CHAPTER 15

Economics of Sector Coupling

Michel Noussan

1 Introduction

The integration of increasing shares of non-dispatchable variable renewable energy sources in power systems requires additional flexibility options, to ensure the continuous matching between demand and supply required to operate the power grids. Traditional technologies to provide energy balance services include electricity storage, transmission networks, fossil-based dispatched energy, and demand response and/or management programs.

In this framework, an alternative solution that is emerging is sector coupling, also called "P2X", where "X" may stand for various applications, such as gas (G), heat (H), vehicles (V), liquids (L) or others. The idea of sector coupling is to convert the excess available electricity into another energy carrier which is required or can be more easily stored than electricity. In some cases, the transformation is reversible, that is, electricity can be generated again, although generally with low roundtrip efficiency.

However, in some cases sector coupling applications can lead to significant benefits in long-term storage, especially for power-to-gas (P2G) or power-to-liquids (P2L). In some current applications, sector coupling is exploited to avoid curtailing of renewable energy sources (RES) in specific hours when production exceeds demand, by exploiting available power at no cost. However, in most cases the limited number of annual operational hours does not allow

M. Noussan (✉)
Fondazione Eni Enrico Mattei (FEEM), Milan, Italy

Decisio s.r.l., Torino, Italy

SciencesPo—Paris School of International Affairs, Paris, France
e-mail: michel.noussan@sciencespo.fr

M. Hafner, G. Luciani (eds.), *The Palgrave Handbook of International Energy Economics*, https://doi.org/10.1007/978-3-030-86884-0_15

acceptable pay-back times, also due to the relatively high investment costs for some technologies. Some applications, including hydrogen and synthetic fuels, may need dedicated RES supply to reach annual load factors that justify current investment costs.

P2X is expected to play a significant role in the energy transition, in parallel with the direct use of renewable energy or the clean power generation from renewable energy sources (RES). However, to unlock the full potential of sector coupling technologies three main aspects need to be tackled: scaling up technologies, defining markets and demand structures, building up favorable investment frameworks to secure supply (Perner and Bothe 2018). While the required cost decrease may be obtained through a scale-up of technology driven by demand, this would require customers to buy and pay for a cleaner alternative to the current use of fossil fuels. Policy-driven incentives or CO_2 emissions markets may support future business models for P2X technologies.

The following sections will present the most promising applications of sector coupling: power-to-gas (P2G), power-to-heat (P2H), power-to-vehicles (P2V), and power-to-liquids (P2L).

2 Power-to-Gas

P2G is probably the most common application when talking about P2X, and although it usually refers to hydrogen production through electrolysis, it may also include a further methanation step to produce synthetic methane. The additional complexity and energy consumption required by methanation may be justified by the opportunity of exploiting existing assets operating with natural gas (e.g. pipelines or turbines). In this case, methane production requires as additional input a carbon dioxide stream, which could be obtained from carbon capture or direct air capture to close the CO_2 cycle and avoid net emissions during the use of synthetic methane. A scheme of the main P2G supply chains is illustrated in Fig. 15.1.

The current energy efficiency of electrolyzers lays in the range 60% to 81%, with variations related to technology type and load factor. The role of electrolysis in the current global production of hydrogen (69 MtH_2) is below 0.1%. A shift to 100% would result in an electricity consumption of 3600 TWh, which is more than the total annual electricity generation in the European Union (IEA 2019a). Thus, a significant role of hydrogen in future energy systems would require massive deployment of electricity generation from RES. An additional side effect is the need of freshwater as input resource, which could be a problem in water-stressed areas. The use of seawater would require an additional desalination process, which could be done through reverse-osmosis technologies, whose costs are in the range from 1 to 2 € per cubic meter (Caldera et al. 2018). Thus, desalination costs are likely to represent a marginal share of total P2G costs, since a cubic meter of water allows the production of more than 110 kg of hydrogen.

