Environmental and Climate Technologies

2019, vol. 23, no. 3, pp. 319–332
doi: 10.2478/rtuect-2019-0098
https://content.sciendo.com

Power Sector Flexibility through Power-to-Heat and Power-to-Gas Application – System Dynamics Approach

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Abstract **– The European Union has set the target for energy sector decarbonization. Variable renewable energy technologies are necessary to reach this target, but a high level of variable renewable energy raises the flexibility issues. In this research paper, the flexibility issue is addressed by analysing possibility of sector coupling via power-to-heat and power-to-gas applications by using system dynamics approach. The model is applied to the case of Latvia. Model results show that power-to-heat is a viable flexibility measure, and with additional financial incentives, it can even help to move towards decarbonization of the energy sector. In the best scenario, heat from surplus power can cover 37 % from total heat production in 2050. Unfortunately, in spite of a well-developed gas infrastructure, power-to-gas application is still very immature, and, in the best-case scenario with high incentives in power-to-gas technologies, only 7 % from available power surplus could be allocated for power-to-gas technologies in 2050.**

Keywords **– Flexibility; power sector; power-to-gas; power-to-heat; system dynamics; VRE**

Nomenclature	
EU	European Union
VRE	Variable renewable energy
P2H	Power-to-heat
P2G	Power-to-gas
OR	Ordering rate for technology
PDR	Production to demand ratio
SH	Power shortage
TDC	Total capacity depreciation
I	Investment decision in technology
α	Coefficient of elasticity
T	Production tariff of technology
P2P	Power-to-power

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P2V	Power-to-vehicle
HPP	Hydro power plant
CHP	Combined heat and power
HOB	Heat only boiler

1. INTRODUCTION

The European Union (EU) is aware that mitigating climate change is one of the main challenges to ensure the sustainable development of Europe, therefore EU officials have set an ambitious targets for decarbonization, and are purposefully moving towards a renewable energy sector [1]. One challenge that the decarbonization target presents is the necessity for a high share of variable renewable energy (VRE), e.g. wind, solar technologies, which have high level of uncertainty [2]. To reach a 100 % renewable power sector, flexibility measures should be implemented to address the issues with supply and demand balancing [3]. There are different flexibility measures analysed by other researchers – supply side flexibility, demand side flexibility, energy storage, cross-border transition, cross-sector coupling, market design [4], [5]. A lot of researchers have analysed different aspects of flexibility.

Ropenus et al. [6] have analysed grids as a flexibility option and shows what kind of planning and operation measures should be taken into account, to optimize the system when VRE share increases. It is important to anticipate VRE increase early to prevent sudden curtailment of VRE generation. Bergaentzle et al. [7] shows how the grid tariff can be used as a tool for flexible energy system. Authors demonstrate the importance of tariff design on VRE development and sector coupling (P2H), and how different tariff designs can send better signals to electricity end-users [7]. Other researchers have analysed cross-border transmission. Thellufsen et al. [8] research is focused on finding the most efficient system by implementing cross-border connections. Results show that cross-border connections help to increase VRE utilization, but in this research costs are not investigated, therefore most efficient solution might not be the most cost effective. Becker et al. [9] however considers not only efficiency, but also costs, and results show that increased cross-border connection helps VRE development. Unfortunately, cross-border transmission can only cover 40 % of balancing energy and cannot be the only flexibility measure. Potential of energy storage is also analysed, by looking at different type of storages – short term (batteries), medium-term (pumped hydro) and long-term (hydrogen) [10]. Storage proves to be valuable flexibility option, however main conclusion is that it is important to evaluate which storage option to consider for each region by its potential, because right energy storage and transmission is economically more beneficial than all energy storages in each region. Sector coupling have also been researched as a flexibility option. Brown et al. [11] have considered different sector coupling options, and concludes that for high share of VRE sector coupling is beneficial – mainly for P2H, but also P2V and P2G shows some promise and are worth considering. Sandberg et al. [12], similar to Bergaentzle et al. [7] indicates that sector coupling development for P2H might be very dependent on future electricity tariff structure. Improved tariff structure, which would be beneficial for VRE, can increase VRE share significantly and also promote sector coupling. Demand side flexibility is also considered as an important flexibility enabling measure [13], [14]. With smart appliances electricity load can be shifted and shedded to better match variation in VRE. Most of the above mentioned research is carried out by utilizing optimization tools – *EnergyPlan*, *GENESYS*, *PyPSA*, *Balmorel*, *TIMES*, etc.

