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Renewable transport fuel production combined with cogeneration plant operation and waste heat recovery in district heating system

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ABSTRACT

For the future energy markets, where the role of fossil fuels will be minimized and district heating systems will become more efficient through the use of waste streams, a new concept is proposed based on tri-generation of Fischer–Tropsch (FT) products, heat, and power. The challenge of combining the transport sector with a District Heating (DH) network and power grid is presented in this article by discussing the operating modes of the gasifier, FT product output (as a raw material for refinery) and waste stream generated after the synthesis reactor, preliminary process management schemes, market factors, and economic attractiveness. The feasibility of the concept was examined for an existing combined heat and power plant in Lithuania, which could become a potential demo plant. To demonstrate the feasibility of this concept, which may help create independence from fossil fuels through the use of syngas (for a sudden increase in heat demand), a techno-economic assessment was performed. The analysis of various scenarios showed that the cost of the FT product may be between 0.67 and 1.47 €/kg for gasifier capacities ranging from 10 to 40 MW. However, the economic attractiveness assessment revealed that the concept is profitable at a liquid biofuel (FT product) prime cost below 1.07 €/kg (without electrolysis capability).

1. Introduction

In recent years, reducing greenhouse gases, promoting the use of renewable energy sources, and increasing the energy efficiency have been among the key energy challenges in Europe [1]. The 2020 target of a 20% share of energy produced from renewable energy sources is almost reached because in 2019 it was equal to 19.5% [2]. However, future challenges will require significant transformations in the EU energy system [3]. At present, European countries are focusing on increasing the share of renewable energy sources (RESs) to 32% by 2030, attaining a growth rate of approximately 1.1% per year instead of the previous 0.7% [2]. The national energy and climate plans of EU member states for 2021–2030 envisage even more ambitious targets for a faster transition to RESs, as high as 33.7% [4]. The new long-term strategic vision for 2050 sets bold challenges to European countries toward climate neutrality [5]. Therefore, the annual average growth rate of RESs from 2030 to 2050 will need to be at least 2.7% annually [2]. To face these challenges, the European Union Strategy [6], the Renewable Energy Directive [7], and national legislations [8,9] promote the development of a sustainable energy system and the use of energy from renewable sources. This is also reflected in many recent works [10,11] that relate the future energy to a 100% use of RESs. In addition, greenhouse gas emissions are expected to be reduced by 2050 in the most extensive sector, heating and cooling, by using RESs [12]. Moreover, Europe must decarbonize the transport sector to reach the CO_2 reduction targets by 2050. Although electric vehicles are becoming a viable solution for urban transport, new renewable transport fuels are considered to be an attractive option, especially in the heavy-duty trucking, commercial aviation, and maritime sectors. According to the European Environmental Agency (EEA), the current pace in the transport sector is still insufficient to reach the 10% target by 2020 [2] (it was 8.9% in 2019 [13]).

