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System Dynamic Model for the Accumulation of Renewable Electricity using Power-to-Gas and Power-to-Liquid Concepts

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Abstract **– When the renewable energy is used, the challenge is match the supply of intermittent energy with the demand for energy therefore the energy storage solutions should be used. This paper is dedicated to hydrogen accumulation from wind sources. The case study investigates the conceptual system that uses intermitted renewable energy resources to produce hydrogen (power-to-gas concept) and fuel (power-to-liquid concept). For this specific case study hydrogen is produced from surplus electricity generated by wind power plant trough electrolysis process and fuel is obtained by upgrading biogas to biomethane using hydrogen. System dynamic model is created for this conceptual system. The developed system dynamics model has been used to simulate 2 different scenarios. The results show that in both scenarios the point at which the all electricity needs of Latvia are covered is obtained. Moreover, the methodology of system dynamics used in this paper is white-box model that allows to apply the developed model to other case studies and/or to modify model based on the newest data. The developed model can be used for both scientific research and policy makers to better understand the dynamic relation within the system and the response of system to changes in both internal and external factors.**

Keywords **– Energy model; energy transition; sustainability; electrolysis; methanation**

Nomenclature		
bg	Volumetric flow of biogas	m^3/hr
BG	Volume of biogas	m^3
ch_4	Volumetric flow of methane	m^3/hr
CH_4	Volume of methane	m^3
E	Flow of electricity	MWh/hr
h_2	Volumetric flow of hydrogen	m^3/hr
H_2	Volume of hydrogen	m^3
U	Energy density	MWh/m^3
η	Efficiency	–
subscripts		
ac	accumulated	–
bio	biomethane	–
CH_4	methane	–
CO_2	carbon dioxide	–

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el	electrolysis	–
gi	gaseous impurities	–
H_2	Hydrogen	–
im	with impurities	–
st	biogas stations	–
w	biodegradable waste	–
superscripts		
init	initial value	–

1. INTRODUCTION

Currently there are no more doubts that climate change is really happening around the globe. In order to contradict climate change new measures should be introduced and the current technologies should be optimized to work with full potential.

In the field of renewable energy technologies the main limitation usually is the intermitted nature of these energy resources, for example, solar and wind power. To better match the supply of renewable energy with the demand for energy, the solution of energy storage should be used.

In the case of electricity production from wind and solar energy, the storage of surplus electricity can take a form of hydrogen. This concept is commonly defined as the renewable power-to-gas concept [1]. Power-to-gas projects have taken rapid development, 41 realized and seven planned projects are review by Gahleitner [2] starting from 1991. The review states that more power plans are projected to be in the operation in near future, since Germany have defined the power-to-gas as one of the step for the development of renewable energy systems.

The bottleneck of this concept is the costs of hydrogen production that create the main share of the total system's costs as given in the review by Gotz et al. [3]. At the same time during the analysis of pilot plants Gahleitner [2] found out that the system's design, control and integration into the grid plays important role in the efficiency of the overall system and consequently the economics of the project. Also the Qadrdan et al. [4] show that the operation cost of integrated power-to-gas system was lower in the case study of Great Britain than anticipated.

Later on hydrogen obtained from electricity can be used in various pathways: in fuel cell, in fuelling stations, in gas distribution system, for methanation or for synthesis of other hydrocarbons [2]. Nevertheless use of hydrogen in its pure form is limited by the applications and moreover by the infrastructure. For example, Reiter and Lindorfer [5] evaluated the possible routes for hydrogen's methanation. A new concept for the transformation of electricity to liquid fuel is studied by Cinti et al. [6], where the estimated efficiency of the process could reach 57 %. The review on methanation processes is carried out by Ronsch et al. [7]; authors conclude, that nevertheless the production processes of methane are studied for more than 100 years the use of the methanation process in sustainable energy system has been the main reason behind intensified research on these processes during last ten years. Our study specifically focuses on the biogas upgrading with hydrogen to biomethane.

The obtained biomethane can then be treated until the quality of natural gas and injected into the natural gas grid. Since the natural gas infrastructure is well developed in various countries, including Latvia, the access to biomethane would be a simple both for industry and households. As for now, the costs of natural gas are lower than the costs of biomethane obtained from hydrogen; therefore without the growth of the price for fossil fuel or decrease of the price for biomethane, the biomethane's injection into the grid do not bring profit [8].

Statistical optimization analysis for the power-to-gas system was done by Guandalini [9], and various scenarios based on the load curves are given for the power-to-gas and power-to-liquid systems in Germany by Varone and Ferrari [10] nevertheless little studies are using dynamic optimization methodologies.

Therefore this paper is dedicated to study hydrogen accumulation from wind sources: in particularly investigating the elements of hydrogen-biomethane accumulation system using system dynamics model. The first idea of this concept is present by the authors in the article [11]. The case study is done for Latvia.

This proposed solution would be an opportunity for 'greening' energy balance by providing alternative renewable resource without the modifications needed for well-developed supply grid. Moreover, the methodology of system dynamics used in this paper is a white-box model that allows to apply the developed model to other case studies and/or to modify the model based on the newest data.

The developed model can be used for both scientific research and policy makers to better understand the dynamic relation within the system and the response of the system to changes in both internal and external factors.

2. BACKGROUND INFORMATION ON CASE STUDY

The case study investigates the conceptual system (given in Fig. 1) that used intermitted renewable energy resources to produce hydrogen (power-to-gas concept) and fuel (power-to-liquid concept). For this specific case study hydrogen is produced from the surplus electricity generated by renewables trough electrolysis process and the fuel is obtained by upgrading biogas to biomethane using hydrogen obtained by electrolysis.

