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SUSTAINABLE INNOVATIVE TECHNOLOGY SOLUTIONS FOR THE ENERGY SECTOR

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Abstract. Innovation is a process by which new ideas, technologies, or developments from different fields are turned into abilities, implemented in the market, and can be reached by any person in the world. That is also called technology-based innovation. Primarily, an innovative product means a product that encourages the establishment of new niches for the market or is significantly different from past products. At the same time, innovative products can be reached without changing the product's principal technological scheme but by improving the quality of the product. For now, Europe still needs to provide itself with energy resources fully. It imports 60.3% of gas, 41.2% of solid fuels, and 82.6% of oil. Still, for example, a World oil production peak could occur in the next ten to fifteen years if it has not already happened, and decisions to be made soon will have a significant impact on our quality of life over the coming decades. The need for energy is divided into sectors like industrial, power generation, transportation, domestic, and commercial, and it generates emissions in the air. Researchers try to foresee the right actions through different calculations, models, analyses, monitoring, policy research, and exploration of various acts from society, economy, and available technologies. This work aims to create a system dynamics model that can capture the dynamics of innovative energy technology development and its impact on the production, distribution, and demand side of the energy system. The focus of the model is on renewable energy technologies, distributed generation and storage systems, and smart energy systems that help to reduce the carbon intensity of the energy supply. A posed hypothesis of the work is that in the future, more and more requests will be for renewable energy sources. As demand increases, the energy cost will reduce, creating a more considerable source demand. Households could be as well as energy consumers as producers. Due to the vital role of energy in manufacturing, saving energy should be included as an essential element of production plans, especially for manufacturing plants that are energy-intensive. To predict the possibilities, of what can reduce impact on the environment, different analyses should be done to reach a concrete action plan that is directed to energy sustainability. A system dynamics model that can capture the dynamics of innovative energy technology development and its impact on the production, distribution, and demand side of the energy system. The focus of the model is on renewable energy technologies, distributed generation and storage systems, and smart energy systems that help to reduce the carbon intensity of the energy supply. Afterwards, the model can be used for testing in different countries.

Keywords: renewable energy; smart energy system; systemic dynamic model; planning; case study; Latvia

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Additional disciplines are environmental engineering, energetics and thermoenergetics.

1. Introduction

One of the biggest struggles is to find the best technology or combination that satisfies all involved parts – environment, society, and economy. Comparing solar collectors with natural gas for cogeneration, there are different advantages and disadvantages for both energy suppliers. As from technical-economic dimension in

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Table 1 can be seen, the specific cost of power generated or saved and installation cost is bigger for solar collectors (Udaeta et al. 2016).

Table 1. Comparison of solar collector and natural gas for cogeneration (Udaeta et al. 2016).

Criterion	Unity	Solar collector	Natural gas for cogeneration
Cost of power generated/saved	EUR / MWh	20.06	19.49
Reliability of the resource	%	70	75
Time for implementation	Time (days/years)	7 days	1 year
Lifetime	Years	10	20
Ease of installation, operation, and maintenance	EUR/hour	5.73	17.20
Installation cost	EUR/KW	573.28	321.32

However, the reliability of resources and lifetime are lower for solar collectors, which explains energy irregularity. However, overlooking other data, ease of installation, operation, and maintenance is three times lower for solar collectors, and the time for implementation is 52 times shorter. The conclusion from Table 1. can be made that each energy supplier has some benefits and advantages. It is hard to say – one significant technology is the best or right choice. Still, the most common researcher's conclusion from articles is that non-renewable resources are economically profitable, but in the long term, these technologies require higher investment and labour. So, adjusting modern strategies and increasing environmental benefits from the cost scene is the worst economic performance Chicco & Mancarella 2009), (Udaeta et al. 2016).

For making different technologies into a fully working system, one of the technological solutions is provided. That is called smart energy systems. These systems are an accession to combine and coordinate smart electricity and heating for optimal solutions in every energy-using field - electricity, heat, cooling, hydrogen, various chemical substances, etc. This system is sustainable, a cost-effective and secure scheme in which, for example, renewable energy production can be prioritized, and consumption is subjected or based on users, enabling technologies and energy services. The system optimally interacts with available resources to reduce environmental burdens, economically expose energy supply, and provide optimal comfort level – without houses overheating or insufficient heat provision (Chicco & Mancarella 2009). The smart energy system increases the conversion efficiency and the consumption of resources and reacts to the electricity market prices; through an optimal market, promotes optimal energy production deployment for resource selection; increases power system flexibility; provides energy reserves or allows the use of available and flexible storage systems; operates in individual buildings, regions and even in countries. This system aims to facilitate an overview of the different types of energy producers and use selections and discussions about specific actions. The system is operating by an independent program that is based on the three values - society, economy, and environment, even including geographical latitude analysis (Mancarella 2014).