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Considering these challenges and consumption trends, it is expected that the demand for RESs will increase due to the environmental impact or political commitments [14], which leads to an increasing need for investment. This investment can be slightly reduced by focusing on energy-saving and energy efficiency measures. For example, investments may be directed toward the consumption of waste energy, thus saving primary fuel resources. However, to achieve a sustainable energy system, it is still necessary to plan the development of advanced technologies that integrate as many secondary by-products, waste streams, and RESs as possible. In this approach, 4th generation district heating (DH) systems [15] should also be considered, which are based on a coherent technological concept that uses industry surplus, biomass conversion technologies, centralized heat pumps, 2-way DH, electricity surplus, waste incineration in combined heat and power (CHP) plants, and other future energy sources. These advanced technologies could be best applied in the Eastern and Northern European countries, which have well-developed DH systems [16]. Various countries, including Lithuania, implemented ambitious plans for DH development in the 2014–2020 period and benefited from EU investments. For example, the biomass for heat production in Kaunas City (Lithuania) (including the incineration of municipal waste) currently accounts for approximately 87% (2018) of the annual heat production, although it was only 4% in 2012 [17]. In line with the aspiration of sustainable energy, the incineration of biomass is not the most appropriate perspective for 4th generation systems. After analyzing various studies, it was observed that there are significant amounts of waste heat generated in industrial plants that are not utilized as a heat source in DH systems. J. Ziemele et al. [18] found that 67.5 MWh of heat could be supplied to the local DH network every month, which could cover from 4% to 12% of the load during the heating season. It was concluded that the cost of waste heat was uncompetitive with the cost of primary energy, as investments were needed in the construction of a new pipeline to connect to the DH system at a distance of approximately 1 km. Significantly larger waste heat streams should be considered to increase the economic attractiveness, and given that distance has a significant impact on payback, it should be kept to a minimum. L. Cioccolanti et al. [19] found that waste heat recovery still increases the efficiency of cogeneration plants and that heat from the industrial sector (e.g., from pulp and paper mills in Italy) has the potential to save as much as 143 kTOE. To improve the energy efficiency of the plant under analysis, Marshman et al. [20] developed an energy flow management algorithm in which waste heat was used to ensure the demand of technological processes (for heat and electricity generation), and surplus electricity was transferred to existing suppliers. The DH system is well developed, and therefore it is easy to integrate energy-saving technologies, and with the 4th generation DH, it is expected that the efficiency will increase [21]. The hybrid combined technologies for heat and electricity generation are discussed in the work of Zhen Wu et al. [22], where their efficiency was established by proving that their use can reduce carbon dioxide emissions by up to 64%. For these reasons, Lithuania is seeking new prospective technologies for the future energy market and aims to move gradually toward a sustainable development in the field of waste-to-energy (WtE) [23]. This study focuses on a forward-looking technology that combines heat, power, and fuel production simultaneously (Fig. 1) while achieving the optimal solution for all of them. The concept combines the advanced thermochemical conversion technology with gasification, catalytic liquefaction, electrolysis, and waste heat recovery in order to use waste biomass in a more sustainable way instead of direct incineration. In addition, the concept of Highly Flexible Combined Production of Power, Heat and Transport Fuel technology (FLEXCHX) [24] provides the flexibility to respond to changing consumer heat demands and can reconcile the seasonal mismatch of surplus electricity from renewable sources.

Considering the working trends in different industrial sectors, it is estimated that up to 40% [25] of unused waste heat may be emitted in general. However, it should be noted that depending on the industry profile and the technologies used, different types and potentials of thermal energy are generated [18], which are divided into low-temperature (<230 °C), medium-temperature (230–650 °C), and high-temperature (>650 °C) [26]. Moreover, it is necessary to emphasize that waste heat recovery and integration in the local DH network will be efficiently used on-site if the energy demands of consumers coincide.

It is often observed that the profile of industrial activity does not coincide with the demand for heat of consumers [15]. In addition, owing to insufficient temperatures for direct injection of waste heat streams into DH networks, the instantaneous use of waste heat for on-site energy generation may also not be appropriate. This diversity between energy demand and energy potential can be solved using thermal energy storage or heat pumps [18]. Nevertheless, these measures are not sufficient to achieve ambitious sustainable energy goals. The FLEXCHX concept offers a future alternative to the long-term strategic vision. Therefore, this research proposes to combine the FLEXCHX concept with CHP plant operation by recovering waste heat into the DH system and producing renewable transport fuel.

A review of the production of renewable aviation fuels from biomass gasification [27] revealed that this is a new effort and that initial plants can face integration challenges and need some time to reach their nominal capacity. To avoid this, a detailed research is needed, as complex hybrid concepts not only offer endless perspectives but also require compatibility. On this basis, this study qualitatively assessed the various potential DH and industrial CHP applications in Lithuania where the waste streams could be integrated considering the surrounding conditions of the process. To design a coherent production concept for cost-effective tri-generation of Fischer–Tropsch (FT) products, heat, and power, the operating modes of CHP plants, the preliminary process management schemes integrating the FLEXCHX concept, and the economic attractiveness were evaluated.