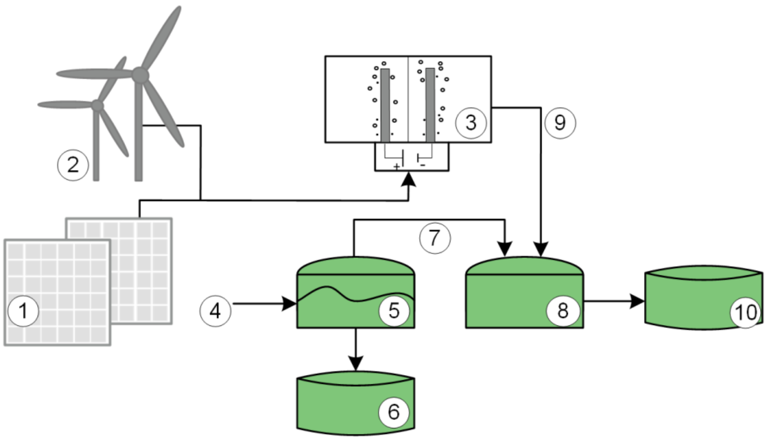

Fig. 1. The conceptual system of renewable electricity accumulation by power-to-gas and power-to-liquid concepts using hydrogen to upgrade biogas to biomethane.

The main elements in this conceptual system (given in Fig. 1) include:

1. solar photovoltaic panels, where sun acts as the source of intermittent renewable energy (not included further in the case study);
2. wind turbines, where wind is as the source of intermittent energy;
3. electrolysis process for hydrogen production from renewable electricity;
4. substrate inlet to the bioreactor; the type of substrate used depends on the available

feedstock, this feedstock can be, for example, agricultural waste, manure, algae or other type of biomass;
5. bioreactor, where biogas is produced at constant temperature under anaerobic conditions; the end product of this anaerobic digestion is biogas and digestate;
6. digestate from the bioreactor is transferred to storage tank;
7. biogas from the bioreactor is transferred to biomethanation process;
8. biomethanation plant where biogas is upgraded to biomethane using hydrogen from renewable electricity;
9. hydrogen from electrolysis process is transferred to biomethanation plant;
10. storage tank of biomethane.

The biogas plants, that are included in this conceptual scheme, produce biogas from renewable resources. The production of biogas is based on the process of anaerobic digestion. During this biochemical process in the absence of oxygen various microorganisms break down organic substrates, such as plant biomass and waste, manure, slurry, organic waste, sewage and sludge, etc. The end products of the anaerobic digestion are biogas and digestate. The share of methane (CH_4) in biogas depends on the used substrate therefore can vary between 55 % and 70 %. The major part of the remaining share is carbon dioxide (CO_2).

The concentration of methane during anaerobic digestion can be increased using various methods, for example, through the use of additives, the reuse of liquid manure and slurry's filtrate, the change of operational parameters and the use of biofilters or fixed-film systems.

The authors propose to supplement existing biogas production plant with methane upgrading unit or biomethanation plant, where the concentration of methane in biogas is increased by adding hydrogen (H_2) from the electrolysis process; see Eq. (1)

$$CO_2 + 2H_2 = CH_4 + O_2 , \tag{1}$$

Biogas that consists of approximately 60 % of CH_4 and 40 % of CO_2 is filled into the biomethanation plant. Hydrogen is constantly being supplied to the biomethantation plant; the supplied volume of hydrogen does not exceed 1/20 of the biomass inlet.

3. METHODOLOGY

System dynamic model was created for the conceptual system of renewable electricity accumulation with the power-to-gas and power-to-liquid concepts. The aim of this proposed model is to find solution for the dynamic problem – intermittent energy resources cannot match the demand for electricity. The proposed dynamic hypothesis is that by utilizing conceptual system of renewable electricity's accumulation, it is possible to integrate large scale intermittent energy sources in the electrical grid and to match the demand for electricity.

The general description of system dynamics methodology can be found in the article by authors on the system dynamics model for the sector of waste portables batteries [12], for the sector of lead-acid accumulators [13], for the remediation of contaminated soil [14], for the diffusion of energy efficient lightning [15], for the technological substitution [16], for the analysis of sectors outside emission trading scheme [17], [18] and for the sector of agriculture [19].

3.1. Causal Loop Diagram

The dynamic behavior of the model is described by five causal feedback loops, see Fig. 2.

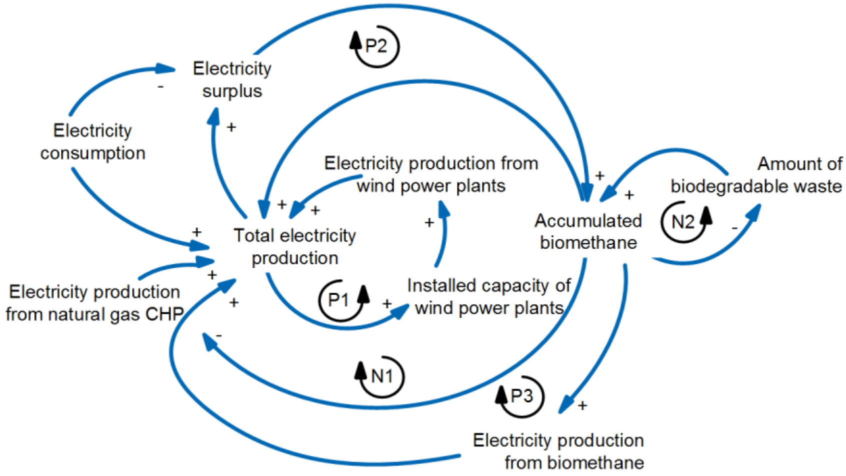

Fig. 2. Causal loop diagram for the conceptual system of renewable electricity accumulation using hydrogen to upgrade biogas to biomethane (P – positive causal loop, N – negative causal loop).