Less known and more innovative are the mentioned energy storages. Moreover, since there exist more cheap and efficient options than electricity storage, there are better solutions for large inflows of variable renewable energy. Electricity storage is also not feasible from an economic view because the storage will only be used sometimes enough to cover investments. Compared to electricity storage, thermal storage is about a hundred times cheaper per unit of storage capacity. However, liquid fuel storage is cheaper and can be stored for years (Lund et al. 2016), (Lyden et al. 2022).

Trends in research and development demonstrate storage technologies in the future, and these energy systems will play an important role. It would be necessary to provide electricity by renewable energy supply continuously or when electricity storage inputs and outputs are not electricity. Still, it is converted to another form of energy. That leads to integrating transportation, biomass, and cooling into the energy system. So, to find the least cost and most efficient storage to approach a Smart Energy System, it is requisite to look at the proper use of storage. Likewise, electric vehicles can be used as electrical fuel storage (Faiz et al. 2016), (Tomc & Vassallo 2016), (Krajačić et al. 2011), (Barabino et al. 2023).

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As one of the significant problems using solar energy is energy variation at daytime and nonexistence at dark times of day, solar energy storage systems are one of the constant energy problem solvers. Heat, the same as electricity, can be stored in various ways. In research of Solar systems integrated with absorption heat pumps and thermal energy storages was mentioned in three ways – sensible and latent heat storages that are physical processes and thermochemical one that consists of chemical processes (Leonzio 2017).

Studies regarding cleaner catalyst with environment-friendly waste, for example, the use of biomass and bio-degradable waste is getting more topical. Digestion processing of domestic biogas heat-only boiler supply varies in types among compositions of produced biogas and yields, but the essential structure is more or less similar. Outputs from biogas digesters are gas and slurry, so at the same time, it is possible to get gas for house heating or cookers and slurry as natural fertilizers. It is not only environmentally friendly but economically favourable and, in addition, provides the benefits of public employment as there is needed maintenance from skilled labour (Yasar et al. 2017).

The situation in cold regions is different and not optimistic due to the digester temperature, which, in winter, without a heating system, cannot work effectively. Using the hybrid heating system to increase the optimal slurry temperature, the biogas production amount could be increased by an average of 0.42 m^3/ (m^3·d), and choosing glass-reinforced plastic as biogas heat-only boiler insulation increase can be higher. This research hybrid system consists of circulating the solar, biogas boiler, and digester heating loops. This system is more advantageous because the solar heating loop substitute's biogas consumption of the boiler and its maintenance and lifetime indicators are improving. Additionally, this system reduces the biogas production effectiveness in winter, is more sustainable, and reduces the pressure on the environment (Zhang et al. 2016).

Energy demand and supply depend on various factors and are mainly divided into sectors like commercial, residential, industrial, transportation, and disaggregated. Factors for these sectors, as previously described, can be socially or economically, as well as dependent on the environment and politics. A wide range of analysis types not only for energy production and consumption but also generally comprehensive. For example, Ecoindicator 99, analyzes the life cycle of a product or any activity itself. The model evaluates the impact of the systems on the environment, which can be done in four main steps – definition of goal and scope, analysis of inventory, impact assessment, and interpretation (Otsuki, 2017), (Pazoukib and Haghifam, 2016).

It is more sufficient to look at the energy system from all energy use impacts together. Energy system analysis generally starts from people's needs and opportunities because we are the ones who regulate the energy balance behaviour (if we are looking at the population as a number). The main factors that make energy dependent on the aforementioned population change their environmental, social, and economic indicators, energy prices, and income. In one research, the goal of Integrated Energy Resource Planning and Full Cost Assessment described the energy balance from four main dimensions – not only social but also society-made dimensions like technical-economical, environmental, and political, which can be considered as main dimensions of socioeconomic and human development (Modarres and Izadpanahi 2016 Mahlia), (Udaeta et al. 2016).