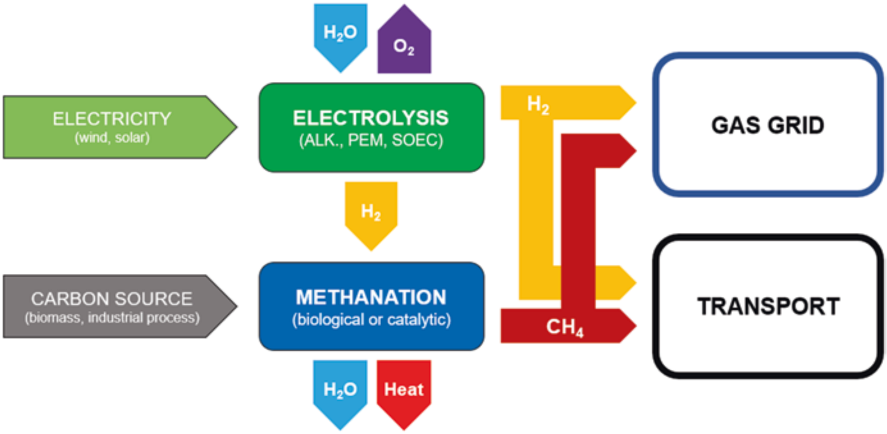

Fig. 15.1 Example of P2G supply chains. (Author's elaboration from: (Götz et al. 2016))

Alternative electrolysis technologies exist, with different performance, operating pressure and temperature, as well as lifetime stack, load range flexibility, and investment cost. The most mature technologies are alkaline electrolysis, proton-exchange membrane (PEM) electrolysis and solid oxide electrolysis cells (SOECs), whose main operational parameters are reported in Table 15.1. The most diffused technology worldwide for energy purposes has shifted in the last years from alkaline to PEM, with almost 90% of the 95 MW of capacity additions in the years 2015–2019.

The production cost for hydrogen based on hydrolysis depends on multiple assumptions, with the most significant parameters being the investment cost, the electricity cost, and the annual hours of operation. Based on the estimation of (IEA 2019a), the production of hydrogen by 2030 in Europe could cost 2–4 €/kg if based on dedicated RES plants, or 3.2–6.5 €/kg when considering grid electricity. Still, these costs are expected to remain higher than the production pathways from fossil fuels (both natural gas and coal), either with or without carbon capture, use and storage (CCUS) facilities.

However, other world regions may experience lower costs related to higher RES potentials, especially for solar energy, although with limited annual operational hours. Wind plants, especially offshore, may lead to higher load factors, representing more interesting options when they are coupled with electrolyzers.

It is important to notice that hydrogen may have a number of applications where it is used directly, but often it involves a further conversion into electricity. In this perspective, P2G (combined with the subsequent process "G2P") can be considered as an electricity storage solution, which is particularly effective for long-term storage (from days to months). Today, hydrogen is already the most effective storage solution for seasonal storage, excluding pumped

Table 15.1 Main electrolysis technologies, operation parameters

	Alkaline electrolyzer			*PEM electrolyzer*			*SOEC electrolyzer*		
	Today	*2030*	*Long term*	*Today*	*2030*	*Long Term*	*Today*	*2030*	*Long Term*
Electric efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90
Pressure (bar)	1–30			30–80			1		
Temperature (°C)	60–80			50–80			650–1000		
Operation (thousand hours)	60–90	90–100	100–150	30–90	60–90	100–150	10–30	40–60	75–100
CAPEX (USD/kWel)	500–1400	400–850	200–700	1100–1800	650–1500	200–900	2800–5600	800–2800	500–1000

Source: IEA (2019a)

hydro and compressed-air storage (Schmidt et al. 2019), and on the long term it is expected to provide better performances.

In last years, P2G projects with methanation seems to catch up with simple hydrogen generation, and they show higher potential for energy efficiency improvement from current levels, especially by strengthening the exploitation of by-products, oxygen and heat, an aspect that is seldom considered in existing projects. Current figures for capital expenditure (CAPEX) costs related to CO_2-methanation, referred to the input power consumed by the upstream electrolyzer, is around 800 €/kW_{el} for chemical methanation and 1200 €/kW_{el} for biological methanation (both values excluding the cost of the electrolyzer). These values are expected to fall by 2030 to 500 €/kW_{el} and 700 €/kW_{el} respectively (Thema et al. 2019). These cost evolutions are expected to rely on production upscaling, although technological development may have an influence.