Positive loop P1 (given in Fig. 2) defines that if the amount of *total electricity production* increases, the *installed capacity of wind power stations* also increase, thereby increasing the amount of *electricity produced from wind power plants*.

Second positive loop P2 shows that if *electricity production from wind power stations* grows, that causes the increase in the amount of *accumulated biomethane* as well, consequently, expanding the *total electricity production*.

The loop P2 limits wind power accumulation and thus *biomethane accumulation* can occur only when *electricity surplus* exists.

At the same time the loop P3 shows that if *accumulated biomethane* increases, the *electricity production from biomethane* increases also, leading to the increase in *total electricity production.*

The operation of positive loops is equilibrated with two negative loops. The loop N1 states that if the volume of *accumulated biomethane* increases, the amount of *electricity production from natural gas CHP plants* is reduced. In the case the amount of *accumulated biomethane* is reduced the electricity will be produced in CHP plants. This loop is includes in the simulation Scenario 2.

Second negative loop N2 shows that the amount of *accumulated biomethane* cannot increase indefinitely, since the *amount of biodegradable waste* is limited; the more bio-hydrogen is produced the fewer biodegradable waste remains.

3.2. The Structure of the System Dynamic Model

The structure of system dynamics model is given in Fig. 3 that corresponds to the conceptual scheme given in Fig. 1 and causal loop diagram given in Fig. 2.

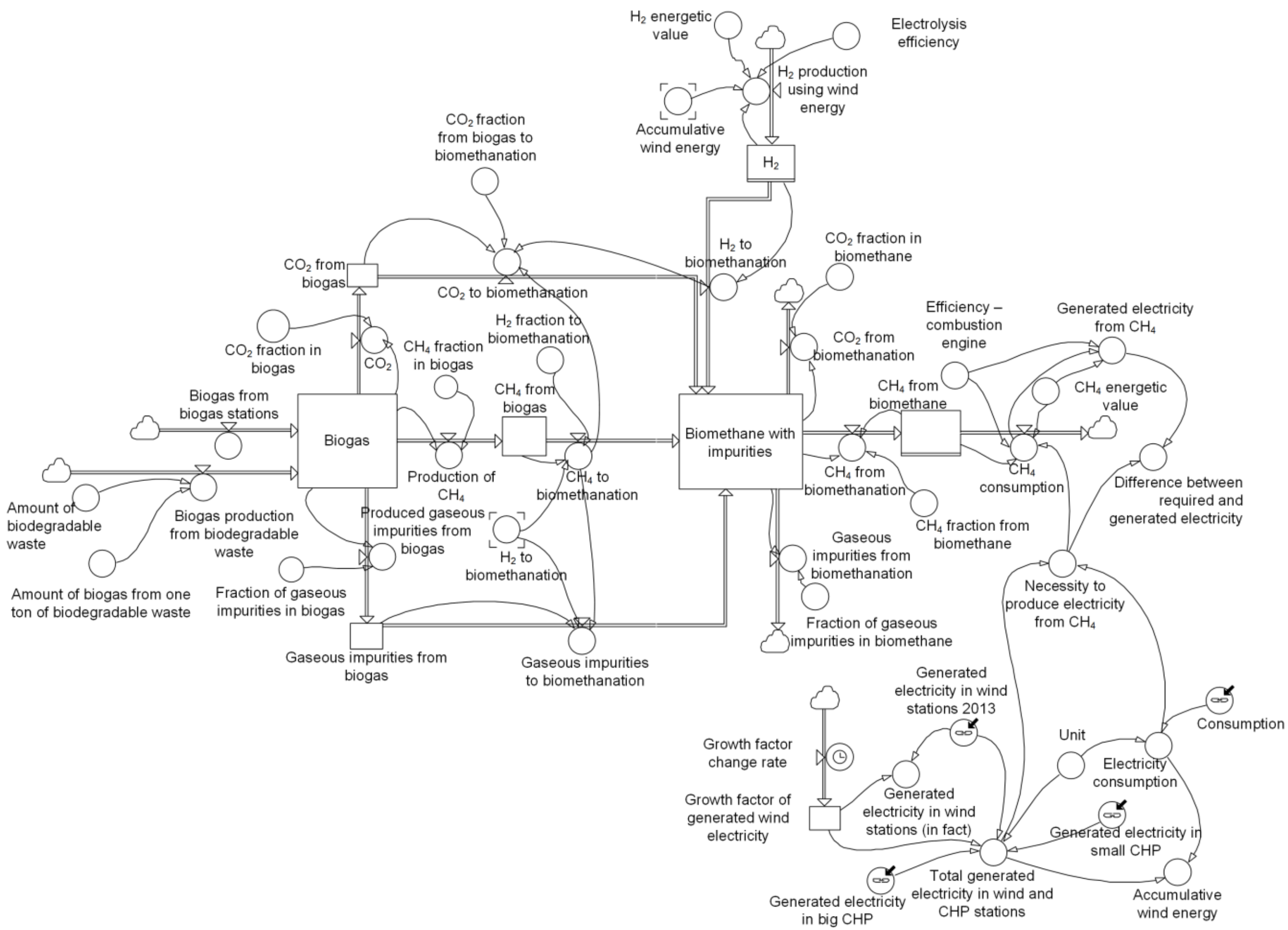

Fig. 3. System dynamics model for the conceptual system of renewable electricity accumulation using hydrogen to upgrade biogas to biomethane.