Modelling is the basis of energy optimization. Existing models are based on theoretical or empirical knowledge. The difference is in the system dynamics model, where you can combine these two parts. Energy modelling includes not only energy demand but all systems together – energy demand and supply, prices, technologies, and pollution. Every model must consist of two points – energy producers and consumers, who can be added to the third one - prosumers. Prosumers are consumers and producers at the same time. Of course, energy balance is mainly calculated by energy demand, which plays the central role of all systems (Zhang et al. 2015).

The summary from the literature review helped to understand the model's desired appearance. Creating a model based on the literature analysis should consider innovative energy technologies and their prognosis for future development. As the aim of the developed system dynamic model is to show the energy consumption and production changes in the future, it was essential to understand which technologies can be used. Soon, natural gas, wood and coal plants or cogeneration plants are predicted to have higher income from solar collectors and

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panels and wind power stations, which still exist but can be called innovative technologies because of nonstop development and more immense installation amounts in the future.

2. System dynamics models

System dynamics is a complex exploring method for any system dynamic development made by Jay Wright Forrester in the 20th 50's. It can be quite a powerful tool for dynamic research and feedback behaviours. Mainly, modelling focuses on feedback loops between diverse systems (Mirzaei & Bekri 2017).

Over 30 years, system dynamics has played a notable role in planning energy policy. Model main key concepts or qualitative tools are stocks and two flows – inflow and outflow as seen in Figure 1.

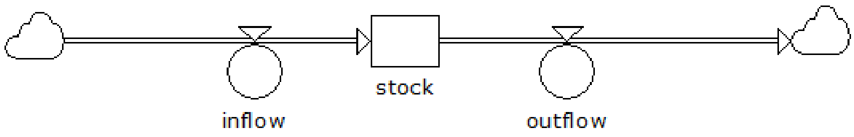

Figure 1. System dynamics simple structure of flows and stock.

Source: (Blumberga et al. 2011)

This modelling system makes it possible to predict the changes in stock if the inflows and outflow rates are known. Adding feedback loops from stock to inflow makes more accurate changes in stock because the provided information at stock helps to change the actions of inflow. For example, if it is known that in stock is enough energy for consumers, it is possible to stop or reduce production. Flows are changed by constants (indicated by lozenge) and parameters (indicated by circle) that are connected by information loops, which also can be delayed loops. Delays are divided into material delays – construction and material extraction time and information delay – in society or elsewhere, information is not directly used in behaviour (Blumberga et al., 2011).

In system dynamics, multiple boundaries have been defined multiple boundaries for sustainable development of supporting decisions and making policies. There is recommended a "boundary adequacy" test where three questions are to be answered:
• Is the model aggregation corresponding?
• How is the model transforming if the model boundary readjusts policy recommendations?
• Does the model answer all relevant questions which it is designed for?
However, all boundary judgments are essential for sustainability by the effective use of System Dynamics (Nabavi et al. 2017).
To create the model, there are some specialized steps to be made. The scheme of model steps is featured in Figure 2.

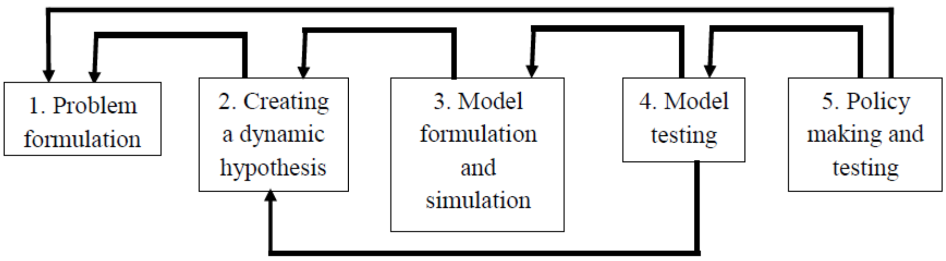

Figure 2. Steps of the system dynamics modelling process.

Source: (Blumberga et al. 2011)

Recommendation for making a model starts with problem formulation, which includes the answers to the aim, role, and type of the model - linear/non-linear or static/dynamic. It is essential to define research agendas for

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easier preformation of system analyses clearly. Afterwards, based on problem formulation, it is suggested to create a dynamic hypothesis that is the expected answer to a defined problem. At the end of modelling are obtained conclusions and the solution to the problem and confirmation or denial of the hypothesis.