In this paper, the case study of Latvia is analysed, more precisely power sector development of Latvia by implementing sector coupling. Research is done by utilizing simulation tool, rather than optimization tool, which in turn allows to consider causalities and non-linearity's of the system more accurately. Sector coupling is done by supplementing the energy sector with power-to-heat (P2H) and power-to-gas (P2G) applications. In this paper power-to-heat is understood as power transformation to heat by utilizing heat pumps, but power-to-gas is understood as hydrogen production via electrolysis and following methanation process in which methane is produced and further introduced in natural gas grid. Other flexibility measures are not considered in this paper. Analysis is done through the means of system dynamics modelling. Main aim of the paper is to determine whether P2H and P2G applications are economically viable flexibility options in Latvia.

2. METHODOLOGY

2.1. Problem Identification

The analysis in this research is done by using system dynamics modelling approach. System dynamics approach was developed by Jay W. Forrester in the 1950s in order to help industrial companies, and later also governments in the decision-making process [15]. The method allows to analyse complicated structures of real-life systems and helps to identify the leverage points, therefore helping to understand and steer the system in the desirable direction. Nowadays system dynamics approach is applied in various research fields, including research related to environmental and energy issues. For example, some of the research is done to observe the CO_2 mitigation from cement industry [16], other research analyse how household electricity consumption is related to cost-income ratio [17]. There is also research done to analyse energy performance gaps in green office buildings [18], to model green economy [19], to analyse the best management scenarios of wetlands [20], or even forest fires [21]. There is also previous research done in analysing power-to-gas and power-to-liquid concept [22], which was adapted and used as a reference for power-to-gas concept in this research.

First step of systems dynamic modelling is identification of the problem and next step is development of causal loop diagram, which helps to understand the main elements of the system and how they interact with each other.

The main research problem that is addressed in this paper is a need for higher share of renewable energy in the system to reach the targets set by the European Union, but to implement high share of renewable energy in the system, it is not enough to replace existing technologies with renewable ones. Due to the different nature of conventional and VRE technologies, it is important to address the balancing issues that comes from intermittent energy production by implementing the flexibility measures, whether those are at supply side or demand side. Due to the fact that district heating in Latvia has a high share of natural gas, it can be argued that power and heating sector coupling can be beneficial for both sectors. VRE energy increase in power sector can result in high uncertainty and, at times when demand is low, but VRE energy production is high, surplus energy can be used in heat production. Not only that, but surplus energy can be used also in P2G applications. As Latvia has very good gas infrastructure due to the fact that natural gas is the main energy source in power and heating sector, it means that for P2G development there is no necessity for new grid infrastructure, and the only barrier is the production technology installation. As there are a lot of gas technologies that are utilizing natural gas, there should be a large enough market for gas from P2G application. Of course, P2H and P2G development depends on ability to compete against current market players.

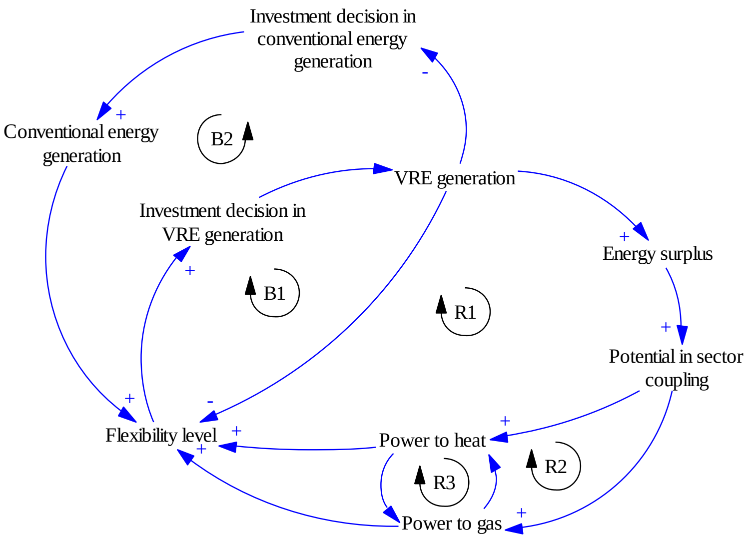


Fig. 1. Causal loop diagram.