The main stocks in this model (given as a rectangle in Fig. 3) are the amount of biogas, CO_2 from biogas, gaseous impurities from biogas, CH_4 from biogas, H_2, biomethane with impurities and CH_4 from biomethane.

The change in these stocks is the function of the input and output flows and these input and output flows are dependent on various factors.

For example, the amount of accumulated biogas (biogas in the stock) depends on the amount of biogas from biogas stations, biogas production from biodegradable waste, the amount of biodegradable waste, production of CH_4, CO_2 and the produced gaseous impurities from biogas; see Eq. (2)

$$BG_{ac} = \int_{t=2013}^{t=2030} (bg_{st} + bg_w - bg_{CH_4} - bg_{CO_2} - bg_{gi})dt + BG_{ac}^{init}, \tag{2}$$

where

BG_{ac}	volume of accumulated biogas, m^3;
bg_{st}	volumetric flow of produced biogas in biogas stations, m^3/hr;
bg_w	volumetric flow of produced biogas from biodegradable waste, m^3/hr;
bg_{CH4}	volumetric flow of methane derived from biogas , m^3/hr;
bg_{CO2}	volumetric flow of CO_2 derived from biogas, m^3/hr;
bg_{gi}	volumetric flow of gaseous impurities derived from biogas, m^3/hr;
BG_{ac}^{init}	initial volume of accumulated biogas, m^3.

The volumetric flow of the biogas from biogas stations is 7000 m^3/hr. Biogas production from biodegradable waste depends on the amount of biogas from one ton of biodegradable waste (110 m^3/t) and the amount of biodegradable waste (35 t/hr). From biogas derived volumetric flow of CH_4, CO_2 and gaseous impurities is calculated according to [19]. The initial value for the volume of accumulated biogas is zero.

The volume of accumulated *CH_4 from biogas* that is derived from *biogas* stock depends on the *CH_4 fraction in biogas*, see Eq. (3)

$$CH_{4,ac} = \int_{t=2013}^{t=2030} (bg_{CH_4} - ch_{4,bio,im})dt + CH_{4ac}^{init}, \tag{3}$$

where

$CH_{4,\,ac}$	volume of accumulated methane, m^3;
bg_{CH4}	volumetric flow of methane derived from biogas, m^3/hr;
$ch_{4,bio,im}$	volumetric flow of biomethane with impurities derived from biogas, m^3/hr;
$CH_{4\,ac}^{init}$	initial volume of accumulated methane, m^3.

Methane derived from biogas is later used during biomethanation process or upgrading of biogas. The volume of *biomethane with impurities* derived from *CH_4 from biogas* is calculated according to [19]. The initial value for the volume of the accumulated *CH_4 from biogas* is zero. The amount of accumulated *CO_2 from biogas* and *gaseous impurities from biogas* is calculated similarly to the amount of the accumulated *CH_4 from biogas*.

The amount of accumulated biomethane with impurities depends on CH_4 supplied to and obtained from biomethanation, CO_2 supplied to and obtained from biomethanation, gaseous impurities supplied to and abtained from biomethanation and H_2 supplied to biomethanation, see Eq. (4)

$$CH_{4,bio,im,ac} = \int_{t=2013}^{t=2030} (ch_{4,bio,im} + ch_{4,bio,im,CO_2} + ch_{4,bio,im,gi} + h_{2,bio} - ch_{4,bio} - \\ - ch_{4,bio,CO_2} - ch_{4,bio,gi})dt + CH_{4,bio,im,ac}{}^{init}, \quad (4)$$

where

$CH_{4,bio,im,ac}$ volume of accumulated of biomethane with impurities, m^3;

$ch_{4,bio,im}$ volumetric flow of biomethane with impurities derived from biogas given as *CH_4 to biomethanation* in Fig 3, m^3/hr;

$ch_{4,bio,im,CO2}$ volumetric flow of CO_2 derived from biogas given as *CO_2 to biomethanation* in Fig 3, m^3/hr;

$ch_{4,bio,im,gi}$ volumetric flow of gaseous impurities derived from biogas given as *gaseous impurities to biomethanation* in Fig 3, m^3/hr;

$h_{2,bio}$ volumetric flow of hydrogen supplied to biomethanation process, m^3/hr;

$ch_{4,bio}$ volumetric flow of methane after biomethanation or biogas upgrading, given as *CH_4 from biomethanation* in Fig 3, m^3/hr;

$ch_{4,bio,CO2}$ volumetric flow of CO_2 after biomethanation or biogas upgrading, given as *CO_2 from biomethanation* in Fig 3, m^3/hr;

$ch_{4,bio,gi}$ volumetric flow of gaseous impurities after biomethanation or biogas upgrading, given as *gaseous impurities from biomethanation* in Fig 3, m^3/hr;

$ch_{4,bio,im,ac}{}^{init}$ initial volume of the accumulated of biomethane with impurities, m^3.

The volume of the *H_2 to biomethanation* is calculated according to [19]. The initial value of the volume of the accumulated *biomethane with impurities* is zero.