3 Power-to-Heat

Power-to-heat (P2H) aims at exploiting the potential synergies between power and heating sectors, either through the coupling with existing district heating (DH) networks or with distributed heat generation for single users. The applications in DH networks are currently more diffused, thanks to the fact that in large centralized plants any potential economic advantage is of particular interest. Thus, also due to the common practice of including multiple generation technologies in the same system, low electricity prices can be exploited to generate heat through electric boilers or large-scale heat pumps. In comparison with other sector coupling applications, P2H shows relatively low investment costs, relying on components that are already broadly used for various applications and have high technological maturity (heat pumps and even more electric boilers). However, again, the trade-off of such additional investment is related to the amount of annual operational hours, which in turn are related to the volatility of the price of electricity, and in some cases of alternative fuels (notably of natural gas when bought with hourly prices). These solutions are often most profitable for large customers, such as DH generation plants or large commercial users, which can have multiple generation options to supply the required heat demand. P2H is currently a reality in limited markets, due to its generally higher cost in comparison with traditional technologies, but it shows an interesting potential, especially through heat pumps, in a future perspective of stronger decarbonization measures and lower electricity prices.

P2H has already a suitable maturity in DH networks applications, especially in some countries in northern Europe, such as Denmark, Sweden and Norway, but there is still a significant unexploited potential (Schweiger et al. 2017). Using electric boilers, which have generally low investment costs, DH network managers exploit the low electricity market prices in specific hours of RES surplus to obtain a lower marginal cost in comparison with alternative generation technologies. The trade-off market prices vary from a country to another, mainly due to different power mixes and to the taxation levels on electricity consumption.

A study on 2014–2015 market data in Denmark, Sweden and Norway (Rosenlund Soysal and Sandberg 2016) analyzed electric boilers in DH systems. Results showed that electric boilers had lower marginal costs than natural gas combined heat and power (CHP) units for 26% of the DH operating hours in Denmark and 46% in Sweden. However, only in Norway they were able to compete with biomass CHP units, showing lower marginal costs in 14% of the annual hours. The trade-off heat prices against gas-powered CHP were 22.7 €/MWh in Denmark and 26.5 €/MWh in Sweden, and in Norway 14.4 €/MWh in competition with biomass CHP units. Although with similar electricity purchase prices, these countries showed very different electric boilers fixed marginal prices (i.e. excluding electricity purchase but including taxes): 51.6 €/MWh in Denmark, 38.9 in Sweden and 12.8 in Norway.

Figure 15.2 shows the comparison of different generation technologies in Sweden and Denmark (data from (Rosenlund Soysal and Sandberg 2016)), comparing the variation of the heat price based on the electricity price. The cost of heat generated from electric boilers increases with the electricity price, while in CHP technologies increased revenues from high-cost electricity lead to a lower price of the produced heat. It is important to remark that this chart is based on the wholesale electricity price, and additional taxes are considered to calculate the marginal price, thus resulting in a positive value for electric boilers even at a null cost of electricity.

A broader application of P2H is the progressive electrification of heating and cooling sector to support higher levels of RES penetrations. This trend is supported by decarbonization policies at different levels, and heat pumps are generally preferred against electric boilers thanks to their higher energy efficiency, although with significantly higher investment costs. However, in countries with high electricity prices for final customers, the total cost over the lifetime of the appliance may justify the choice of a heat pump. However, in

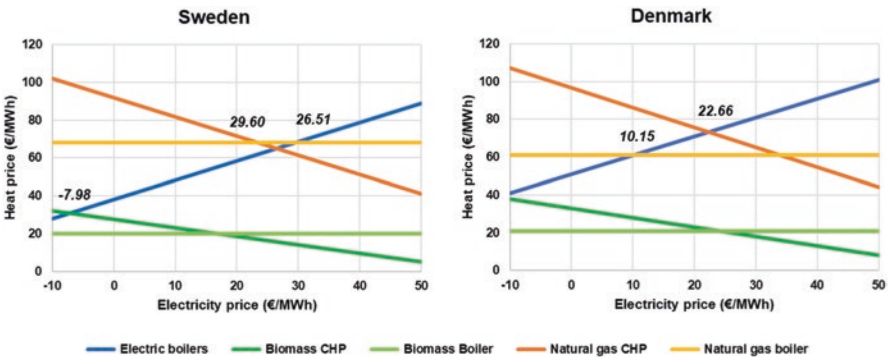

Fig. 15.2 Marginal costs of different heat generation technologies in Sweden, based on electricity price. (Source: Author's elaboration on: (Rosenlund Soysal and Sandberg 2016))

most countries, the total cost remains significantly higher in comparison with traditional fossil-powered boilers, and incentives are often in place to support the users in transitioning toward cleaner fuels.