As can be seen in Fig. 1, the causal loop diagram consists of five loops – three reinforcing loops (R1–R3) and two balancing loops (B1, B2). Reinforcing loops are responsible for growth of the system, while balancing loops are limiting the growth and keeping the system in balance. In order to reach the preferable outcome, it is necessary to identify the reinforcing and balancing loops in the system, and based on the desired result, adjust the system at certain leverage points within the loops.

First and second reinforcing loops (R1 and R2) are responsible for the development of VRE sources and growth in their installed capacity. As VRE share increases, more common is the situation, when electricity supply is not in balance with demand, therefore resulting in energy surplus, which cannot be absorbed by consumers. If cross-border transmission infrastructure is well developed, surplus energy can always be sold to the neighbouring countries at low prices, and it ensures a system flexibility, but in this research it is assumed that cross-border transmission is not an option and energy surplus must be consumed within the country. In this research power sector flexibility is analysed via sector coupling, e.g., power-to-heat and power-to-gas applications. The higher the power surplus, the more it can be used in power-to-heat and power-to-gas technologies, therefore resulting in an increased flexibility level of the system, which in turn allows to increase VRE share even more. The third reinforcing loop (R3) shows the competition between power-to-heat and power-to-gas applications. As energy surplus is limited in amount, also P2H and P2G capacities are limited, because it is assumed that P2H and P2G concepts are developed only by using renewable energy. The technology that proves to be more profitable, gains more of an advantage over the other technological solution.

First balancing loop (B1) shows that VRE sources on their own cannot ensure the system flexibility, therefore the higher the share of VRE, the less flexible is the system, resulting in slower adoption rate of VRE. Second balancing loop (B2) shows how conventional power generation technologies are able to maintain the high share of energy production in the system. Conventional power generation technologies are those that ensure the power system flexibility at times, when VRE technologies are unable to cover the energy demand due to weather conditions, because they have short start-up time, and they can react fast to an increase in demand, therefore, if there are no other flexibility measures in place, conventional generation technology capacity level will remain high.

The overall conclusion is that high share of renewables in power sector can be achieved only if there are certain flexibility measures in place.

2.2. Model Structure

Fig. 2 shows the main building blocks of the model – stocks and flows. The example in Fig. 2 illustrates two hypothetical technologies and the principle on how their capacities increase and decrease due to changes in the system. Although in the example there are only two technologies, in the actual model a total of six power production technologies, e.g., wind, solar PV, biogas, biomass, natural gas and hydro power, are included and interact with each other on the said principle illustrated in Fig. 2.

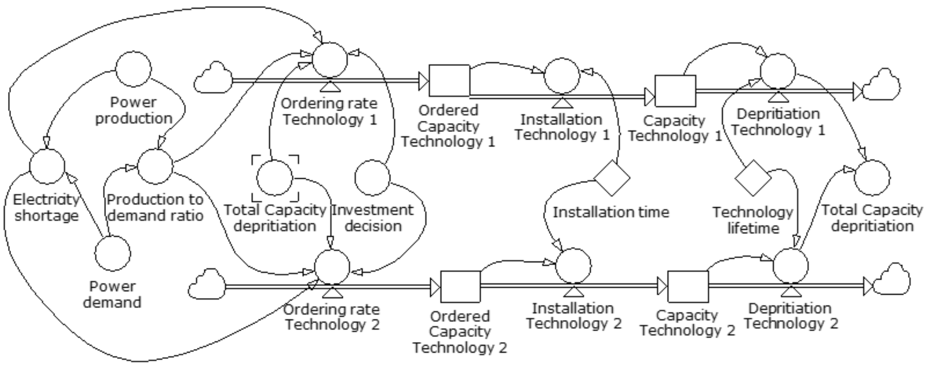


Fig. 2. Stock and flow diagram of production technology capacity development.

The same basic principle is used also in modelling district heating technologies, e.g., natural gas, biomass, solar and heat pump, and also decision making between P2H (heat pumps) and P2G (electrolyser + methanation reactor) technologies. There are also common interaction points between power and heating sectors (combined heat and power (CHP) plants), as well as between heating sector and flexibility options (heat pumps). Gas from P2G application can be used in both the power and heating sector by replacing natural gas.