The amount of accumulated H_2 depends on the accumulatated wind energy, efficiency of electrolysis and the energetic value of H_2, see Eq. (5)

$$H_{2,ac} = \int_{t=2013}^{t=2030} (E_{ac} \cdot \eta_{el} \cdot U_{H_2} - h_{2,bio})dt + H_{2,ac}{}^{init}, \quad (5)$$

where

$H_{2,ac}$ volume of accumulated hydrogen, m^3;

E_{ac} flow of accumulated electricity to electrolysis process; MWh/hr;

η_{el} efficiency of electrolysis;

U_{H2} energy density of hydrogen, MWh/m^3;

$h_{2,bio}$ volumetric flow of hydrogen supplied to biomethanation process, m^3/hr;

$H_{2,ac}{}^{init}$ initial volume of the accumulated hydrogen, m^3.

Accumulative wind energy that is supplied to electrolysis process (*H_2 production using wind energy*) is the *difference between required and generated electricity*, therefore surplus electricity is used for the electrolysis process.

The model is based on hourly data about electricity consumption and electricity production by wind power plants and combined heat and power (CHP) plants running on natural gas. Data was obtained from the database of electricity supplier. The time step for modelling is one hour.

The model assumes that from the year 2016 electricity generated by wind power will grow linearly. As a result in the year 2030 electricity generated by wind power plants will grow by factor of 31 in the comparison to the year 2015. Another assumption is that electricity consumption during simulation time will remain constant. The efficiency of electrolysis is assumed to be 50 %, but the energy density of hydrogen as 0.006 MWh/m^3 and the initial value of the accumulated hydrogen of 500 m^3.

In the biomethanation process or during biogas upgrading obtained methane is used for the production of electricity in internal-combustion engines (with assumed efficiency of 80 %) thus substituting fossil fuels (the efficiency of fossil CHP was time variant, since the real operational data was taken from the statistical databases). The internal-combustion engines start to operate when the difference between electricity consumption and supply is higher than 0 or in other words when there is energy deficit.

4. Results

The amount of electricity generated by wind power plants is small and production capacity does not increase (based on the historical data) until 2016, but (it is assumed) from the year 2016 the installed capacity of wind power plants increases, therefore also the amount of electricity produced grows; see Fig. 4.

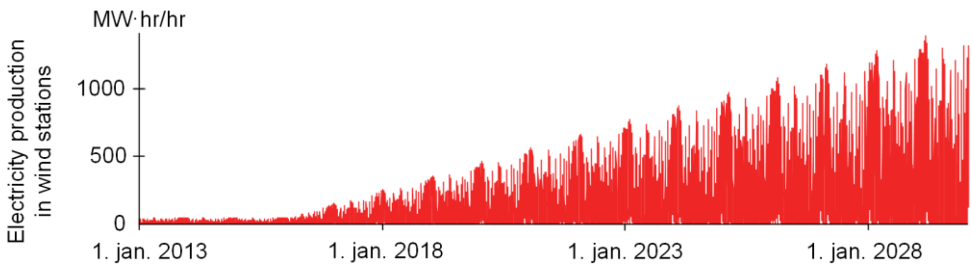

Fig. 4. Electricity generated by wind power plants.

The results are presented in the units of MWh/hour since these units shows the simulation time step and therefore cannot be simplified to just MW.

For the formulation of scenarios this developed case study is used, where the capacity of intermittent renewable technologies will grow. The outlined problem is to use the electricity generated by the wind power plant efficiently, thus studying the opportunity for the power-to-gas and power-to-liquid concepts.

The developed system dynamics model was used to simulate 2 different scenarios:

1. electricity generated in CHP plants by fossil fuel remains constant until year 2030;
2. electricity generated in CHP plant by fossil fuel declines towards zero until 2030.

4.1. First Scenario: Electricity Generated in CHP Plants by Fossil Fuel is Constant until Year 2030

In the case of first scenario, most of the electricity can be accumulated; see Fig. 5.

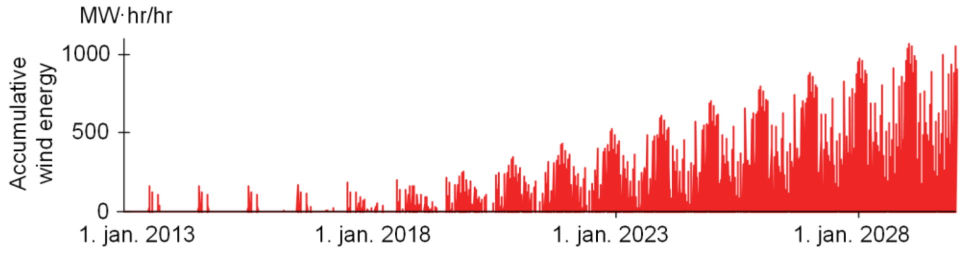

Fig. 5. Accumulated wind energy in first scenario.

In the first years of the simulation wind energy is accumulated during summer only. However due to the increase in the installed capacity of wind power plant, surplus electricity is available all year round at the end of the simulation.

Since the accumulated wind energy in this case study is used for hydrolysis process, the volumetric flow of hydrogen is directly proportional to the amount of accumulated wind energy. Where at the beginning of the simulation hydrogen production around 15000 m^3/hr is possible at summer only, but at the end of the simulation hydrogen production is possible all year round, with the peak production around 80000 m^3/hr in summer. Also the amount of accumulated hydrogen at beginning is negligible, because hydrogen is supplied during summer only. However the amount of accumulated hydrogen increases to the end of the simulation reaching around 80000 m^3 during summer months and around 40000 m^3 during winter months.

Two underlying processes ensures this dynamics – the increasing electricity production from wind power plants (see Fig. 4) and the lower demand for electricity in summer months with creates possibility to accumulate electricity (see Fig. 5).

