first, reaching zero by 2040, while some emissions remain in 2050 in sectors that are harder to decarbonize, such as residential and tertiary demand (primarily space and water heating, and also cooking), industry, transport and agriculture. Electricity is prioritized, since the strategies for decarbonizing the other sectors often rely on electrification with low-emission electricity sources. For example, space and water heating can be electrified efficiently using heat pumps and transport using electric or hydrogen fuel cell vehicles. Some industry branches, such as ammonia production or direct reduction of iron ore, can also be electrified indirectly with hydrogen produced by electrolysis of water.

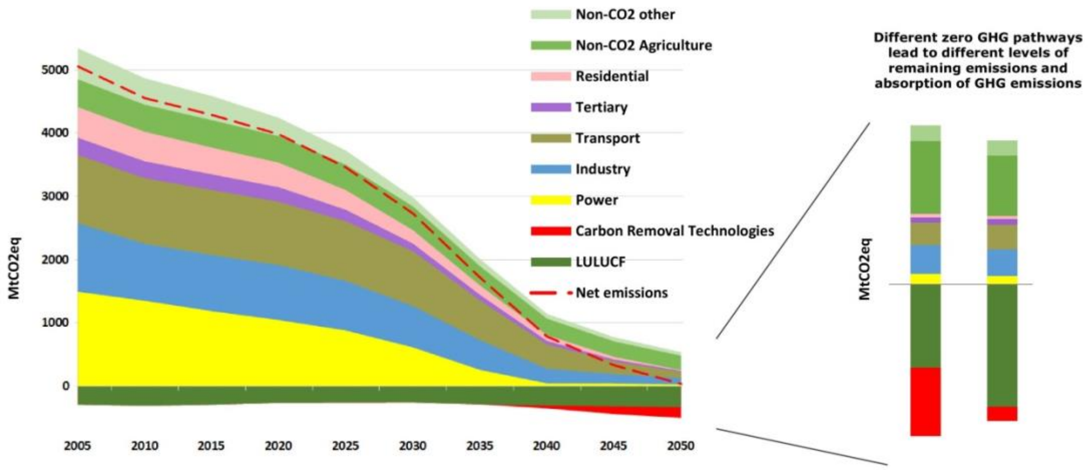

Figure 3 Pathway for sectoral greenhouse gas emissions in the European Commission's 1.5°C scenarios (source: European Commission communication "A Clean Planet for all", COM (2018) 773, 2018)

3. In brief: challenges for systems with a high share of renewable energy sources (RES)

Reducing emissions in the power sector often starts by replacing fossil fired power plants with variable renewables (VRES). Increasing the share of VRES in energy supply, places challenges on power systems, especially when this share is very large. Systems with more than 50-70% of electricity demand provided by VRES (depending on the system) experience a growing need for operational flexibility to balance production variability against demand over the course of each day. Additionally, VRES often press thermal plants out of the market, due to the low marginal cost of wind and solar sources. These thermal plants traditionally provide important system services and vital operational flexibility, which then have to be provided through other means, such as improved market designs and market products on both the generation and demand side to ensure there are sufficient balancing mechanisms. Balancing mechanisms can be delivered by various means at different voltage levels and with very different lead-times, e.g. building strong high voltage transmission systems, using smart grids/microgrids and storage at lower voltages and operating actions such as accurate forecasting and demand side management.

Challenges for electricity systems dominated by a high share of VRES (wind, solar) can be described as follows:

- **Regulation and Reserves Requirements:** Since output from VRES has potential to lead to high ramps, additional regulation and flexible generation or reserves may be required, as well as flexible loads to handle unanticipated generation or load needs. Dispatch signals to meet demand or prevent voltage issues can secure the system in stressed situations such as correlated sunset and evening peak.
- **Foreseeing and Mitigating Transmission Overloads:** Sudden changes in output of VRES can cause overloads on transmission equipment that require immediate mitigation, especially in situations with lines and transformers taken out of service for maintenance.
- **Load and VRES Forecasting:** Since output from renewables generally does not correlate well with any of the traditional input variables for load forecast models (temperature, time of day, day of week, etc.),

load forecasts for systems with high penetrations of behind-the-meter renewables can be susceptible to increased error, especially when prosumers optimize their own consumption.

Usually, studies on high-share VRES systems focus on supply-demand balancing with hourly resolution. Today, additional concepts for sharing operational flexibility across sectors and advanced methods for their investigation are needed. Investigation of shorter operational time periods has been intensified, to allow systems frequently dominated by inverter-connected VRES production to manage increasing issues with stability, frequency, lower inertia, and related matters when faults must be cleared. Thus, Table 1 outlines operational flexibility needs within the energy sector that span several time horizons, from instantaneous to long term disruptors.