2. Methodology

2.1. Concept of flexible combined technology

To increase the share of RESs in the heating and cooling sectors, the energy production companies are interested in new opportunities. This study focuses on the adaptability of an advanced technology that integrates the FLEXCHX concept (Fig. 2) into CHP plants and industrial sites. The concept [24] combines different technologies such as gasification [28], FT synthesis [29], and electrolysis [30] by arranging the work regimes. In general, biomass gasification and FT synthesis plants cannot be considered especially flexible because they produce fuels and by-product heat at constant capacities. The flexibility of the FLEXCHX concept is based on the possibility of operating the same plant under different scenarios. In terms of the flexibility of this highly innovative technology, the core of the FLEXCHX concept focuses on the FT conversion unit, as shown in Fig. 2, under the base *scenario A* (Fig. 2). This FT synthesis reactor has the ability to receive supply flows of syngas in the range of 30%–100%. Hence, at peak power and heat demands, the FT conversion unit can be bypassed and the syngas can be supplied directly to the CHP plant to maximize the heat and power production rapidly. However, the consumption of syngas for heat production responds to the output of the main hydrocarbon products, the so called FT products. Such a scenario is also

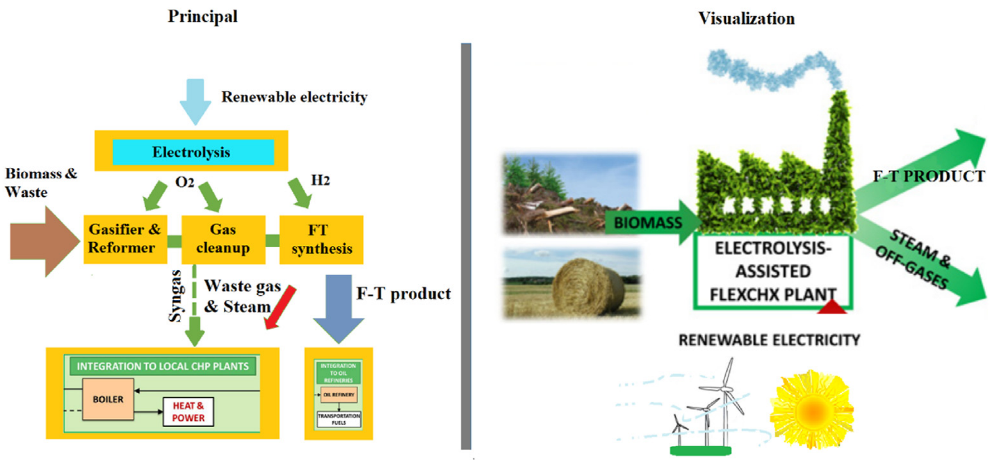

Fig. 1. The concept of a highly flexible combined technology (FLEXCHX) [24].