Stock is the element that describes the state of the system at any point in time (Eq. (1)), while flows describes how the state of the system changes over time. In this case, capacities of the technologies (both ordered and actual) are the stocks, while the ordering rate, installation and depreciation are the flows that are responsible for the state of the stock. Stocks can be expressed with an equation:

$$\mathrm{Stock}_t = \int_{t_0}^{t} [\mathrm{inflow} - \mathrm{outflow}]\mathrm{d}t + \mathrm{Stock}_{t_0} \cdot \tag{1}$$

There are two stocks – ordered capacity and actual capacity, because new capacities are not fully operational instantly after they are ordered, but there is rather some time delay before they get from one stock to other. In this case this time delay is described as time to install the technology. In Fig. 2 it is illustrated as identical for both technologies to show the principle, but it can vary for different technologies. Same can be said about technology depreciation – technologies do not depreciate immediately, but it takes time for the technology to leave the stock. In this case technology lifetime is responsible for the technology depreciation. Technology lifetime can also vary for different technologies.

To keep the system in balance, it is necessary to match energy supply with energy demand, which means that if demand increases or technology capacity decreases, there is a risk of power shortage, and in case there is shortage, additional capacity is required. If the demand is constant over time, then only depreciated technologies needs to be replaced.

$$\mathrm{O}R_1 = if\,(\mathrm{PDR} < 1;(\mathrm{SH} + \mathrm{TCD}) \cdot I_1;\mathrm{TCD} \cdot I_1\,, \tag{2}$$

where

OR_1	Ordering rate for technology 1;
PDR	Production to demand ratio;
SH	Power shortage;
TCD	Total capacity depreciation;
I_1	Investment decision in technology 1.

Investment decision is made by utilizing logit function in which production tariffs of all technologies are compared and based on the profitability the investment share for each technology is calculated [23]:

$$I_1 = \frac{\exp(-\alpha \cdot T_1)}{\exp(-\alpha \cdot T_1) + \exp(-\alpha \cdot T_2) + \ldots + \exp(-\alpha \cdot T_n)'}\,, \tag{3}$$

where

α	Coefficient of elasticity;
T_1	Tariff of technology 1;
T_2	Tariff of technology 2;
T_n	Tariff of technology n.

Tariff for each technology is calculated, by summing all the production costs, including yearly capital costs, operation & maintenance costs, fuel costs (if applicable), taxes, etc.

This decision-making process is also used when comparing district heating technologies as well as in comparing power-to-heat and power-to-gas technologies.

2.3. Studied Scenarios

In this research, four different scenarios were tested and compared. Scenario 1 describes the situation when no supporting policies are implemented, therefore system development happens based on market principles.

TABLE 1. STUDIED SCENARIOS

	Subsidies in capital costs		
	P2G	P2H	Wind
Scenario 1			
Scenario 2	70 %		
Scenario 3		30 %	
Scenario 4			30 %

In scenario 2 power-to-gas technology capital costs are subsidized in order to promote the development of power-to-gas. As Latvia is taken as a case study, P2G application was considered as a viable flexibility option due to a well-developed gas infrastructure.

Scenario 3 analyses the impact that power-to-heat technology could have on power and heating sector development. In this scenario P2H technologies (heat pumps) receive 30 subsidies for capital costs.

In scenario 4 wind technologies (both on-shore and off-shore) receive capital cost subsidies in order to promote VRE development, and in case of increased energy surplus, analyse whether it also promotes the development of P2H and P2G technologies.

2.4. Input Data and Assumptions

This research focuses on the energy supply side, mainly on the power sector and P2H and P2G applications, therefore the demand side was modelled in less detail.

TABLE 2. TECHNOLOGY DATA [25], [26]

	Investment costs, EUR/MW		Fixed O&M, EUR/MW/yr		Variable O&M, EUR/MWh		Technical lifetime, yr	Efficiency, %
	2017	2030	2017	2030	2017	2030		
CHP – natural gas[A]	1 300 000	1 200 000	30 000	27 800	4.5	4.2	25	48
CHP – biomass[A]	3 700 000	3 500 000	158 400	144 000	3.8	3.8	25	27
CHP – biogas[A]	6 700 000	6 000 000	96 500	87 400	5.8	5.8	25	22
Wind on-shore[A]	1 070 000	910 000	25 600	22 300	2.8	2.3	25	37
Wind off-shore[A]	2 460 000	1 640 000	57 300	37 800	4.3	2.7	25	50
Solar PV[A]	1 460 000	690 000	12 800	8 800	0	0	30	17
HOB – natural gas[B]	60 000	50 000	2 000	1 900	1.1	1	25	93
HOB – biomass[B]	700 000	650 000	32 800	31 200	1	1	25	90
Solar collectors[B]	615 000	530 000	2 780	3 130	5	0	25	43
Heat pumps[B]	700 000	590 000	2 000	2 000	3.3	3.7	25	350
PEM Electrolyser[A]	1 500 000	700 000	60 000	30 000	0	0	20	70
Methanation reactor[C]	1 500 000	1 000 000	75 000	50 000	0	0	20	80