Table 1 Time Horizons for Flexibility in the Energy Sector

Instantaneous	Hour/ day	Month/ year	Long term disruptors
Security of supply during system faults and actions	Balancing variable wind and PV	• Dry/ wet year, • Wind year variation, • Extreme years, • Change of market prices for fuels shifting primary resource.	• Breakthrough for new technologies,(fuel cells, hydrogen); • Price-setting and requirements for emissions; • Focus on bio-resources and sustainability; • Focus on balance food vs. fuel; • New fuel types (DME, metanol, hydrogen etc.) • Digitalization

4. Sector coupling study results

The higher the share of VRES, the more potential is available for sector coupling to open up new operational flexibility sources and reduce carbon emissions in other sectors as well. Efforts in coupling sectors can today be seen at the R&D, policy, experimental, and even commercial levels. All synergies aim at a transition to decarbonize sectors at reasonable cost without violating systems' adequacy or security requirements.
While the electricity sector enters new markets via electrification, gas and heat systems get a new role as a fuel integration and storage system. The gas system must cover extreme weeks integrate green gas, and adapt to the control of power-to-gas (P2G) units to facilitate their participation in different markets (electricity, district heating, renewable energy sources (RES) gas). The heat system can further be used for energy systems stabilization by combining several heat resources and leveraging thermal storage. The following sections provide examples for sector coupling to illustrate the main focus in different parts of the globe.

4.1 Sector coupling results in Europe

The European Commission's 2018 "Clean Planet for all" modeling results provide a comprehensive picture of what compliance with the Paris agreement would look like in electricity, heating, transport, industry and agriculture (Figure 3).

As heating, transport and industry demand are electrified, the share of electricity in final energy consumption rises from just over 20% in 2015 to 50% in 2050. Gross electricity generation doubles from 2015 to 2050 and is even higher in scenarios with a large share of power-to-fuel technologies. At the same time as electricity demand rises, it is also decarbonized, with the share of renewables ranging from 81% to 85%. The share of wind and solar alone in total generation rises from 65% to 72%. This means that total wind and solar generation in 2050 would be larger than all electricity generation today.

In the heating sector, in 2050 the share of residential space heating demand met by electricity (primarily heat pumps) rises to 30%. In the transport sector in 2050, 80% of vehicles are completely electric, while just over 15% have hydrogen fuel cells.

When analyzing future European scenarios, it is important to represent the full continental weather variability and events that unfold over several days, such as cold weather situations coinciding with a continent-wide lull in wind and solar generation. Such events are particularly challenging for the power system with wide-scale electrification of heating. Flexibility provided by long-term storage such as thermal energy storage or synthetic fuels can help to bridge these difficult periods and keep costs low.

A doubling of electricity generation, with a majority coming from VRES, requires detailed grid modelling to assess the impact on the energy system's behavior and costs. As a first step, as well as answering the legal request for interlinked modeling of the electricity and gas sectors, the European Network transmission system operators for electricity and gas (ENTSO-E, ENTSOG) applied jointly developed scenarios when elaborating the infrastructure development plans for electricity and gas ('TYNDP's) 2018. This allowed investigation of the same possible futures to deliver a more consistent picture than ever before, while also quantifying developments in other sectors.

4.2 Sector coupling results in the USA

The United States Mid-Century Strategy for Deep Decarbonization, produced in 2016, calls for near elimination of greenhouse gas (GHG) emissions by 2050. The strategy to achieve this is focused on decarbonization of the electric power sector, electrification of transportation, buildings and the industrial sector, as well development of carbon capture, utilization, and storage technologies. The result of this transition is estimated to nearly double end-use electricity demand, with half of the increase coming from transportation. The potential for end-use efficiency measures has been shown to mitigate the increase in electricity demand significantly, or entirely.

However, much of the specific action on renewable energy integration has taken place at the state level. Currently, 29 US states and the District of Columbia have adopted renewable portfolio standards (RPS), with the most ambitious goals in Vermont (75% by 2032) California (60% by 2030), and New York (50% by 2030). While RPS policies have existed for over a decade, nearly all have been updated and revised to increase targets under improving performance and economics around renewables. Most states have managed to attain RPS standards, and in some states and regions renewable energy source development has even outpaced RPS targets, for example in Texas and the Midwest.

In pursuit of these goals, the share of renewable sources in the US energy sector continues to grow; reaching 18% of total energy consumption in 2017, including 7% hydro generation and (11% in total from wind, solar, geothermal, and biomass). To fully realize any decarbonization strategy, and the state-level RPSs, penetration of variable renewable resources will have to increase significantly, nearing 80% by 2050. Recent studies by the National Renewable Energy Laboratory have been exploring the efficacy of leveraging geographic diversity to provide resource and operational flexibility. One example is the Interconnections Seams project, in partnership with several other national laboratories, universities and industry partners. This effort is exploring cost-effective options for upgrading the North American electric grid to leverage geographic diversity among renewable generation sources, which show distinct patterns in resource quality across the continent (Figure 4).