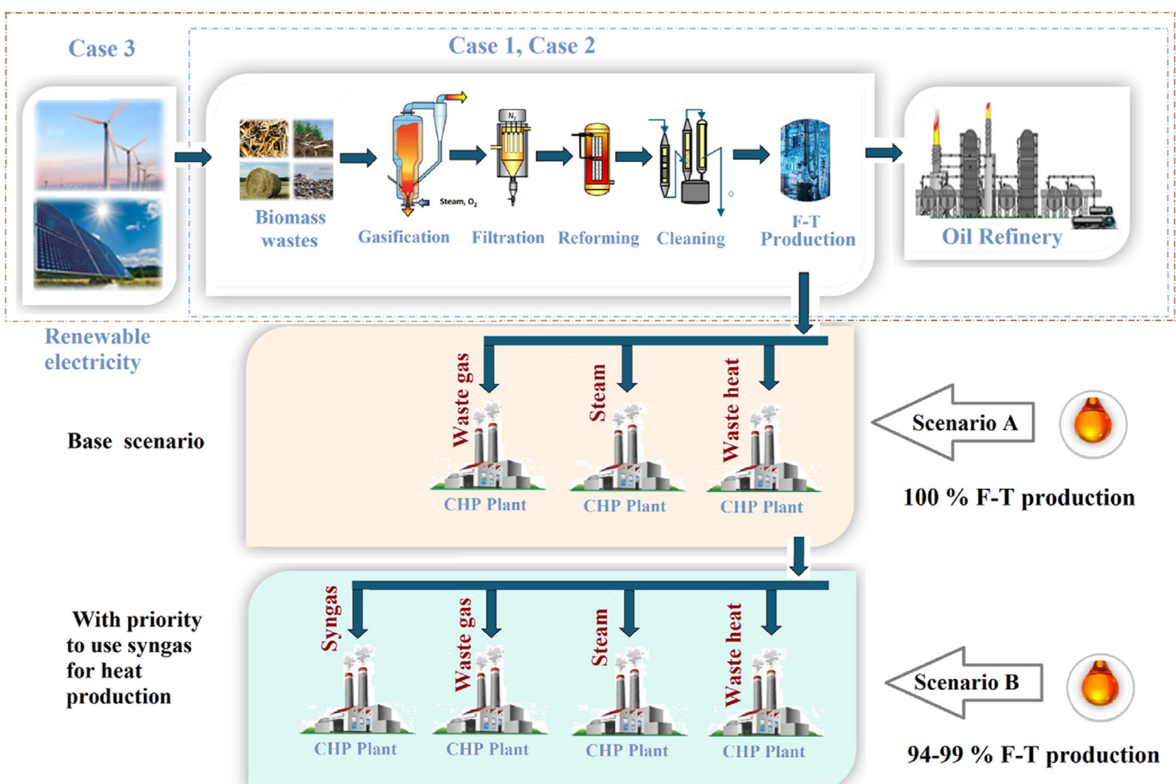

Fig. 2. Combined hybrid process integration into the DH system (FLEXCHX).

considered in this work and is named *scenario B* (Fig. 2), which gives priority to the use of syngas for heat production (Fig. 2). Nevertheless, this short-term redistribution of flows inside the FLEXCHX block allows a flexible response to changes in consumer heat demand without interrupting the stable gasification process. Thus, the proposed system makes it possible to smooth out fluctuations in heat capacity in response to the changing demand of heat consumers. For a long time, it has been accepted that the suddenly changing demands of consumers can only be met with the use of natural gas boilers. The proposed alternative allows energy companies to eliminate the use of natural gas for heat production, replacing it with syngas. This variation may prove that independence on fossil fuels can be reached in heat generation sources such as boiler houses and CHP plants by integrating the FLEXCHX concept.

Considering that the gasification and FT process concepts have many design and operation alternatives, the composition of the gas may also vary depending on the use of gasification agents (oxygen, air, steam, recycled CO_2) to ensure the best options for other processes. Various biomass residues and organic waste fractions are being gasified using a new two-stage fixed-bed (SXB) gasifier [24] (developed at the Technical Research Centre of Finland Ltd, Finland (VTT)). In terms of the conversion efficiency, it is known that the FT synthesis reaction depends on the H_2/CO molar ratio of the gas [31].

By approaching a gas ratio close to 2, the conversion becomes more efficient owing to the increasing FT product yield. Nevertheless, a molar ratio larger than 2 is not required in FT synthesis. Considering that the H_2/CO ratio in the syngas can be changed by boosting with higher hydrogen content, the electrolysis unit can allow this to be achieved. However, to achieve a cost-effective process, this unit should operate by consuming surplus electricity from an RES when it is cheapest.

Another alternative for increasing the H_2/CO molar ratio is the use of steam [31] on the gasifier instead of an additional electrolyzer unit. The main difference in these ways of increasing hydrogen is the gas yield, despite the uniform H_2/CO molar ratio, which in both cases can become close to 2. In addition, steam as a gasification agent is very important for the gasification process not only for hydrogen generation [32] but to avoid ash sintering [33]. However, it has been observed that an excessively high steam feed rate can result in increased O_2 consumption and reduce the gasifier efficiency.