[A]Electric capacity (MW_e), electricity production (MWh_e), electric efficiency; [B]Heat capacity (MW_{th}), heat production (MWh_{th}), heat efficiency; [C]Methane production capacity (MW_m) and methane production (MWh_m), methane production efficiency.

Latvia was used as a case study for simulation, therefore energy balance data was taken from the Central Statistical Bureau of Latvia [24], whereas technology specific data and future price as well as efficiency forecasts were taken from the Danish Energy Agency [25] and ENEA consulting [26].

Initial resource prices were taken from Central Statistical Bureau of Latvia [24] and research done by CIVITTA [27]:

- Natural gas – 287 EUR/thous. m^3;
- Biomass – 8 EUR/bulk m^3;
- Biogas feedstock – 30 EUR/t.

It was assumed by the authors that resource prices will increase in the future by:

- 4 % per year for natural gas;
- 2 % per year for biomass and biogas feedstock.

It was assumed that due to energy efficiency measures, total power demand in all sectors, except transport, will decrease by 0.6 % per year. Meanwhile adaption of electric vehicles will increase by 0.6 % per year, therefore slightly increasing the total demand for power. While changes in power demand for transport and other sectors are defined by above mentioned values and are constant for all scenarios, power demand in P2H and P2G applications is calculated by model, based on policy measures exploited. Due to global warming and the ambitious EU climate targets, it was assumed that CO_2 price will increase up to 130 EUR/t_{CO_2} in 2050 for all scenarios to promote renewable energy development. CO_2 price is assumed to be identical for operators under and outside Emission Trading Scheme.

3. RESULTS

After simulating 1st scenario, it can be seen that power sector development towards full decarbonization is very slow, and without additional incentives for renewable energy technologies, natural gas remains as one of the main power production technology (see Fig. 3). Although power produced by natural gas decreases by 34 %, it is not fully replaced by renewable energy, and amount of renewable energy increases only by 17.4 % due to the fact that power demand has decreased in 2050. A large share of current power production comes from hydro power plants, and it was assumed that hydro power plants will not be demolished and will continue to produce at the same rate throughout simulation. HPPs are not considered VREs in this research. In this research only solar and wind technologies are categorized under VRE. It can be seen that wind technologies experienced the highest increase in capacity (+508.5 %), while solar technologies were unable to gain momentum. It should be noted that only centralized power production is considered in this research, therefore residential PVs and other decentralized production units are not modelled and will not be illustrated in total energy balance.