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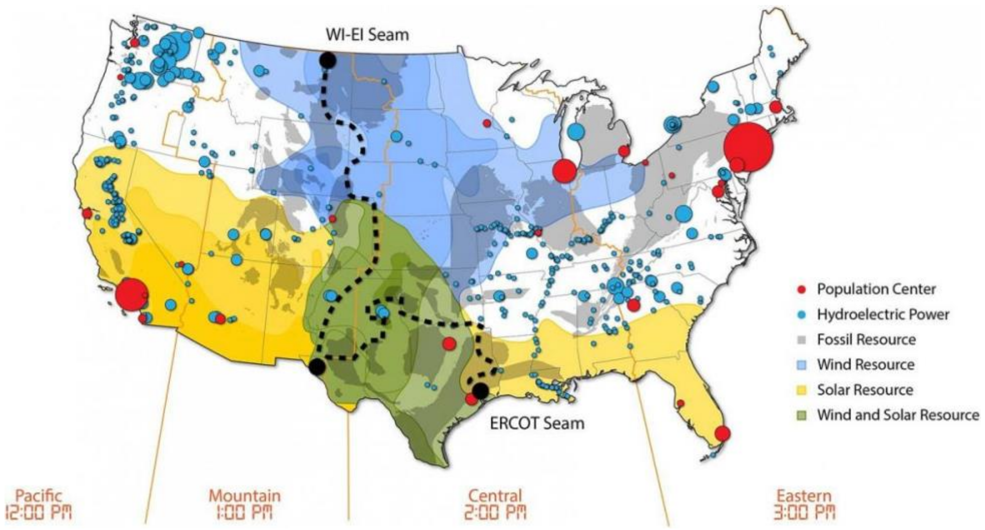

Figure 4 Resource quality and potential HV transmission expansion to support VRES integration across the USA (source: NREL Interconnections Seams Study –at the courtesy NREL)

Integration across sectors is becoming increasingly important, as demand side resources will be crucial to achieve renewable integration and decarbonization goals. Of particular importance are the transportation and building sectors. Not all buildings will generate sufficient energy on-site, and community or regional level renewable energy projects will develop to meet these needs. The overall result will be a system of both centralized and distributed energy resources, some of which will contribute to supply side variability, complemented by flexible end-use in smart homes and buildings. Transportation sector integration is developing through pilot studies on smart EV charging rates and test beds which are under development, as well as testing mechanisms and incentives to access inherent flexibility in EV charging.

Integration of the building sector through demand-side management has been on the horizon for many years, starting in California in 2007, with demand response pilot programs. Although its implementation has been slow, currently the majority of the US population has advanced metering, and new time of use rate and demand response pilot programs are being developed in many states. While there is immense operational flexibility potential on the demand side, its growth depends on the ability to engage consumers across all segments, and the development of data architectures that can ensure their data security and privacy.

5. Linking various sectors

5.1 Electricity and Gas: Flexibility and Gas-Electric Coordination in PJM

Natural gas combined cycle generators are well positioned to meet increasing needs for operational flexibility, as coal, nuclear, and some combustion turbines offer limited or no load following capability. In the PJM Interconnection (located in the eastern and midwestern U.S.), installed capacity from natural gas generation is on track to increase by over 50% between the 2007/2008 and 2021/2022 delivery years, which extend from June 1 through May 31. (Figure 5). This has been largely driven by gas production from the Marcellus and Utica shale reserves, both of which are in the PJM footprint. Meanwhile, installed capacity from coal and nuclear generation that has cleared in the PJM capacity market decreased by nearly 40% over the same time period. In addition to providing increased overall operational flexibility, this changing fuel mix has steadily reduced CO_2, SO_2, and NO_x emissions since 2005 (Figure 6).

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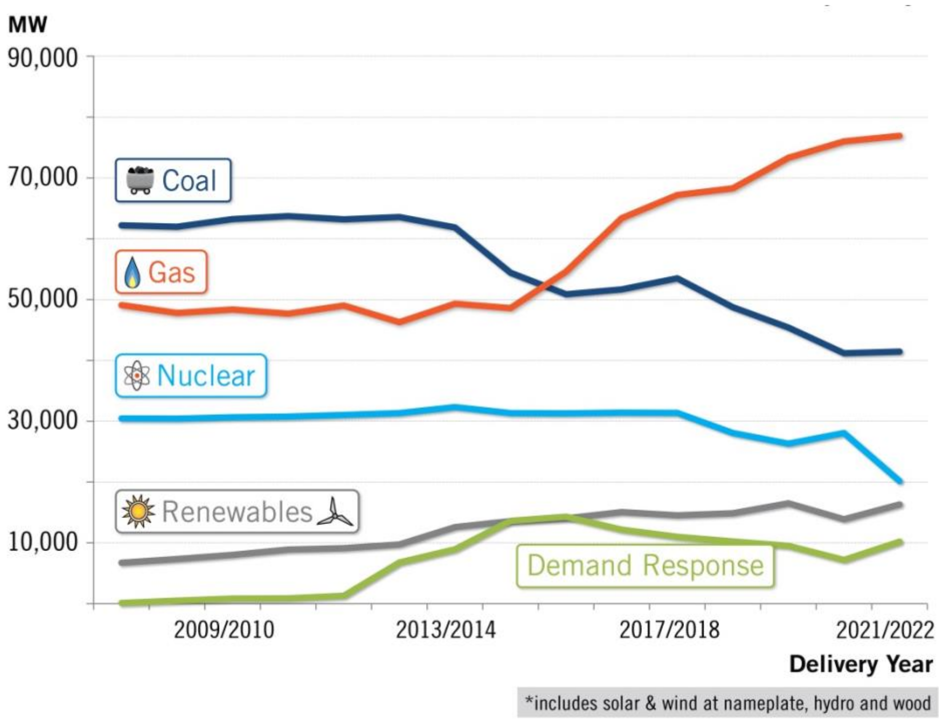