Experimental insights obtained by the VTT [24] show that high energy conversion efficiencies for liquid FT products can be achieved through the use of biomass alone and by the integration of biomass gasification and electrolysis. This depends on the surrounding conditions created by varying from high oxygen purity to enriched air gasification. It can be noted that the advantage of electrolysis is not only the production of hydrogen but also by-products such as oxygen, which is particularly important for the gasification process throughout the years.

In this concept of combined heat, power, and fuel production, the main focus is on the efficient production of the FT product, which as a renewable transport fuel is considered to have a higher value than power and heat. Furthermore, in the FT synthesis, the by-product steam is produced when the exothermic reactions are cooled [35], and an energy-containing tail gas flow is also generated. To increase the energy efficiency, these waste streams should be utilized onsite. Such technology could be integrated into small- and medium-size CHP plants, biowaste plants, or decentralized areas as an additional renewable energy or biofuel source for energy and transport systems.

2.2. Application cases of the FLEXCHX process

The preliminary process design was made by the VTT [24] for different application cases of the FLEXCHX process depending on the boundary conditions:

- Case 1: base case with biomass alone, enriched air gasification, and once-through FT synthesis.
- Case 2: maximized production of FT hydrocarbons from biomass using pure steam/O_2 gasification and recycling FT waste gases back to the gasification process.
- Case 3: electrolysis-assisted FT production targeting the maximized conversion of biomass to FT hydrocarbons during the solar energy dominating season.

Case 1 (Fig. 2) will be analyzed as the base case and will most often be described as the current season. With the absence of surplus electricity in Lithuania, especially during the winter period, it is difficult to expect to apply the case with an electrolysis unit; therefore, Case 1 could be evaluated for the period up to 2030. Additionally, if steam or hot water boilers without electricity production are applied, electricity must be purchased from the grid in addition to the biomass input. In Case 2 (Fig. 2), the quantity of by-products is significantly reduced owing to the return of FT waste gas to the gasification processes, but this solution increases the yield of FT products, which have the highest energy value. Therefore, if the case is oriented to the demand of the heat consumers without disturbing the production of the main FT product, then the capacity of the gasifier should be selected according to the thermal capacity during the summer season. Considering that significant changes will take place in the energy market in 2030, the surplus electricity could be used to ensure the operation of the electrolysis device and the gasifier, which is important for the operation mode of Case 3 (Fig. 2).

There are no constraints on switching from one case to another, but control of the whole FLEXCHX process needs to be integrated into the CHP in order to react quickly to changes in energy markets. To achieve the best controllability and flexibility of the FLEXCHX control system, the entire system must be divided into separate distributed control system (DCS) subsystems, as well as should have main nodes with separate programmable logic controllers (PLCs). The control system of the process should be split into the following subsystems:

- ✓ Biomass feeding: controls the biomass preparation and handles processes such as drying, crushing, and supply of biomass to the gasification process.
- ✓ Gasification and gas cleaning: control the SBX gasifier and biomass gasification process, as well as gas cleaning.
- ✓ FT Synthesis: controls the FT synthesis, which is load-flexible, matching the flexibility of the gasifier (30%–100%).
- ✓ Electrolysis: controls the electrolysis process, which is load-flexible (10%–100%). From a process control point of view, the electrolysis process control is foreseen as a separate and independent control (black box).

2.3. Possible FLEXCHX integration cases depending on the market structure and integration level

The economic performance of the proposed solution depends heavily on the technical conditions and on a set of additional factors such as market structure, price setting mechanisms, state support availability, and taxation issues. Although the rules in usually integrated electricity markets are more or less similar in different locations across Europe, the behavior of DH market participants might be very different depending on the properties of each particular system and the rules used in its operation. This may also affect the economic performance of the FLEXCHX concept in each case.

Various possible situations could be analyzed using a two-dimensional system with different degrees of integration to the DH network and different degrees of competition in the DH market (see Fig. 3). The vertical axis in Fig. 3 represents the degree of competition, with strictly regulated and, in many cases, monopolistic markets as an extreme point. A pure competition market represents the opposite extreme, with many independent heat producers competing in the DH market. Although the FLEXCHX process is expected to be technically connected to a DH network, based on its owner's interest and relationship with a DH system operator, real integration to the system may range from full integration to full autonomy.