For model visualization, causal loop diagrams consist of variables and arrow loops with pluses and minuses. Plus, the sign means that two correlated variables are changing similarly, and thereby, minus – variables change oppositely. As in Figure 3, energy production is visualized due to the availability of resources.

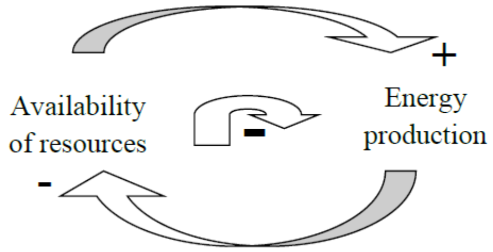

Figure 3. Causal loop diagram example.

Source: (Blumberga et al., 2011)

When the availability of resources simultaneously increases energy production, the increase in output reduces the availability of resources. By this, it is said that those two components interact, making a negative loop type visualized in the middle of the loops (Walrave & Raven 2016).

One of the most significant energy-integrated models used in 20 countries, focusing on Canada and the United States, is called Energy 2020. In the List of Clientele are companies such as Latvenergo, from Latvia, and Lithuanian State Power. The model overlooks sectors of energy demand, supply, and pollution accounting. The model energy demand part consists of categories like:
- Multi-family, single-family, and agricultural holdings;
- Industrial and over 40 commercials;
- Transportation services, like off-road, passenger and freight.

All energy users need heat for processes, water and space heating and electricity for lighting, refrigeration, conditioning, etc., provided by natural gas, coal, oil, biomass, solar, and electric products. Transportation contains different components - transport types, cogeneration, energy-based feedstock, fungible demands, and end-uses. However, the model does not include the number of households, vehicles, square meters of buildings or even population as a driver. Supply parts include similar parts to demand - natural gas, coal, oil, ethanol, refined petroleum products, landfill gas, ethanol, and electricity. If supply is not needed to model, it offers a simplified product price (Backus & Amlin 2009).

One part of the model simulates primary energy production and related emissions from them, and the other one - is energy distribution. Another – is the changes in energy use and output, what is regulated by different aspects. The transfer of information is unmanageable and creates a gap between the decision-makers and the model. The model allows the user to insert a future case, so there are many degrees of freedom (Backus & Amlin 2009) (Ibanez-Lopez et al. 2017).

Because of environmental impacts, energy security is getting more pressing, and the main topic has come to coal-chemical industries, particularly affected coal-chemical industry areas highly dependent on resource availability and demand. The system dynamics model analyzes economic changes caused by the warring of coal and oil prices and the effect on the regional evolution of the economy by different policies. Researchers established three scenarios for oil and coal prices scenario. The first one was a simulated coal price slump. They went on to conclude that the coal industry's oversupply will stay at the same level as it is now, and prices from the baseline scenario of 2015 will fall by around 5%. The second scenario is an oil price slump. Because of America's shale gas, oil prices will continue. The last one – simultaneous price slump also was a base scenario

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where industrial output profit and value are the lowest. They also investigated five policies on how the price decrease can be reached – reduce the value-added tax and production limit, increase the financial support and technological investment, and develop alternative industries. By increasing technological investment, production value will be the highest, but by reducing the value-added tax – the lowest. Together with everything, the model showed that the oil and coal prices between other resources would be the lowest, and by different policies, it is easy to make them even more down. So, because of incomparably low prices, there is needed immense pressure on environmental policies; otherwise, traditional material society will choose the most economically advantageous option (Lunney et al. 2016), (Wang et al. 2017).

Another system dynamic analysis is based on the simple framework of China's oil supply chain. They concluded that for the Chinese government, the rates of new refinery buildings should be diminished. However, upgrading the existing refining facility with innovative technologies would be the best option to balance the environmental requirement and capacity. The model is made for crude oil import disruption in the future and reveals the strategic ability to cope with supply risks and petroleum reserve interactions. Besides that, the model design could be used to determine system dynamics for other energy supplier analyses of security and capacity-relevant problems (Mahlia et al. 2014), (Pan et al. 2017).