Figure 5 PJM Installed Capacity by Fuel Type (source: PJM Interconnection)

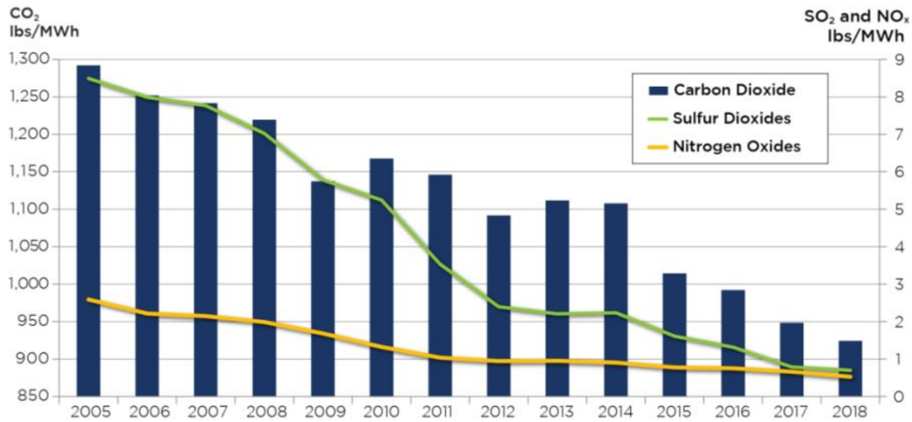

Figure 6 PJM Emissions Decrease (source: PJM Interconnection)

In 2017, PJM published "PJM's Evolving Resource Mix and System Reliability," which documents how the availability of such generator attributes – including operational flexibility, fuel assurance, frequency response, reactive power, and ramping capabilities – changes with potential future generation portfolios. This study was motivated by a concern that the system could become so dependent on the rapidly growing amount of natural gas and renewable resources that reliability would be negatively affected. While natural gas combustion turbines provide fast and accurate ramping control and great amounts of operational flexibility, they offer little in the form of fuel assurance capability, as they do not store fuel on-site and are dependent on the pipeline infrastructure. Thus, even if a plant is physically capable of following sharp changes in load or starting up on short notice, there is no guarantee fuel will be available for the plant to meet the grid's essential reliability needs.

During the cold weather conditions of the 2014 North American polar vortex event, interruptions in service from natural gas pipelines caused nearly one-fourth of the total generator outages. Such outages occur during cold weather events because the delivery of natural gas is prioritized based on different levels of contracts, with firm transportation contracts (primarily for on-site residential heating) being guaranteed delivery under all circumstances except the most extreme. Approximately 16,000 MW of gas generation in PJM relies on non-firm transportation contracts, which may be interrupted based on demand. Following the polar vortex event, PJM launched a cross-divisional gas-electric coordination team to evaluate pipeline capacity postings and critical notices, as well as establish a knowledge base of the pipeline industry and relationships with pipeline companies that serve PJM generators.

To more closely examine the nuances of supply chain risks such as limited gas availability during extreme conditions, PJM initiated a study in 2018 to specifically evaluate threats to fuel security. While no imminent threat was identified, PJM will continue to work with the gas pipeline industry to increase transparency of firm gas markets and to evaluate and refine pipeline contingency impacts. These efforts will help ensure that fuel is available to the most flexible generators when needed.

5.2 Electricity and Transport

The transport sector can also contribute to cover the need for increased intra-day balancing. This has been shown in an analysis evaluating interactions between the transport, electricity, and heat sectors in hourly resolution for an entire year. For example, Figure 77 shows the simulation results of a typical February week for the German energy system, illustrating the ability of controlled charging of electric vehicles (EVs) to contribute to smoothing wind and solar PV based electricity production. An extreme situation has been modeled with only wind and PV as generation, and only electric vehicles as an operational flexibility source.

The net load (black dashed curve), i.e. the load (w/o EV) minus generation from wind and solar PV, neither includes other generation like thermal or hydro, nor trading with neighboring countries. Many occasions with a surplus of power, i.e. negative net load values, can be exploited to charge EVs by applying a controlled charging algorithm (blue line). The algorithm uses the EV's operational flexibility with respect to charging profiles and avoids negative impact on the available transport service. The result for the electricity system (yellow line) is a much smoother net load. Coordination between user's and system needs is necessary in order to avoid voltage and overloading issues.

In the US, new rate cases that will provide incentive for consumers either to charge EVs off-peak or to provide charging deadlines that support VREs in the system are being explored.