The case of full integration and strict regulation (lower-left quadrant in Fig. 3) means that the interests of the FLEXCHX owner fully correspond to the DH system operator's interests. In this case, the FLEXCHX process is used as part of the system to ensure the reliable operation of the DH system. In such a case, the cost coverage and some regulated profit are usually guaranteed by the legislation and verified or approved by regulating institutions. When the integration with the DH system operator is not as strong (right part of Fig. 3), the FLEXCHX system is free to maximize its

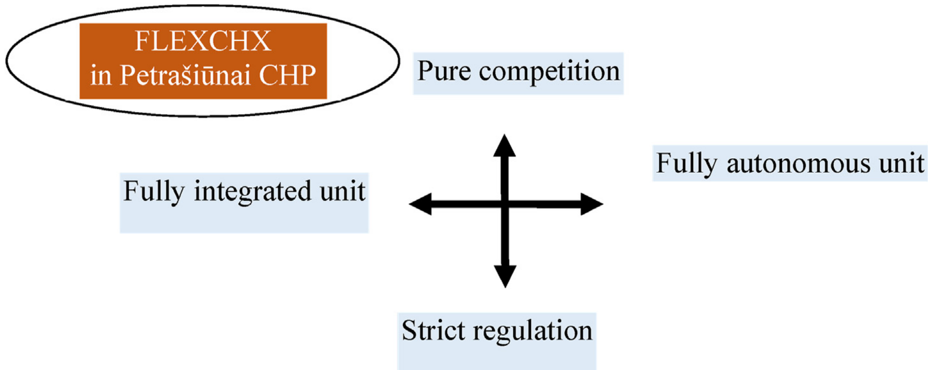

Fig. 3. Possible FLEXCHX integration cases depending on the market structure and integration level.

own profit by choosing the operation mode. Its contribution to the DH system depends on the financial incentives provided. In a competitive market (upper-right quadrant in Fig. 3), the FLEXCHX operator participates in the DH system as an independent heat producer. It is worth noting that the FLEXCHX system operator would likely control some other DH system units. Therefore, it would orient the strategic behavior in a competitive DH market toward profit maximization of the entire suite.

In a competitive DH market, the interest of market participants may diverge. In addition, a competitive market can be organized in different ways, that is, using auctioning rules and defining market participants' responsibilities. The upper-left quadrant of Fig. 3 represents the situation of FLEXCHX in the Kaunas DH system: there is a highly competitive market (not only the network operator produces heat but also several participants compete in the market; the available generation capacity exceeds the demand for heat; the market is not dominated by a single producer) and FLEXCHX is at the network operator's disposition. Thus, the needs of the DH network must be prioritized. In this case, the FLEXCHX system needs to work along with other units that are directly controlled by the DH system operator and react to the behavior of independent market participants. For example, in the case of a sudden disconnection of an independent heat producer, FLEXCHX might be required to compensate for the capacity loss.

In this analysis, the peculiarities of local conditions are explicitly or implicitly reflected. Owing to competition in the market, the network operator and, consequently, the operator of the FLEXCHX unit are unable to set heat prices. Thus, it is assumed that price takers follow exogenously defined prices. The legislation in Lithuania provides different options to reduce corporate income tax levels (there are incentives for research and development activities, investments in technological renewal, etc. [38]). In fact, the activity (and sometimes creativity) of management plays an important role in the optimization of taxes. Therefore, corporate income taxes were not included in the analysis, assuming that the possible options to minimize taxation are employed to the level that makes profit taxes negligible. However, the government supports various innovation activities. Therefore, the economic analysis of all cases is performed considering an additional scenario that assumes that a subsidy for the demonstration plant (25% of the investment) is provided.