The current operation of small-size heat pumps is generally bound to fixed electricity tariffs, and there is a limited application of time-of-use tariffs that can follow the wholesale market price. However, there is an interesting potential for power aggregators that may exploit large pools of small-size heat pumps, especially when coupled with local thermal storage, to provide services to the power system. The participation to balancing markets is among the most interesting applications for aggregators, although with the need of fast reaction times, a bi-directional communication and generally a minimum pool size of few MW (Spreitzhofer 2018). Some undergoing projects of P2H through heat pumps are available in different countries, including Austria (BMVIT and FFG 2019), Switzerland, Germany, and the United States (IEA HPT 2017).

4 Power-to-Vehicles

Another sector that may face a significant increase of electricity penetration in next decades is transport, in particular with the deployment of electric vehicles (EVs) in the market of private cars. The need for recharging car batteries will unlock additional electricity demand, but also flexibility options through the management of the charging timing and profiles of a large number of distributed batteries. There are basically two distinct levels of integration, from delayed charging (also called smart charging, or P2V) to bi-directional sector coupling, often referred to as vehicles-to-grid (V2G). The latter requires a specific battery design, due to the need of discharging toward the power grid upon request, which is seldom available in the current generation of electric cars.

The future deployment of P2V schemes is tightly related to the market share of electric vehicles, whose sales are showing exponential increases in last years, with 2018 sales reaching 2 million units at global scale, roughly doubling the previous year (IEA 2019b). Future scenarios show high variability from one source to another, and they have often been revised upwards each year. Figures from IEA 2019b estimate annual global EV sales between 23 and 43 million by 2030, with electric car stocks in the range 130–250 million.

A crucial aspect will be the number of available charging points, and the share between public and private charging points, and between slow and fast charging. The interaction between power grid and a pool of EVs will require them to be continuously connected through dedicated charged points, especially during daytime, when electricity balance needs are higher. Thus, high numbers of publicly accessible charging points will be required, since private charging points in households are mostly used overnight. The current global ratio of publicly accessible charging points per electric car has decreased from 0.14 in 2017 to 0.11 at the end of 2018 (IEA 2019b). Figures show a wide variation from one country to another, from one public charger every 20 electric cars in Norway or in the United States to one charger every four to eight electric cars in Denmark or in the Netherlands.

P2V is based on EVs smart charging strategies, with the aim of shifting the additional power demand from peak hours to off-peak hours. Researchers found that most current EV users are charging their vehicles in the early evening, when electricity demand is high, thus a shift toward the night hours may lead to better power network operation. P2V may require either time-of-use tariffs, or a third-party player that directly controls the charging process (based on the specific requests from the final user). Customers should be able to set some charging targets based on their needs, that is, the amount of charge required at a specific hour, while at the same time keep some room for unpredicted early need to use their cars. A dedicated research work in UK found that user-managed charging was preferred over supplier-managed charging, because of perceived personal control and lower perceived risk that a vehicle might not be fully charged at the required time (Delmonte et al. 2020). On the contrary, preference for third-party charging of users was based mainly on perceived advantages to society. At a system level, different research studies analyzed the effect of smart charging strategies to support an increased use of RES share in power generation, with favorable results in different countries (Daina et al. 2017; Jian et al. 2018).

V2G goes beyond the simple schedule of EV charging, by exploiting the vehicle as a battery when the grid needs balancing services. In comparison with P2V, further aspects are involved. EV batteries should be technically allowed to operate in discharge mode toward the grid, charging points should have higher average power, battery state-of-charge should be carefully monitored (and stay in restricted ranges) to meet the required levels when the users need it, and there may be potential issues related to battery quality depletion over time due to additional cycles. Dedicated algorithms will be needed to optimize the charge/discharge strategies, and ideally, large EV pools would provide more flexibility to the aggregator, considering the multiple constraints. Results from a test study on the behavior of a real pool of EVs showed that the ratio of available battery capacity over the nominal capacity of the pool at specific times of the day could fall to very low values (Irie 2017). The worst case happened for daytime charging, when only 2.1%–3.9% of capacity was available, due to few connected vehicles and remaining state-of-charge levels. Nighttime charge and peak-hours discharge reached up to 30% of available capacity, but in some days resulted in shares as low as 14% and 8% respectively.