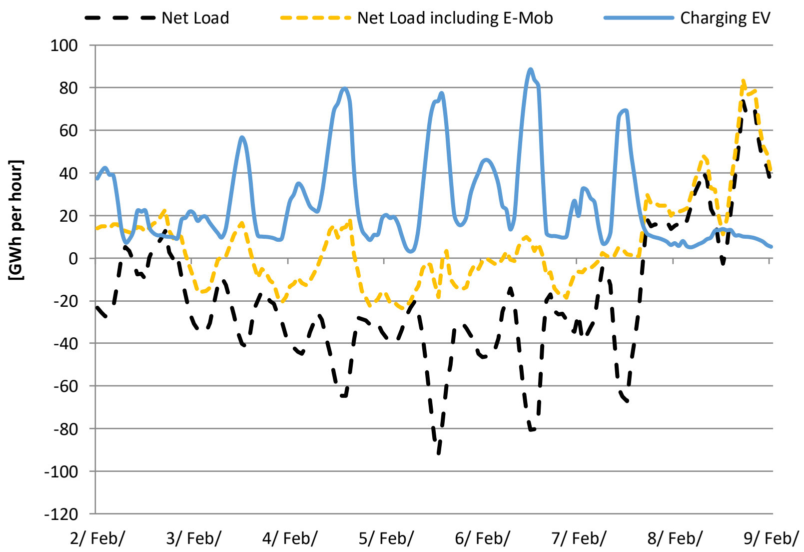

Figure 7: Modified net load (i.e., load minus wind and PV generation) without EV, net load including demand for EV (trucks and cars) and the load from charging EV for one example February week in Germany. (source: Fraunhofer IEE)

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5.3 Electricity and Heat: Economic Benefits of Integrating Heat and Electricity Sectors

The flexibility in the heat sector provides excellent opportunities to contribute to the electricity sector's balancing services, to reduce system peaks, or to use excess VRES output by converting electricity into heat. For the UK system, the related economic benefits can be huge. Technologies such as combined heat and power generation (CHP), electric heating (heat pumps, resistive heating), thermal energy storage (TES), and heat networks which link the heat and electricity systems can provide cross energy vector resource flexibility.

Studies using the future UK energy scenario with high RES penetration demonstrate that the investment and operating costs of a non-integrated heating and electricity system are higher than the case in which both systems are integrated. The net benefits of coordinated operation of the heat and electricity systems are between £2.4bn/year and £5.4bn/year for the scenario with a carbon target of 100g or 50gCO_2/kWh respectively. The stricter the carbon target, the higher is the value of resource flexibility.

Given that CHP can provide ancillary services to the electricity system besides providing heat, combined cycle gas turbine (CCGT) plant would be replaced by CHP in the integrated system, saving fuel costs. A higher CHP penetration leads to a reduction of industrial network heat pumps (NHP) capacity and consequently, reduces the need to reinforce high-voltage distribution networks.

Deeper decarbonization of the UK heating system will require major electrification of the heating system. However, there are concerns related to implications for electricity infrastructure, system operation, and security. To avoid major reinforcement, hybrid technologies such as hybrid heat pumps (HHP), which combine a domestic gas boiler with an air/ground-source end-use heat pump (EHP), have attracted significant interest. Given this hybrid nature, the consumers' heating demand can be met by the consumption of either gas or electricity, implying a "dual-fuel" capability.

The FREEDOM project in the UK has demonstrated that HHP technology can still achieve the environmental potential of a fully electrified heat sector, yet with significant economic savings with respect to a standalone EHP pathway. This is because this hybrid technology can significantly reduce both upfront building costs and electricity system costs. Additionally, HHP technology can save a significant amount of system costs compared to the standalone EHP case (Figure 8). In a low-carbon system, these gross savings in total system costs can be 5.8 and 9.3 £bn/year compared to the standalone EHP case.

HHP technology requires additional operating expenditure (OPEX) for the gas system. It also requires additional capital expenditure (CAPEX) in low-carbon generation to offset gas emissions by decarbonizing more of the electricity system. These additional costs are shown as negative benefits in Figure 8. Considering this, the remaining net system benefits of HHP technology are between 4.9 - 7.4 £bn/year. The benefits of HHPs over EHP are lower in a highly flexible system, as the operational flexibility from HHPs competes with other flexibility sources such as controllable loads (industrial and commercial loads, electric vehicles, smart appliances) and electricity storage.

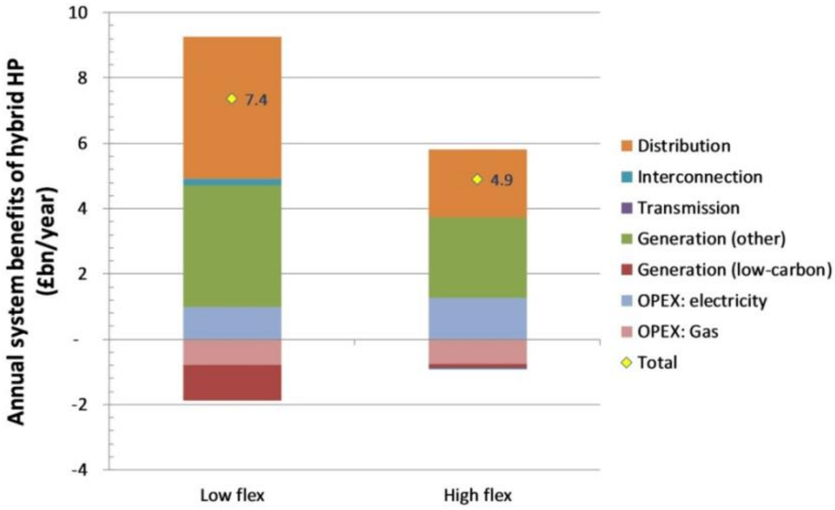

Figure 8 Annual cost savings attributed to the use of hybrid heat pumps (HHPS) instead of end-use heat pumps (EHP) in a system with low and high flexibility. Positive values show benefits, while negative values show additional costs. Results show that transmission does neither add costs nor benefits. (source: Imperial College)