The economic analysis in the present study also assumed pure competition in other markets, which means that the FLEXCHX system is unable to affect market prices of products sold, but production cost and, consequently, other indicators may differ depending on the situation in each case considered. The main indicators considered were the payback period that shows the time needed for an investment to be returned to the investor and the internal rate of return (IRR) that allows a quick comparison of different investment projects. These indicators were calculated using annual cash flows of the investment project. Payback period is assessed by calculating cumulative cash flow for each year, while the IRR was calculated ensuring that the net present value of the investment project under certain IRR value is equal to zero.

To enable comparisons of different cases, the surrounding environment is fixed (i.e., district heat, FT product prices do not differ depending on the case analyzed). It is worth to note that the results of the calculations are heavily influenced by the assumptions about such external factors as the market price of the FT product for which an additional analysis was performed.

To validate the inclusion of the FT product in the market as a feedstock, the quality of the raw materials is important for the refinery, and it is necessary to evaluate the investment in additional refining, logistics requirements, and raw material competitiveness. In oil refining processes, it is necessary to avoid acid components, metals, and especially olefins in the feedstock, which may cause process challenges and require additional hydrogenation. Studies [35] on the raw material (FT product) have shown that this product most often does not contain the above-mentioned additives and is practically sulfur-free, although it may contain small amounts of olefins. Furthermore, it does not contain any other harmful components and, therefore, is potentially suitable for co-refining installations. As a result, the raw feedstock becomes more competitive in the market, and it is an attractive alternative material for existing refineries. In terms of the competitiveness of alternative liquid biofuels, it is difficult to expect their price to be lower than the price of oil. It is expected that in 2021 the price of crude oil will range from 50 to 66 USD/bbl, which corresponds to approximately 0.31–0.40 €/kg. Despite the low price of oil, the current transport fuel market is facing very important changes to the RED II Directive [36]. The changes relate to the traceability requirement for renewable energy sources in transport fuels, which has not been implemented so far, and therefore, the development of raw materials from renewable sources has not been encouraged. A compliance obligation with the standards would increase the prospects of the integration of raw materials from renewable sources, including the prospects for FT production. The market analysis revealed that the demand for raw materials such as palm oils [37], which are also not cheap in the market, is growing. In 2019, the price [38] of palm oil was 430 €/t, and in 2020, it was already 896 €/t for the same raw material, and it was still growing. On this basis, the calculations assumed that the price of the FT product to the refinery would be 850 €/t.

2.4. CHP plant sustainable for FLEXCHX concept

In the two largest cities of Lithuania, Vilnius and Kaunas, natural gas was used until 2012 as the main fuel for heat production in the DH system. To implement the EU environmental requirements, the heating sector has undergone changes that aim to replace fossil fuels with renewable fuels. The Kaunas DH company has set ambitious plans for DH development and has made use of EU investments; currently, biomass accounts for approximately 87% of annual heat production [17]. The final target of this company is to produce 100% of the heat using renewable energy sources. For this reason, Lithuania is an example of a country where the present energy policy and infrastructure are favorable to the market entry of FLEXCHX technologies; therefore, one of the cities, Kaunas, will be analyzed in more detail.

To evaluate the integration ability of waste streams and their demand, a detailed review of heat producers was carried out considering the location, installed heat capacity in the power plant/boiler houses, facilities, and liabilities of heat production to industries. Despite the huge thermal capacity (over 2000 MW) installed during the Soviet period, the thermal capacity of peak demand in Kaunas City is only 500 MW [17]. It is important to note that the average thermal capacity demand during the heating season in Kaunas city is approximately 200–250 MW [39], while biofuel boilers are currently operated at approximately 340 MW. All the other facilities operate with natural gas. It is obvious that the capacity of existing facilities significantly exceeds the heat demand of Kaunas City. In the heat market, the heat price [17] depends on the conditions created by competition. For this reason, during the summer, when the thermal capacity demand is less than 50 MW, the price is the lowest, while the competition is fierce; therefore, most of the facilities are unused. However, during the winter period, there is no competition during peak periods, which allows prices to rise. In pursuit of a low-price policy, it is desirable to integrate new technologies that reduce not only the heat price for consumers but also allow facilities to be beneficially loaded by directing work to the production of the most needed product at the time.