A system dynamic model looks at the effects of the economy, energy production and consumption, and environment from 2000 to 2025 by variables like CO2 emissions, energy intensity, and others. The model included Vensim PLE software and was made for the situation in Iran. The energy production part of the model is made from production limit rates and energy demand. Furthermore, the need arises from energy consumption, which includes data from previous years on future variable functions. One of the model scenarios' aims was to reduce energy intensity and consumption, which could lead to lower environmental costs. To reach the model target, there were set two optimization policies – five and ten present of energy intensity reduction, which led to conclusions that both policies are short-term effective for reducing energy consumption. Energy consumption changes from 2157 million barrels in 2025 to 1975 from 5% energy intensity reduction scenario and 1867 million barrels from 10%. Still, the results show that Iran will be largely charged with increased CO2 emissions and energy production, and energy consumption will increase faster than energy production, which will foster more CO2 emissions (Mirzaei & Bekri 2017), (Zhao et al. 2022), (Kirikkaleli et al. 2023).

Research about government and municipality-owned buildings was aimed at a dynamic description of the energy efficiency in these buildings by changing policy tools to reach the energy efficiency targets. They made an integrated system dynamics-based model, where results show that in the short term, the most significant impact on energy efficiency increase can be made by CO2 tax policy implementation. However, the goal for 2016 still needs to be reached. The CO2 tax is easy to implement and can work long-term. Also, study shows that when all of the financial support is spent, the energy efficiency increase of buildings will dramatically decrease. Because the funds mostly compensate around 50% of all investments, and by this support, inhabitant investments pay off around 10 years, which is a safer future investment than it would be for 20 or more years. Still, there exists another energy-saving possibility – monitoring of these financed buildings. The real saved energy must be equal to or lower than what is written in the building energy certification; otherwise, money must be refunded. By this kind of punishment, inhabitants must consider more useful energy use. Otherwise, in most cases, after renovation, the temperature in the building increases, but instead of reducing heating power, people for cooling use ventilation or just open the windows (Blumberga et al., 2011), (López-González et al 2016), (Luckow et al. 2016).

3. Results and discussion

Results of the model show the indicative values of total unit production costs, produced energy, used area, investments, and released CO2 emissions in air from 2017 to 2050. Starting with the indicative total unit production cost overview, as shown in Figure 4, the changes for each technology are different. Almost all simulation time cheapest technology is solar collectors, which in time between 2018 and 2020 are almost at the same value as for wood cogeneration plant. At first, solar collector produced energy cost was 14.53 EUR/MWh, which is increasing because of investments made, but when it is paid off, from around 2041, thermal energy production is almost for free – 0.18 EUR/MWh.

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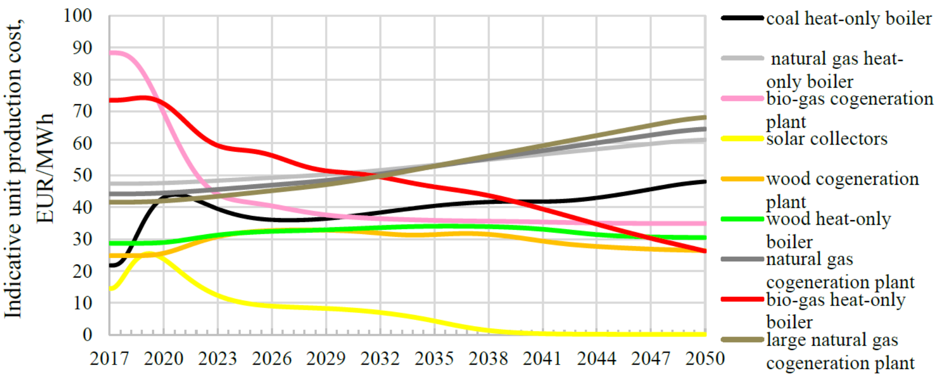

Figure 4. Total indicative thermal energy unit production cost for different technologies

Produced thermal energy cost from wood cogeneration plants, compared to other technologies, is also low. Passing the time, it stays at the same value around 29.50 EUR/MWh. A similar situation is for a wood heat-only boiler, whose average price is 32 EUR/MWh. This difference is because of the cost mentioned above changes, which make the income from sold electricity. In the beginning, coal heat-only boiler cost was only around 3 EUR/MWh lower than wood cogeneration plant. Still, with investments, this technology costs increased over large natural gas cogeneration plant costs. Hence, the requirement for this technology dropped, and the cost stayed higher than for wood heat-only boilers. In technologies that use natural gas, indicative unit production costs are changing similarly. Passing the time, it is slowly increasing from around 44EUR/MWh to 64EUR/MWh, because of the increase in CO2 emission and operation and maintenance cost changes. Compared to other technologies, the indicative unit production cost stays high, so investments for new capacity building are not made. From natural gas users, the cheapest one is a large natural gas cogeneration plant, then the natural gas cogeneration plant and most expensive one – a natural gas heat-only boiler for the same reason as a wood heat-only boiler. Large natural gas cogeneration plant unit cost is lower because it produces more electricity than a natural gas cogeneration plant.