5 Power-to-Liquids

P2L applications can prove to be a necessary solution in the decarbonization of some sectors that lacks other alternatives, such as long-haul aviation, international shipping and specific high-temperature industrial processes (Perner and Bothe 2018). Synthetic fuels may become a complementary solution to biofuels in these key sectors, and like biofuels they can often exploit existing appliances and infrastructures (e.g. gasoline, diesel, and kerosene), with the possibility of an immediate shift in some existing applications without the upfront costs associated to convert the appliances of the final users or the different components in the supply chain.

P2L applications include a variety of processes, of which the most mature are methanol synthesis and Fischer-Tropsch synthesis. Methanol can be used directly (with some limitations) or it can be further converted to other fuels, such as petrol, diesel, or kerosene. In comparison with hydrogen, methanol has some advantages, including the lower safety procedures related to its liquid state under normal conditions, requiring no further actions in terms of high-pressure (or low-temperature) storage. Moreover, methanol synthesis is a well-known industrial process, and so are further processes to convert it to other fuels for specific sectors (Varone and Ferrari 2015). Fischer-Tropsch synthesis requires carbon monoxide and hydrogen to produce a raw liquid fuel that is then upgraded toward a traditional fuel by different processes. It is a relatively established technology, which has also been applied to obtain synthetic fuels from coal and natural gas.

Few studies address P2L costs in comparison with available literature on hydrolysis or methanation. Synthetic liquid fuels production relies on more mature technologies, with a smaller potential of further cost reductions related to process improvements. However, investment costs could decrease in the next decades thanks to standardization effects driven by large-scale plants deployment. Current specific investment costs related to the output production lay in the range 800–900 €/kW_{P2L} for both processes, depending if they are coupled with high-temperature or low-temperature electrolysis (which in turn have different costs). Future developments are expected to lower the costs to 544–828 €/kW_{P2L} by 2030 and 300–800 €/kW_{P2L} by 2050, depending on different scenarios (Agora Verkehrswende et al. 2018). These values do not include CO_2 capture, which may have a significant impact on the total cost, especially when relying on direct air capture. The cost associated to CO_2 direct air capture coupled with P2L applications is currently as high as 2200 €/kW_{P2L}, and also with an expected decrease to 1600 €/kW_{P2L} by 2050 it would remain the most expensive part of the process.

The total supply chain costs of producing synthetic fuels are always higher than for P2G, both due to the additional required components and the lower supply chain efficiency, with current values in the range 46%–64% depending on the hydrolysis temperature (Blanco et al. 2018). The higher costs may be justified considering the energy system with a broader perspective, with potential benefits such as the use of existing infrastructures and the easier storage procedures. For some applications, especially aviation, the energy density of the fuel will be another key aspect in the choice between available alternatives. It is important to highlight the need of dedicated CO_2 streams from carbon capture technologies in order to close the cycle and allow for carbon-free synthetic fuels, which is the main driver in comparison with fossil-based alternatives. In the long term, direct air capture may be preferred, thanks to the possibility of using it anywhere (i.e. without the need of the proximity of a CO_2 generating system, or a dedicated CO_2 supply chain), although with additional electricity consumption as well as higher investment costs.

6 Economic Comparison of Sector Coupling Options

An economic comparison of sector coupling alternatives is not straightforward, since multiple parameters are affecting the operation and the business models of these technologies. As already mentioned, the first applications of P2X rose from the opportunity of exploiting the excess of electricity from RES, especially in the cases where low CAPEX investments did not require high annual operational hours. These applications were particularly successful in some niche markets, such as P2H in district heating networks in Nordic European countries. However, for many applications the operational hours remain a critical issue, due to the high prevalence of CAPEX over operational expenditure (OPEX). In these cases, P2X technologies could provide some degree of flexibility to exploit an available excess of electricity from RES, but they could not rely solely on that excess.

While the availability of excess electricity in some hours of the year, which may even be considered with a null cost, can be a significant advantage, such a limited operation would not be compatible with the high CAPEX of multiple P2X applications. Similarly, on-site generation from RES shows promising levelized costs of electricity (LCOE), but annual load factors of wind and solar resources are limited.