The obtained hydrogen then can be supply to the biogas upgrading or biomethanation processes, later the obtained biomethane can be used for electricity generation. Nevertheless the growth of the hydrogen production is limited by the capacity of wind power plants and the growth of biogas is limited by the availability of the feedstock.

The total balance of the electricity generated and the demand for electricity in Fig. 6.

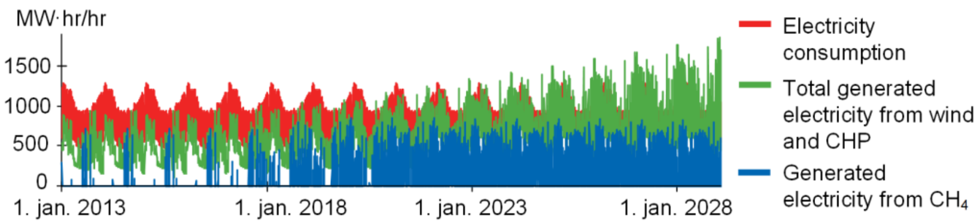

Fig. 6. The total balance of the electricity generated and electricity demand in first scenario.

During the first years of the simulation the electricity generation by wind power plants accounts only for a small share in the total electricity production. However the situation changes due to the increasing electricity supply from wind power plant and the use of biomethanation system for power-to-gas and power-to-liquid. As the result the electricity production by 2030 exceeds the demand for electricity.

Also the marginal role of the electricity produced by methane becomes significant player before the year 2020. While the electricity production by wind power plants increases (the green line in Fig. 6) and the CHP production remains the same (initial assumption of this scenario), the electricity generated by the methane has already reached the maximum capacity of 800 MWh/hour by the middle of the simulation. The reason for this trend is the limited amount of feedstock for biogas production, which in our case translates to the limited amount of methane available for upgrading with hydrogen.

This dynamics of the limited feedstock for biogas can also be illustrated by the Fig. 7.

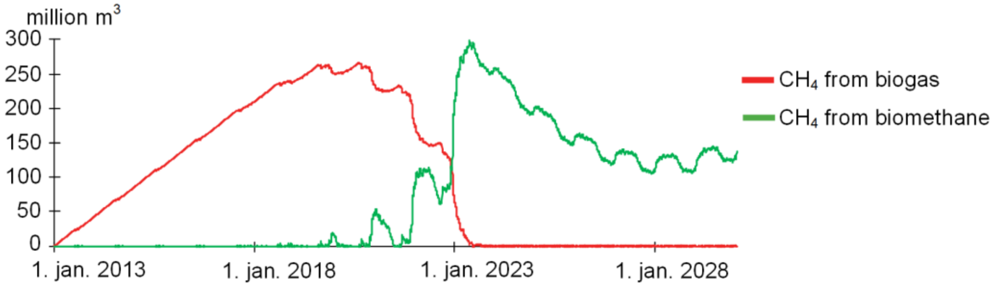

Fig. 7. The amount of accumulated CH_4 from biogas and CH_4 from biomethane for the first scenario.

While the capacity of wind power plants is small and there is no surplus electricity that could be accumulated, the amount of methane from biogas increases. This methane if necessary can be used for the example in transportation sector. Nevertheless it is not upgraded to biomethane quality since there is a deficit of hydrogen from electrolysis.

However, when the capacity of wind power plant is sufficiently high to provide surplus electricity for hydrogen electrolysis, the methane from biogas stations is derived to the upgrading processes with hydrogen or biomethanation, therefore the amount of biomethane starts to increase, while the amount of methane from biogas begins to decrease.

4.2. Second Scenario: Electricity Generated in CHP Plant by Fossil Fuel Converge to Zero by 2030

The amount of electricity generated by wind power plant in the second scenario is the same as in the first scenario (see Fig. 4). However, the amount of accumulated electricity is significantly lower than in the first scenario; see Fig. 8.

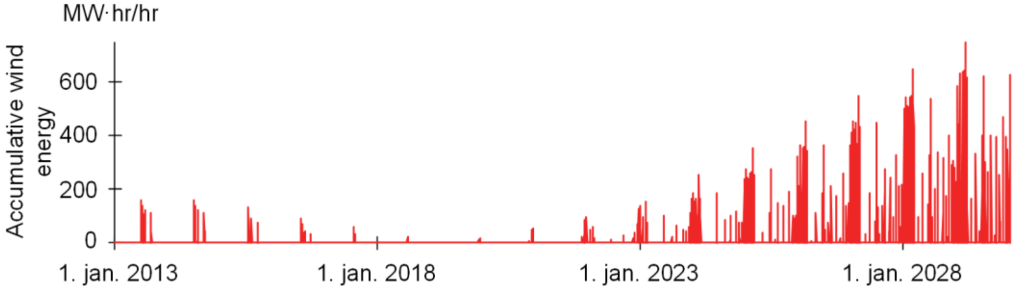

Fig. 8. The amount of accumulated wind energy in second scenario.

The difference between the amounts of accumulated wind energy in both scenarios is due to the decrease of electricity production in CHP plants by fossil fuel, thus creating energy deficit and the opportunity to supply more electricity from the wind power plant directly to the grid, without accumulation. It is assumed for this scenario two that electricity that is produced in CHP plants by fossil fuel decreases steadily from around 900 MWh/hour at the begging of the simulation to zero at the end of the simulation.