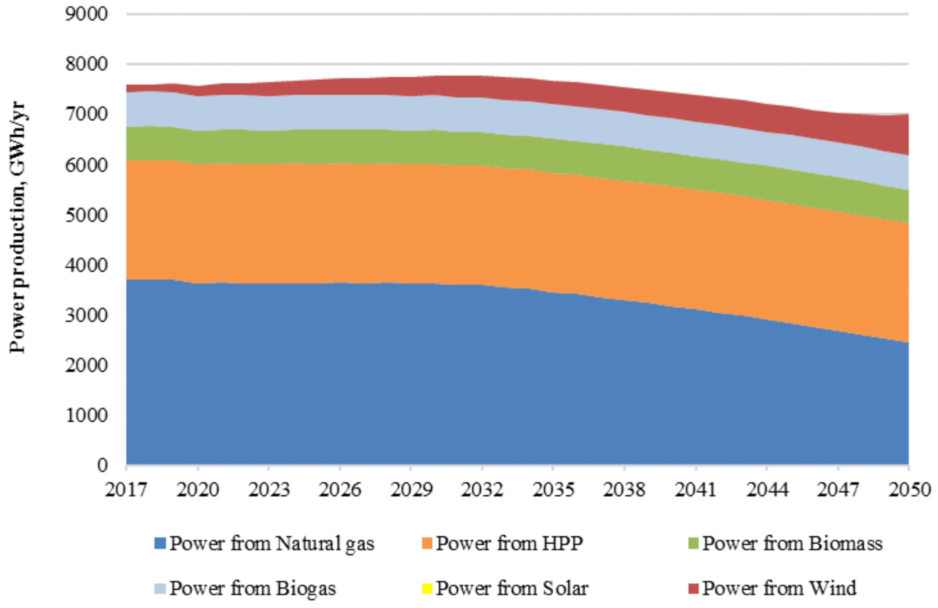
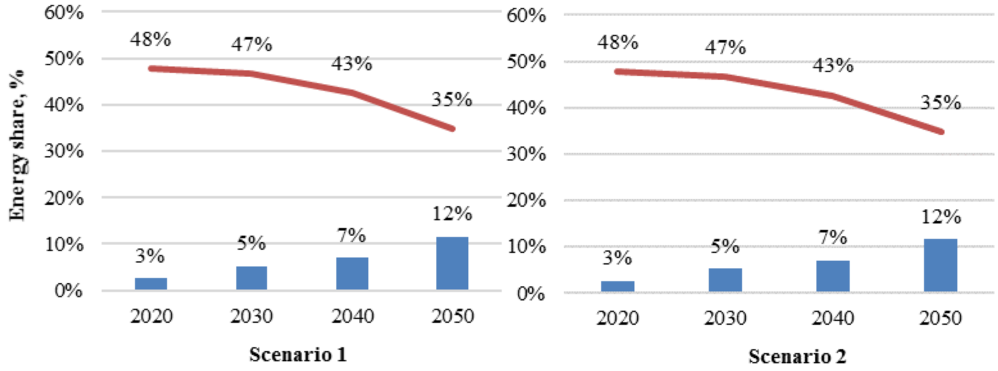


Fig. 3. Power production development (Scenario 1).

When comparing all four scenarios, it can be seen that the highest impact comes from subsidizing heat pump technologies (see Fig. 4).



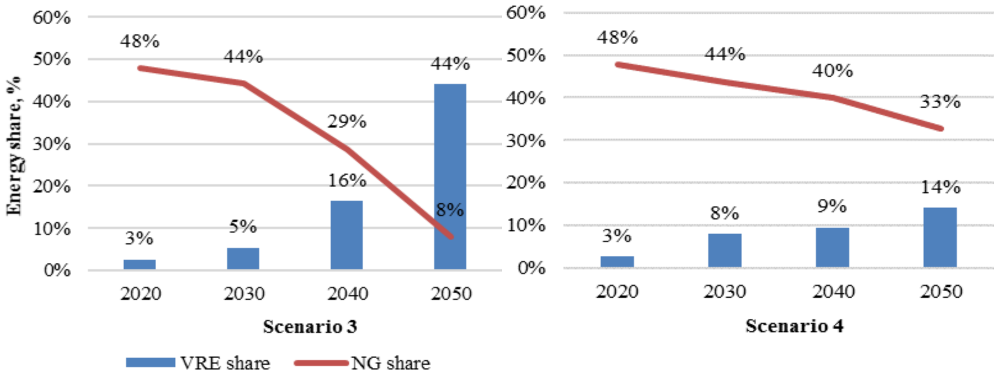


Fig. 4. Comparison of VRE and NG share in all scenarios.

Scenario 1 in which no subsidies were granted and Scenario 2 in which subsidies for P2G technologies were granted are practically the same, when comparing VRE and natural gas share in 2050. This can be explained by the fact that, although there is good gas infrastructure, and 70 % of P2G capital costs were subsidized, still the total costs of production were too high to use P2G as a viable flexibility option. Only 7 % of power surplus was used in P2G application in Scenario 2. In other scenarios it was less than 1 %. Other incentives, like reduction of power grid costs might be necessary to make it more competitive.

It can be seen that also Scenario 4 in which wind generation technologies are subsidized, only 2 % improvement in VRE share can be observed. This might be due to the fact that large share of energy still comes from HPP, and to increase VRE share, it is necessary to decrease natural gas share, but 30 % subsidies are not enough.