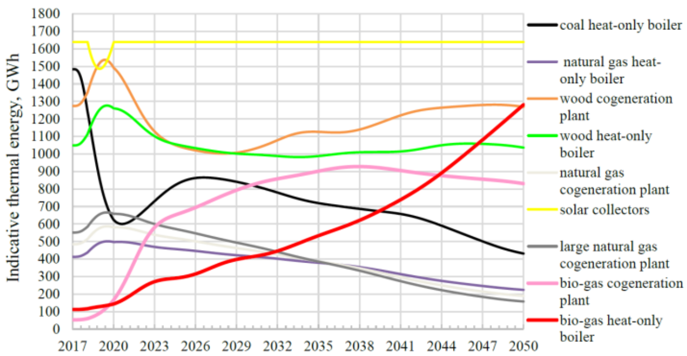

Figure 5. Indicative thermal energy output from different technologies

Initially, a coal heat-only boiler would be required for production, but it will drop fast. The next one is the wood cogeneration plant, which, also by solar collector investments, could produce more because of changes in indicative total unit costs. However, after investments in its capacity increase, the thermal energy output drops. As was written before, these thermal energy outputs are impacted by total unit production costs, so when the price increases, the energy output drops, but when the price gets lower, the energy output increases. The same can be seen in interactions in Figures 4 and 5. As the rise of natural gas technology prices is made, the thermal energy output drops. An opposite situation would be in bio-gas heat-only boilers – price drops, so the energy output increases.

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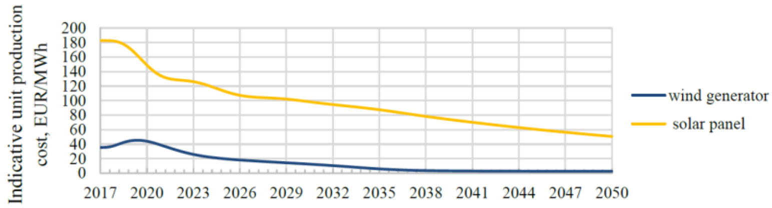

Figure 6 Total indicative electricity unit production cost for different technologies.

Another part of the model concerns indicative electricity production and its technology interaction. If we overlook the indicative total unit production cost in Figure 6, in this case, the price was divided between two technologies. The results show a big indicative unit cost difference between solar panel and wind generator costs per one production unit. Solar panel cost at the beginning is 182.61 EUR/MWh, even more than the electricity price for consumers in Latvia. In the case of wind generators, the price is lower than the market price even at the beginning – 35.48 EUR/MWh, which would drop to 2.59 EUR/MWh in 2050. So, this technology is starting to pay off in the first year of installation.

As this technology is less expensive than solar panels, it is installed more, which makes it a necessary investment. Comparing indicative investments between those technologies, as in Figure 7, the wind generator together in all simulation time asks for 5053.05 million EUR.

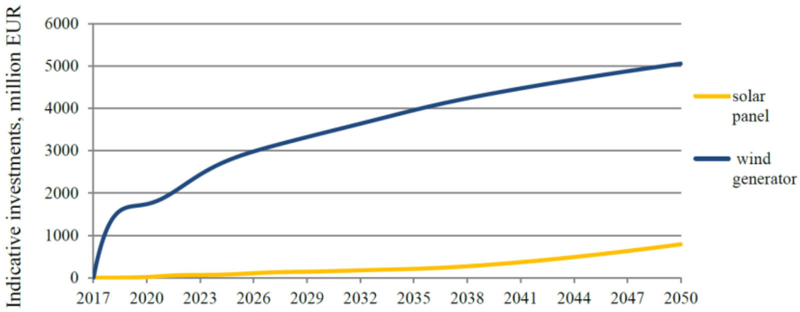

Figure 7. Indicative cumulative investment changes for electricity producers.