Since there are low amount of surplus renewable electricity to accumulate and use in the hydrolysis processes, the amount of the hydrogen produced is lower than in the first scenario. During the first years of the simulation hydrogen is produced during the summer only when energy surplus exists. At the middle of the simulation hydrogen is not being produced, but in the year 2030 its generation begins again, reaching around 60000 m^3/hour at the end of the simulation. This dynamic occurs due to the decrease of the CHP's capacity and the negligible amount of electricity that is generated in the wind power stations at the beginning of the simulation. As a result there is no energy surplus. By increasing the number of wind power plants, at some points of the simulation, usually summer months, energy surplus starts appears, therefore hydrogen can be produced.

The total balance of the electricity generated and the demand for electricity for the second scenario is given in Fig. 9.

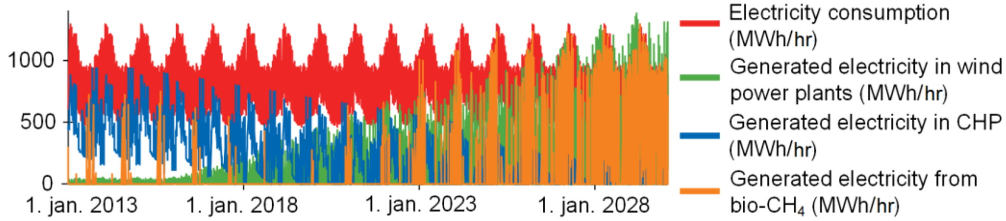

Fig. 9. The total balance of the electricity generated and electricity demand in second scenario.

The assumption that the electricity generation in the second scenario will decline in the CHP plants using fossil fuels, significantly influences the total electricity production. In particularly at the beginning of the simulation while wind power stations operates with low capacities and the electricity production in the CHP stations decreases the total electricity production reduces. However when the capacity of the wind power plants increases, the electricity that is produced from these wind power plants can compensate the reduction of CHP's capacity. From the year 2020 produced electricity in wind stations and biomethane obtained by upgrading biogas can compensate the reduction of CHP plant's capacity.

The internal dynamics for biomethane production is shown in Fig. 10.

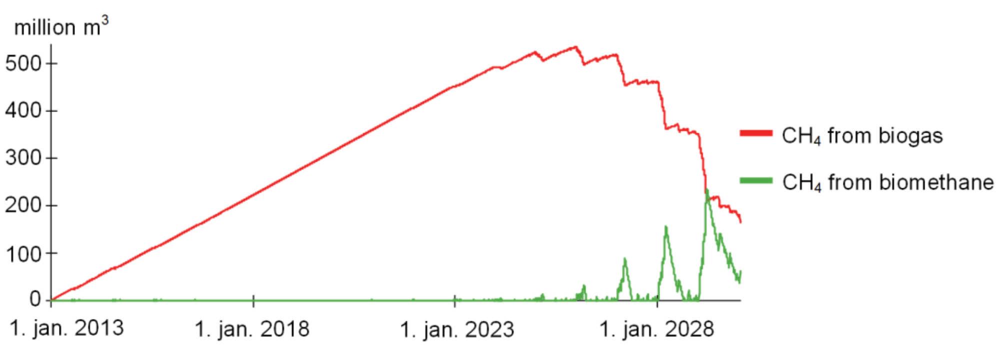

Fig. 10. The amount of accumulated CH_4 from biogas and CH_4 from biomethane for the second scenario.

In the beginning of the simulation, while the volume of produced hydrogen is small, since there are small amount of surplus electricity available for the electrolysis process, the amount of the cumulative CH_4 from biogas increases. Nevertheless this cumulative amount is not used for the production of biomethane, because of the hydrogen's deficit. However, at the end of the simulation, when the electricity's deficit starts to diminish (see Fig. 9), thus causing the amount of hydrogen to increase, the amount of biomethane increases as well.

The proposed dynamic hypothesis is confirmed in this research that by utilizing the conceptual system of renewable electricity accumulation, it is possible to integrate large scale intermittent energy sources in the electricity grid and to match the demand for electricity, since in both scenarios the point at which the all electricity needs are covered is obtained.

5. CONCLUSION

This paper is dedicated to hydrogen accumulation from wind sources. The case study investigates the conceptual system that uses intermitted renewable energy resources to produce hydrogen (power-to-gas concept) and fuel (power-to-liquid concept) in Latvia. For this specific case study hydrogen is produced from surplus electricity generated by the wind power plant trough electrolysis process and fuel is obtained by upgrading biogas to biomethane using hydrogen.

The system dynamic model is created for the conceptual system of renewable electricity accumulation with power-to-gas and power-to-liquid concepts.

The developed system dynamics model has been used to simulate 2 different scenarios: 1) electricity generated in the CHP plants by fossil fuel remains constant until year 2030; 2) electricity generated in the CHP plant by fossil fuel declines towards zero until 2030.

In the first scenario, during the first years of the simulation the electricity generation by the wind power plants accounts only for a small share in the total electricity production. However the situation changes due to the increasing electricity supply from the wind power plant and the use of biomethanation system to convert power-to-gas and power-to-liquid. As the result the electricity production by 2030 exceeds the demand for electricity in Latvia. Also the marginal role of the electricity produced by methane becomes significant player before the year 2020.

The assumption that the electricity generation in the second scenario will decline in the CHP plants using fossil fuels, significantly influences the total electricity production. Particularly at the beginning of the simulation for the second scenario while the wind power stations operates with low capacities and the electricity production in the CHP stations decreases the total electricity production reduces. However when the capacity of wind power plants increases, electricity that is produced from wind power can compensate the reduction of CHP's capacity. From the year 2020 produced electricity in wind stations and biomethane obtained by upgrading biogas can compensate the reduction of CHP plant's capacity.