Both HHPs and EHPs can deliver a number of valuable flexible demand response services to the electricity system. These include "preheating", which involves heating the households earlier than would be otherwise carried out, while utilizing inherent heat storage in the fabric of the houses and not compromising user comfort requirements. Furthermore, smart control of HHPs can increase their operating efficiency. It has been demonstrated that rolling out smart control strategies would considerably improve the value proposition of HHPs. Respective additional annual benefits are between 5.1 £bn/yr and 15.2 £bn/yr, depending on the availability of other operational flexibility sources in the system (Figure 9).

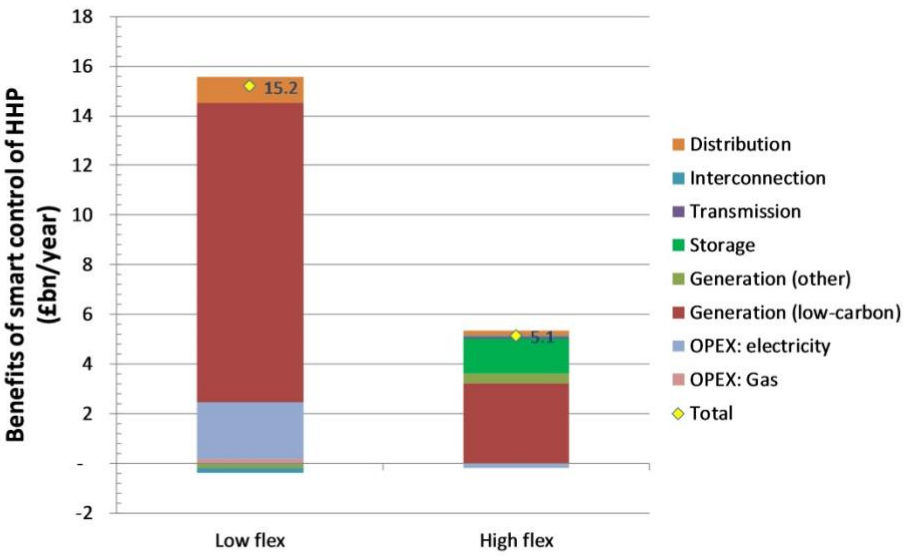

Figure 9 System-level benefits of HHP smart control strategies in a system with low and high flexibility. Positive values show benefits, while negative values show additional costs. Results show that transmission does neither add costs nor benefits. (source: Imperial College)

The most significant value stream of this flexibility is associated with reductions in investment in low-carbon generation capacity including VRES and nuclear. This is driven by the operational flexibility of the HHPs with smart controllability to provide system balancing services and related increase of VRES utilization, thus meeting carbon targets cost-effectively.

5.4 Electricity and Water

There are three ways in which the interdependencies of the electricity and water systems influence the provision of operational flexibility.

1. Hydroelectric and pumped storage facilities: Run-of river hydroelectric generation offers large amounts of operational flexibility depending on available water and environmental constraints. Pumped storage is typically able to contribute to short-term regulation and ramping services. Additionally, it can respond on a diurnal basis by levelizing demand net of renewable production. .
1. **Water-related electric loads:** There are two types of water-related loads that are large enough to represent flexibility opportunities: water treatment plants (WTPs) and wastewater treatment plants (WWTPs). Both represent a relatively large amount of load, offer significant operational flexibility, and are available throughout the year on a daily basis. In the region of the US operated by the Midcontinent Independent System Operator (MISO), the total nameplate capacity of WTPs and WWTPs is about 1000 MW. Motors for pumping load consume over 90% of this load. If 30% of this load is on at any given moment and available for the provision of flexibility, this could contribute 270 MW of flexible load. A typical weekday regulating reserve requirement in the MISO region is 400 MW, whereas 10-minute ramp-up requirements range between 10 and 1300 MW and 10-minute ramp-down requirements range between 70 and 1500 MW. Thus, a 270 MW contribution to these requirements would be significant. WTPs often utilize water storage tanks, many of which can gravity-feed water demand for hours before they require replenishment, and both WTP and WWTP have wait-time built into their processes, offering load shifting abilities by minutes or hours. New plant pumps with variable speed drives offer the ability to modulate load, which is an attractive feature for frequency regulation. Investment costs associated with initiating WTP and WWTP as controllable demands are likely low, as they would require only costs associated with their communication infrastructure.
2. **WWTP cogeneration resources:** WWTP produce methane, which can be captured with anaerobic digesters. The biogas is then used to fuel an internal combustion engine or gas turbine to produce electric energy. The system may be used to provide operational flexibility services to the grid. Of the approximately 16,000 WTPs in the US today, about 1,500 of them employ anaerobic digestion to produce biogas that is used on-site. Of these, only 133 fuel electric generation, so WWTP cogeneration represents a largely untapped opportunity to increase flexible resources.