A simplified economic comparison of the P2X technologies presented in this work is reported in Fig. 15.3, where an average economic margin is calculated as the difference between the revenues and the generation costs of different solutions, which are compared on the basis of a unit of available electricity. The revenues are estimated as the avoided cost of generation by a reference

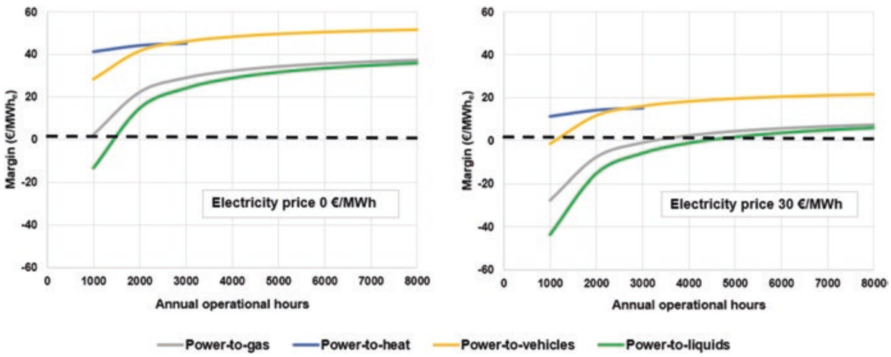

Fig. 15.3 Economic comparison of different P2X technologies with variable electricity cost and hours of operation (estimated values for 2040). (Source: Author's elaboration)

Table 15.2 Hypotheses for economic comparison of P2X technologies (year 2040)

Parameter	*Unit*	*P2G*	*P2H*	*P2V*	*P2L*
CAPEX	*€/kW$_e$*	600	90	400	850
Efficiency	*MWh$_u$/ MWh$_e$*	0.75	0.99	1	0.65
Alternative solution	–	Hydrogen via SMR	Heat from natural gas boiler	EV charging from power grid	Gasoline
Alternative solution cost (incl. Emissions)	*€/MWh$_u$*	56.4	47.6	55.0	66.3
Alternative emissions	*t/MWh$_u$*	0.30	0.21	0.05	0.26
Alternative emission costs[a]	*€/MWh$_u$*	29.6	21.3	5.0	25.9

Source: author's elaboration

[a]Based on a carbon price of 100 €/t_{CO2}.

alternative technology (see Table 15.2 for further details). Given the different contexts in which these technologies are operating, there are not only different CAPEX and OPEX costs and logics, but also different benefits depending on the energy carrier or service that needs to be supplied.

This simplified analysis highlights the role of the electricity cost and the annual operational hours on the profitability of some P2X solutions in the long term. The results suggest that the applications with higher conversion efficiency show the higher margins, but at the same time, it may be more difficult to ensure a high number of operational hours due to demand constraints. The lower conversion efficiencies of P2G and P2L, which are also part of the cause of their higher CAPEX, may be compensated by the flexibility value associated with the possibility of long-term storage for their products. However, such an evaluation would require a detailed analysis taking into account daily and seasonal demand profiles.

The main hypotheses used in this analysis are listed in 2, which is based on figures on a 2040 time horizon, obtained from different literature sources integrated with expert opinions. All the P2X technologies are considered on a 15-years lifetime, and the revenues are estimated as the avoided costs of a corresponding traditional solution for the production of the very same service (including a CO_2 cost of 100 €/t, where appropriate). The alternative solutions are presented in the table on the basis of the useful energy that is made available for the final users (expressed in MWh_u).

It is important to remark that the objective of this exercise is to provide the readers with a qualitative comparison of the effects of different drivers, since the uncertainty of estimating these parameters may lead to huge variations in the results.

7 Conclusions

This chapter provided a description of the main aspects involved with the potential profitability of sector coupling applications. While each application has the peculiar features that have been described in the previous sections, some common patterns are worth mentioning.

For all P2X application, the two main drivers are the decreasing electricity price and the policy push toward decarbonization, through an increased penetration in different sectors of clean electricity. As a result, each P2X solution will most probably be deployed firstly in regions with favorable renewable potential, with high annual capacity factors from either wind or solar plants. As a result, applications that lead to the production of a storable fuel will benefit from the implementation of an international market, with specific agreements that are based on the advantages of synthetic fuels over traditional ones, with particular emphasis on the benefits related to their contribution in decarbonization strategies (Perner and Bothe 2018).

Such an international market would benefit from a distributed potential for solar and wind on many countries, in contrast with the current strong concentration of fossil fuels reserves in a limited number of areas on a global scale. Different countries in various continents could play complementary roles in the deployment of various P2X technologies, depending on their resource potentials, existing infrastructures, and national policy trajectories.