The proposed dynamic hypothesis is confirmed in this research that by utilizing the conceptual system of renewable electricity accumulation, it is possible to integrate large scale intermittent energy sources in electricity grid and to match the demand for electricity, since in both scenarios the point at which the all electricity needs are covered is obtained.

Moreover, the methodology of system dynamics used in this paper is a white-box model that allows to apply the developed model to other case studies and/or to modify model based on the newest data. The developed model can be used for both scientific research and policy makers to better understand the dynamic relation within the system and the response of system to changes in both internal and external factors.

REFERENCES

[1] Schiebahn S., Grube T., Robinius M., Tietze V., Kumar B., Stolten D. Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany. *International Journal of Hydrogen Energy* 2015:40(12):4285–4294. doi:10.1016/j.ijhydene.2015.01.123
[2] Gahleitner G. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. *International Journal of Hydrogen Energy* 2013:38(5):2039–2061. doi:10.1016/j.ijhydene.2012.12.010
[3] Götz M., Lefebvre J., Mörs F., McDaniel Koch A., Graf F., Bajohr S., Reimert R., Kolb T. Renewable Power-to-Gas: A technological and economic review. *Renewable Energy* 2016:85:1371–1390. doi:10.1016/j.renene.2015.07.066
[4] Qadrdan M., Abeysekera M., Chaudry M., Wu J., Jenkins N. Role of power-to-gas in an integrated gas and electricity system in Great Britain. *International Journal of Hydrogen Energy* 2015:40(17):5763–5775. doi:10.1016/j.ijhydene.2015.03.004
[5] Reiter G., Lindorfer J. Evaluating CO_2 sources for power-to-gas applications – A case study for Austria. *Journal of CO_2 Utilization* 2015:10:40–49. doi:10.1016/j.jcou.2015.03.003
[6] Cinti G., Baldinelli A., Di Michele A., Desideri U. Integration of Solid Oxide Electrolyzer and Fischer-Tropsch: A sustainable pathway for synthetic fuel. *Applied Energy* 2016:162:308–320. doi:10.1016/j.apenergy.2015.10.053
[7] Rönsch S., Schneider J., Matthischke S., Schlüter M., Götz M., Lefebvre J., Prabhakaran P., Bajohr S. Review on methanation – From fundamentals to current projects. *Fuel* 2016:166:276–296. doi:10.1016/j.fuel.2015.10.111
[8] Schiebahn S., Grube T., Robinius M., Tietze V., Kumar B., Stolten D. Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany. *International Journal of Hydrogen Energy* 2015:40(12):4285–4294. doi:10.1016/j.ijhydene.2015.01.123
[9] Guandalini G., Campanari S., Romano M. C. Power-to-gas plants and gas turbines for improved wind energy dispatchability: Energy and economic assessment. *Applied Energy* 2015:147:117–130. doi:10.1016/j.apenergy.2015.02.055
[10] Varone A., Ferrari M. Power to liquid and power to gas: An option for the German Energiewenden. *Renewable and Sustainable Energy Reviews* 2015:45:207–218. doi:10.1016/j.rser.2015.01.049
[11] Blumberga D., Vigants E., Romagnoli F., Blumberga A., Kalnins S.N., Veidenbergs I. Hybrid System with Biomethanation for Wind Energy Accumulation in the Baltic Countries. *Energy Procedia* 2015:75:754–759. doi:10.1016/j.egypro.2015.07.507
[12] Blumberga A., Timma L., Romagnoli F., Blumberga D. Dynamic modelling of a collection scheme of waste portable batteries for ecological and economic sustainability. *Journal of Cleaner Production* 2015:88:224–233. doi:10.1016/j.jclepro.2014.06.063
[13] Blumberga A., Timma L., Vilgerts J., Blumberga D. Assessment of sustainable collection and recycling policy of Lead-Acid accumulators from the perspective of system dynamics modelling. *Chemical Engineering Transactions* 2014:39(Special Issue):649–654. doi:10.3303/CET1439109
[14] Vilgerts J., Timma L., Blumberga A., Blumberga D., Slišane D. Application of system dynamic model for the composting of petroleum contaminated soil under various policies. *Agronomy Research* 2013:11(2):391–404.
[15] Timma L., Bariss U., Blumberga A., Blumberga D. Outlining Innovation Diffusion Processes in Households Using System Dynamics. Case Study: Energy Efficiency Lighting. *Energy Procedia* 2015:75:2859–2864. doi:10.1016/j.egypro.2015.07.574
[16] Timma L., Blumberga A., Blumberga D. Understanding the technological substitution by hybrid modelling practice: A methodological approach. *Chemical Engineering Transactions* 2015:45:379–384. doi:10.3303/CET1545064
[17] Lauka D., Blumberga A., Blumberga D., Timma L. Analysis of GHG Reduction in Non-ETS Energy Sector. *Energy Procedia* 2015:75:2534–2540. doi:10.1016/j.egypro.2015.07.280
[18] Blumberga A., Timma L., Lauka D., Dace E., Barisa A., Blumberga D. Achieving sustainability in non-ETS sectors using system dynamics modelling practice. *Chemical Engineering Transactions* 2015:45:871–876. doi:10.3303/CET1545146
[19] Dace E., Muizniece I., Blumberga A., Kaczala F. Searching for solutions to mitigate greenhouse gas emissions by agricultural policy decisions - Application of system dynamics modeling for the case of Latvia. *Science of the Total Environment* 2015:527–528:80–90. doi:10.1016/j.scitotenv.2015.04.088

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