5.5 Denmark Case Study: Benefits of coupling multiple sectors

In Denmark, the coupling of the electricity and heat sectors has already been realized for several decades [*see Lew article in this magazine*]. A widespread district heating system including CHPs with large heat storage tanks facilitates a certain degree of decoupled production of heat and/or power. Some electric boilers convert inexpensive excess electricity into heat. The electricity and gas sectors are implicitly coupled via the Danish TSO Energinet, who is responsible for both systems, thus capturing synergies through their joint planning.

Energinet investigates further sector coupling to determine what a cost-optimized fossil-free future energy system with all sectors coupled might look like. For this, the sector-coupled energy system has been modeled through so called energy plants of different sizes. Energy plants can be understood as extended combined heat and power units with more functionalities, such as electrolysis and gasification. These plants deliver more than just electricity and heat and operate at low prices as consumers of electricity, while they shift at high prices to become producers of electricity (Figure 10).

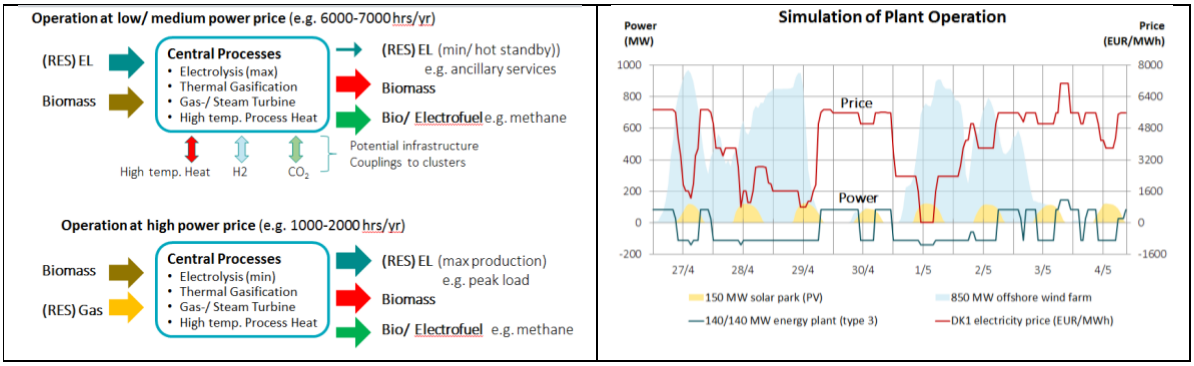

Figure 10 Principle of an energy plant and its operation (source: Energinet)

The underlying ENTSO's European scenarios point at a further significant increase of wind/solar energy in the whole North Seas region, which reduces options to share large amounts VRES across countries with highly correlated VRES. A typical example is that North-South exchange corridors for wind energy might be congested at times when fronts of (typical) west-wind approach several neighboring countries simultaneously. Nevertheless, results show that average electricity prices will continue to be competitive and regionally aligned, even with the whole region adopting green energy (Figure 11). However, there will be periods with extreme high or low prices due to weather conditions, faults, or maintenance activities. These periods increase economic opportunities to install flexible electricity demand, such as heat pumps, power-to-gas devices or Power-to-X (P2X) applications. These devices can convert inexpensive electricity via electrolysis and a parallel gasification of organic material or synthesis with nitrogen into high value products such as fuel, fertilizers, plastic, etc., which traditionally are produced based on oil or natural gas (Figure 1). This is expected to be possible at competitive prices, as the Levelized Cost of Energy (LCoE) of VRES is expected to be well below prices for natural gas by 2030 and development of technology for electrolysis is accelerating. The right level of sector coupling can even help increase the value of VRES, which is important for VRES producers wanting to recover their costs, while low electricity prices are necessary for electrolysis, i.e. hydrogen production, which is needed for e.g. biofuel or ammonia production to supply heavy transport.

What is needed for sector coupling to take off is the market providing the right signals, regulatory rules not hampering cross-sector interaction and attractive locations with infrastructures of several sectors being close enough to each other offering opportunities to build the missing links. First pilot projects have already emerged, such as a business-park in Central Denmark ('Greenlab'), where several companies interact via several infrastructures and exchange their (surplus) energy products, such as heat, electricity, biogas, hydrogen, oxygen, steam, methane, biofuel. At country scale investigations are ongoing how an additional massive amount of offshore wind could best be integrated, including considerations of transformation into other forms of energy at suitable locations. International investigations propose that this transformation could already take place offshore - on energy islands or -hubs, as proposed by the 'North Sea Wind Power Hub'- idea, which even might connect several countries and send energy to where it is needed and where the market price is best.