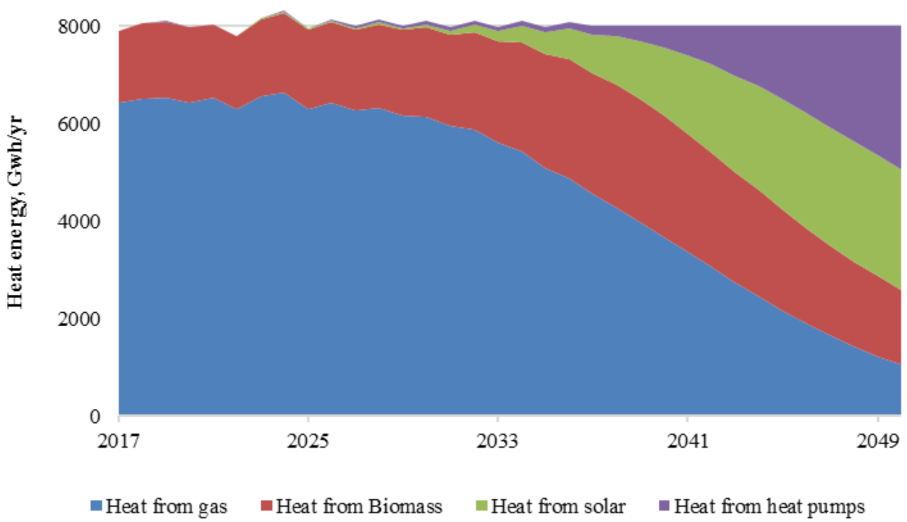


Fig. 5. Heat production development (Scenario 3).

Completely different results come from subsidizing P2H applications in district heating. Fig. 5 shows that heat pumps (technology used in P2H application) are responsible for 37 %

of total heat energy production in 2050 in Scenario 3, while natural gas production drops from 81 % to 13 % from total energy production. It should be underlined that P2H can develop only when there is enough surplus energy from VRE, and in Scenario 3 both wind and P2H technologies developed faster than in other scenarios. This can be explained by a fact that power and heat sector is connected via natural gas technologies, that utilize CHP plants and in order to replace natural gas in one sector, it should be at the same time replaced also in the other sector. As heat production is a priority for CHP plants, as they have to cover certain heat demand at their district, they cannot be shut down if there is no replacement in heat generation, even if there is incentive to replace power generation capacity. Different situation is when there is incentive to replace heat generated by CHP, because power shortage from closing CHP plant in the short term can be replaced with power import, and it would be more cost effective than using CHP plant in condensing mode.

Subsidies in heat pump capital costs results in 44 % of VRE share in power production, and 8 % natural gas share in power production in 2050 (see Fig. 4). This is by far the best decarbonization scenario and also best sector coupling scenario with highest flexibility.

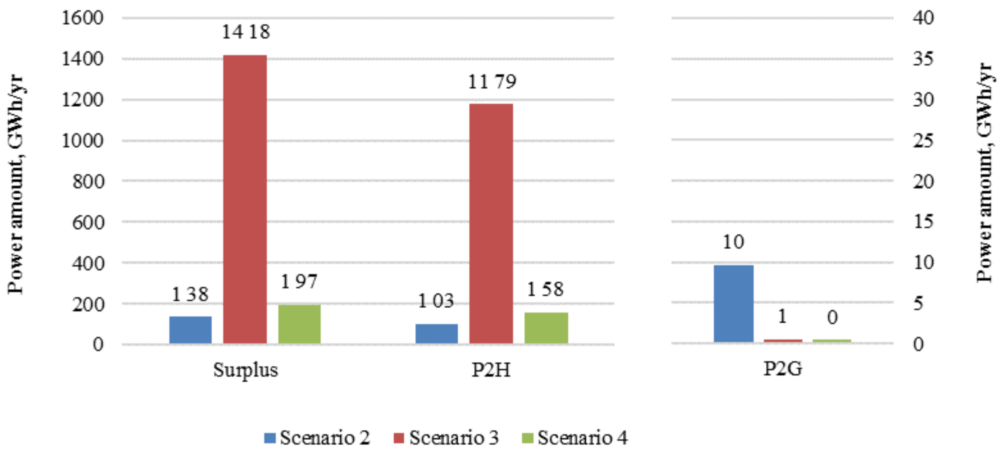


Fig. 6. Level of sector coupling in different scenarios.

Fig. 6 shows the level of sector coupling. As described before, it can be seen that the largest energy surplus and P2H production amount is in Scenario 3, when heat pump capital costs are subsidized, followed by Scenario 4, when wind capital costs are subsidized. Unfortunately, only in Scenario 2 there is noteworthy production of synthetic natural gas via P2G application, and even then it could not quite compete with P2H application and with natural gas price. There is still a lot of research and technology development necessary to make P2G application more competitive.