As the requirement for a wind generator was the biggest, it also would produce most of the electricity. The next highest producer would be the hydroelectric power plant, which was set as a constant energy producer without any investments or profit. After time passes, the bio-gas cogeneration plant could produce the third biggest amount of electricity. The rest of the technologies – large natural gas cogeneration plants, natural gas, and wood cogeneration plants produce 607GWh in 2050, from which the most minor producer is the natural gas cogeneration plant, which would produce 90GWh. The next one is a large natural gas cogeneration plant that produced indicative electricity of 147GWh, and the biggest one – a wood cogeneration plant – 370GWh.

As electricity output changes, the electricity import and export, as Latvia, for now, cannot produce enough amount of electricity for its consumption. By this model results and investments, it is possible to provide electricity for ourselves and even export it, as shown in Figure 8.

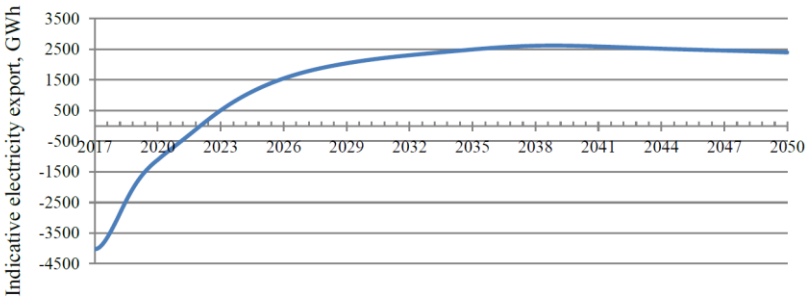

Figure 8 Indicative electricity export changes.

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At first, 4025GWh of electricity was imported, but the installation of wind generators (mostly) made changes, and from 2022, it will be possible to export more energy than import. And in 2038. reach value smoothing around 2400GWh.

Looking at the impact on indicative area use and what causes new technology building, wind generators request quite a large amount of area. In total, is needed 357.65 km2 with a maximum point of 2041. Almost half of the area would be required by the year 2022. Together it is only 0.55% of all country's land. The following most significant area requirement is for solar collectors – 31.09 km2 (0,05%), which is needed already in 2020, and the lowest amount is for solar panels – 8.80 km2 (0,01%), which is a small amount number, but quite a big. If we compare it to lakes, it is almost the same size as "Lielais Ludzas" lake, the 17th largest lake in Latvia.

Of course, these energy production changes also impact the indicatively released CO2 emissions; CO2 emission amounts would change the same as produced energy amounts in Figure 3.1. In 2017, coal heat-only boilers would make 635GtCO2 emissions, but lately in 2021. it will drop to 259GtCO2, which again increases till the year 2026 to the amount of 370GtCO2, and later it would slowly decrease till 2050 of value 184GtCO2. All other technologies gradually reduce released emissions after solar panel reaches their maximum point in around 2020. So, these changes are because of the reduction of indicatively produced energy. At first, natural gas heat-only boilers made 92GtCO2, natural gas cogeneration plants – 160GtCO2, but large natural gas cogeneration plant 239GtCO2, which in 2050 smoothed around equal amounts of 60GtCO2.

Conclusions

From different case results, it can be seen that the main thermal energy production part goes to solar collectors. Also, a big market share goes to wood plants for all simulation time. The lower requirement is for natural gas plants. In electricity production, a big range of cost differences are between solar panels and wind generators, so more requested is wind power. Most of the total investments go to wind generators and bio-gas heat-only boiler installation, but there is no need for investments in natural gas plants. As there are extensive requirements for wind power, it also requests for area.

Overlooking different scenarios, in cases of emission tax changes, the lowest amount of released emissions are in high tax cases, but it requires the most significant investments. Supporting the bio-gas cogeneration plants, there are released emissions almost the same amount as in the high tax case, but it costs even more than in the case of the high emission tax case. In the case of solar panel support, there are needed the biggest amount of investment, and it makes no changes in released emissions. Combining support for renewable energy sources and increased emission tax impact on the environment could be reduced even more, and a result would be better than doing only one activity.

Scientific novelty/practical value of the findings

Due to the vital role of energy in manufacturing, saving energy should be included as an essential element of production plans, especially for manufacturing plants that are energy-intensive. To predict the possibilities, of what can reduce impact on the environment, different analyses should be done to reach a concrete action plan that is directed to energy sustainability.

Using the model in various countries, it is possible to calculate which type of energy is the most financially efficient and the most environmentally sustainable. According to the created module, it is possible to optimize and adjust the integration of renewable energy into the existing system. Afterwards, the model can be used for testing energy systems in different countries.

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