P2X may also operate as a storage alternative, especially for long-term storage, and therefore it has some similarities with batteries (see Chap. 14), including the need of upscaling technology deployment to decrease investment costs, and ensure an acceptable amount of operational hours to guarantee fair returns to investors.

While some applications have already proven their economic sustainability in specific markets under current conditions, a broader policy support is required to trigger the further development of these technologies, which are often in competition with incumbent fossil-based alternatives. In this perspective, carbon pricing models or similar policies to factor in the climate externalities may prove to be a key aspect to unlock the potential of P2X technologies in contributing to the decarbonization of the energy system.

Bibliography

Agora Verkehrswende, Agora Energiewende, Frontier Economics, 2018. The Future Cost of Electricity-Based Synthetic Fuels.

Blanco, H., Nijs, W., Ruf, J., Faaij, A., 2018. Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization. Appl. Energy 232, 617–639. https://doi.org/10.1016/J.APENERGY.2018.09.216.

BMVIT, FFG, 2019. fit4power2heat research project [WWW Document]. URL https://nachhaltigwirtschaften.at/en/sdz/projects/fit4power2heat.php (accessed 11.21.19).

Caldera, U., Bogdanov, D., Afanasyeva, S., Breyer, C., 2018. Role of seawater desalination in the management of an integrated water and 100% renewable energy based power sector in Saudi Arabia. Water (Switzerland) 10. https://doi.org/10.3390/w10010003.

Daina, N., Sivakumar, A., Polak, J.W., 2017. Electric vehicle charging choices: Modelling and implications for smart charging services. Transp. Res. Part C Emerg. Technol. 81, 36–56. https://doi.org/10.1016/J.TRC.2017.05.006.

Delmonte, E., Kinnear, N., Jenkins, B., Skippon, S., 2020. What do consumers think of smart charging? Perceptions among actual and potential plug-in electric vehicle adopters in the United Kingdom. Energy Res. Soc. Sci. 60, 101318. https://doi.org/10.1016/J.ERSS.2019.101318.

Götz, M., Lefebvre, J., Mörs, F., McDaniel Koch, A., Graf, F., Bajohr, S., Reimert, R., Kolb, T., 2016. Renewable Power-to-Gas: A technological and economic review. Renew. Energy 85, 1371–1390. https://doi.org/10.1016/J.RENENE.2015.07.066.

IEA, 2019a. The Future of Hydrogen, The Future of Hydrogen. https://doi.org/10.1787/1e0514c4-en.

IEA, 2019b. Global EV Outlook 2019.

IEA HPT, 2017. Annex 42 -Heat Pumps in Smart Grids—Market status summary per country.

Irie, H., 2017. NEDO Smart Community Case Study.

Jian, L., Yongqiang, Z., Hyoungmi, K., 2018. The potential and economics of EV smart charging: A case study in Shanghai. Energy Policy 119, 206–214. https://doi.org/10.1016/J.ENPOL.2018.04.037.

Perner, J., Bothe, D., 2018. International aspects of a power-to-X roadmap.

Rosenlund Soysal, E., Sandberg, E., 2016. Electric boilers in district heating systems—A comparative study of the Scandinavian market conditions, in: SAEE-Conference, Luleå.

Schmidt, O., Melchior, S., Hawkes, A., Staffell, I., 2019. Projecting the Future Levelized Cost of Electricity Storage Technologies. Joule 3, 81–100. https://doi.org/10.1016/J.JOULE.2018.12.008.

Schweiger, G., Rantzer, J., Ericsson, K., Lauenburg, P., 2017. The potential of power-to-heat in Swedish district heating systems. Energy. https://doi.org/10.1016/j.energy.2017.02.075.

Spreitzhofer, J., 2018. Electricity-market participation of heat pumps in single family houses and district heating networks, in: Workshop—Energy Sector Coupling: Electric-Thermal Interaction through Heat Pumps.

Thema, M., Bauer, F., Sterner, M., 2019. Power-to-Gas: Electrolysis and methanation status review. Renew. Sustain. Energy Rev. 112, 775–787. https://doi.org/10.1016/J.RSER.2019.06.030.

Varone, A., Ferrari, M., 2015. Power to liquid and power to gas: An option for the German Energiewende. Renew. Sustain. Energy Rev. 45, 207–218. https://doi.org/10.1016/J.RSER.2015.01.049.