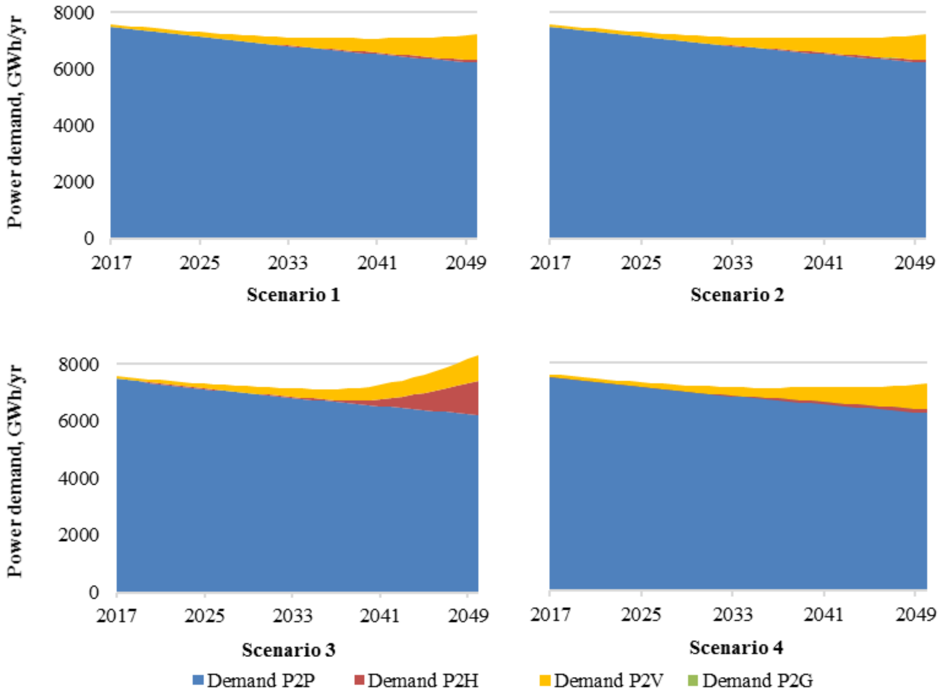


Fig. 7. Power sector demand.

Fig. 7 shows how the power demand changed in all four scenarios. As changes in consumer demand and power-to-vehicle demand are not affected by scenarios and increase and decrease fraction are identical for all scenarios (see Section 2.4.), the only noteworthy difference can be seen in Scenario 3, when, by subsidizing heat pumps, power demand in heating significantly increases, while in other scenarios power demand increase due to P2H and P2G development is insignificant and only slightly changes total power demand. Fig. 7 shows that P2H subsidies can enable electrification of heating sector, therefore promoting sector coupling. P2H development also promotes faster adaption of wind energy, because it solves the issue of where to utilize excess wind energy at times when wind power production exceeds consumer power demand. Unfortunately, there is no indication of increased power demand in renewable gas production.

4. Conclusion

It can be concluded that sector coupling can be used as a flexibility measure, but at the moment only power-to-heat technologies can be somewhat competitive. The result section shows that there is potential for power-to-heat applications even without financial incentives. Model was built based on energy balance of Latvia and assumptions relevant to Latvia, therefore results are valid for Latvian case, however generic model structure allows to analyse also other countries by substituting current input data and assumptions to the relevant values. Countries without well-developed gas infrastructure must consider additional costs related to non-existent infrastructure.

The best scenario shows that sector coupling, and financial incentives can be a very useful tool in moving toward total energy system decarbonization in Latvia. In best scenario natural gas share dropped to 8 % in power production, and 13 % in heat production, while in worst case scenario natural gas share was 35 % and 60 %.

Power-to-gas application proved to be immature, and there is still a lot of research and development necessary to make it competitive against power-to-heat application, and also against natural gas.

Current model includes only detailed production part, but energy sector consists also from demand side, therefore in the future the model should be implemented with a more detailed demand side. Another important improvement that should be accounted for is decentralized energy production, which could have a huge impact on future energy system. Decentralization should be implemented in future research, because current development trends and a lot of different researches show that the energy system might move towards decentralization, which can be another source of flexibility.

In the future the model can also be supplemented with other flexibility options.

ACKNOWLEDGEMENT

The work has been supported by Nordic Energy Research project Flex4RES.

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