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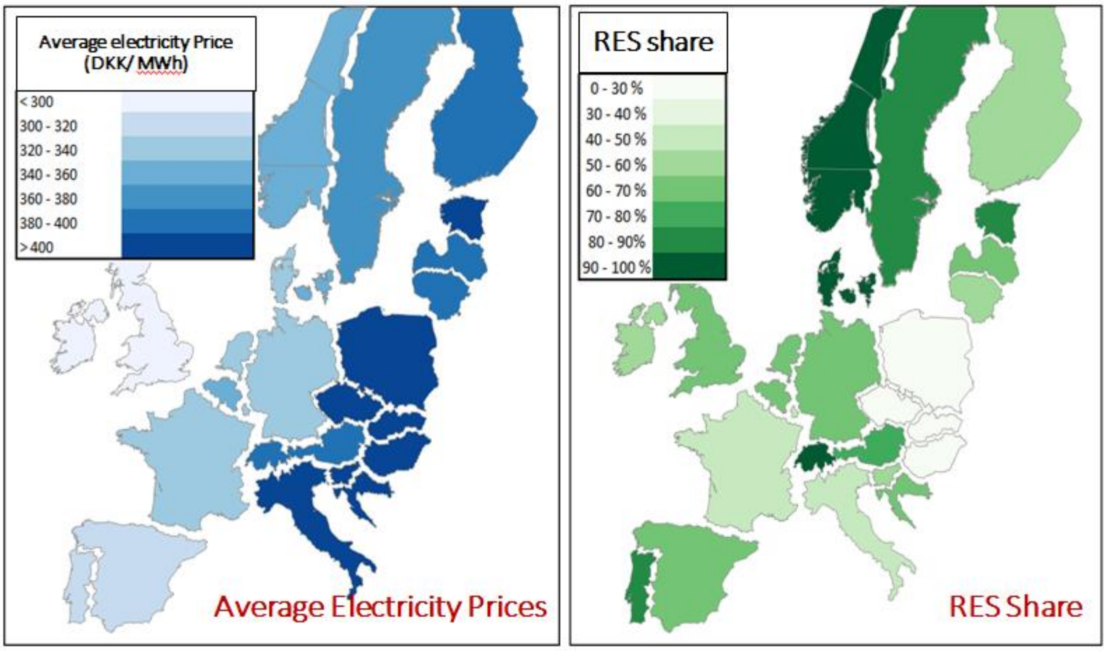

Figure 11 RES share and average prices for Europe in 2040 according to the ENTSO-E's TYNDP 2018 projection (source: Energinet; data from ENTSO-E's "Sustainable Transition" Scenario 2040)

When going towards a 100% VRES energy system, coupling of sectors is essential for the electricity system: potential bottlenecks in the electricity grid can be resolved while at the same time getting access to low cost storage facilities in the gas or heat system. Heat at high temperature from some conversion processes could directly be used in steam turbines. These steam turbines could deliver regulating power, ancillary services, or peak load capacity. This might lead to a reduced need for traditional power plants running during low electricity price periods in standby mode - without losing options to provide ancillary services. In the case where these plants deliver grid reserve, the utilization of the transmission grid could be increased as well.

6. Summary

Cross-sector system integration is essential in decarbonization and mitigation of climate change impacts. However, the challenge of sector integration lies in the development of scalable, effective methods of co-optimization across these sectors. Historically, very little operational flexibility existed in distribution and end-use, and grid operations focused on forecasting inelastic demand and balancing with supply. The proliferation of smart meters, smart home devices, EVs, distributed generation, and storage will challenge the current paradigm of data management and optimization for operations and control. In addition, cross-sector integration introduces a new synergistic flexibility that will increase as electrification proceeds. Within these systems, energy management systems must be informed and controlled in each sector to provide operational flexibility. Optimization methods for coordinated decision making within multi-level energy systems and between integrated sectors will require appropriate information sharing and algorithms that are solvable in reasonable computation time. This paradigm will produce and leverage ever more data which must be both protected on behalf of the consumer and used for decision making. It is also worth noting that devices and algorithms are not a complete solution. Cross-sector integration will also increase consumer involvement, such as activation of the demand side flexibility via decentralized markets and markets for ancillary services. The inclusion of new market players and new business models will be a part of innovative solutions. All measures need to be facilitated by digital market processes allowing free data and low transaction costs. Understanding the needs and motivations of all stakeholders in the integrated energy system will be critical in achieving large-scale impact.

For further reading:

Energinet; "System perspective 2035", available at https://en.energinet.dk/Analysis-and-Research/Analyses/System-Perspective-2035

ENTSO-E; European "Ten-Year-Network-Development plan TYNDP2018", available at: https://tyndp.entsoe.eu/tyndp2018/
(series of reports, among others the "Scenario Summary", which is a joint publication with ENTSOG).

Luc van Nuffel, Trinomics, "Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?" available at: http://www.europarl.europa.eu/supporting-analyses

T. Brown, D. Schlachtberger, A. Kies, S. Schramm, M. Greiner, "Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system," Energy 160 (2018) 720-739, DOI: 10.1016/j.energy.2018.06.222

PJM's Evolving Resource Mix and System Reliability
https://www.pjm.com/~/media/library/reports-notices/special-reports/20170330-pjms-evolving-resource-mix-and-system-reliability.ashx

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