After evaluating the capacities of different CHP plants [40] in Lithuania, the **Petrašiūnai Power Plant** (Petrašiūnai CHP) in Kaunas City was chosen for the analysis of the integration of FLEXCHX. This CHP plant (Table 1) (installed thermal capacity: 295 MW, power capacity: 8 MW) is integrated into the DH network of Kaunas City. In addition, this heat producer (Fig. 4) is one of the main components in the Kaunas city system and is responsible for providing the reserve of thermal power, because it balances the heat production (it works as an operator) of all the DH networks. The main facilities for heat and power production at the Petrašiūnai CHP are presented in Table 1.

The total capacity installed at the Petrašiūnai CHP is 295 MW (of which 24 MW corresponds to biofuel boilers, and 6 MW to the economizer). The annual load duration curves (Fig. 4) represent the heat production mode at the Petrašiūnai CHP in recent years. This can be divided into three operating modes. By operating the power plant in a basic operating mode during the winter period, the power plant constantly ensures the fulfillment of demand for approximately 30 MW (biofuel boilers and economizer) of thermal power. As the Petrašiūnai CHP balances production in the network, in the case of a sudden increase in demand for thermal power in the city (up to 100 MW), the heat producer must cover the resulting fluctuations. To ensure the response to a sudden change in the demand for thermal power in the CHP, natural gas PTVM boilers are used (for the smallest fluctuations, GM-HHB units are used).

According to Fig. 4 (PE_B), the maximum power fluctuation in such cases reached 40 MW, which is only 6.7% (11515 MWh) of the total amount of heat produced. An 18 MW natural gas boiler is used to regulate insignificant power fluctuations. The workload of this boiler was not significant, and the approximate amount of heat produced was only 1.2% (2017) of the annual heat production. The average heat capacity was approximately 6.6 MW (the load varies from 0.9 to 18 MW). During the summer period, if there is a lack of heat power or whenever repair works are implemented in other boiler houses, the Petrašiūnai CHP (which is in a strategically chosen place) works using its biofuel boilers.

By observing the dynamics of the operating modes of the heat-generating equipment in Fig. 4, it can be found that the change in capacity using natural gas amounted to 90 MW (Fig. 4; PE_C). During certain periods, owing to the influence of the factors of free competition in the market, the heat production was carried out using the natural gas installation, not only to compensate for fluctuations (Fig. 4; PE_A) but also for continuous heat supply assurance.

In this study, an alternative for the analysis is adopted, where the small fluctuations in thermal power are covered by a low-capacity gas boiler (18 MW). The high-capacity boilers (116 MW) would be adapted to the combustion of syngas and waste gas, according to the need, when the minimum thermal power requirement is at least 20 MW. If the quantity of waste gas and syngas is insufficient, natural gas is inevitably used to attain the required thermal power. Independence from natural gas usage can be achieved only by increasing the gasifier capacity. This can be realized by installing a gasifier with a capacity of at least 40 MW.

Because the main product, generally the FT product, is obtained during the thermochemical process because of exothermal reactions, considerable amounts of steam are generated, which would also be used on the heating surfaces. To accomplish this, it is also necessary to calculate the costs of the specific equipment installation and labor costs.

Table 1
Data of Petrašiūnai Power Plant facilities (provided by JSC Kauno Energija).

No.	Heat Generation device	Installation year	Last overhaul	Installed capacity		Power by fuel type			
				MW	t/h steam	Biofuel, MW	Oil Fuel, MW	Natural gas, MW	Liquid fuel, MW
1.1.	Boiler BKZ	1956	2011		75		50	57.8	
1.2.	Boiler PTVM	1963	2010	116			80	98	
1.3.	Boiler PTVM	1965	2010	116			80	99	
1.4.	Boiler VHB	2015		12		12			
1.5.	Boiler VHB	2015		12		12			
1.6.	Boiler GM-HHB	2017		18				18	18
1.7.	Economizer KDE CEG	2014		10					
1.8.	Economizer KDE CEB	2015		6					
1.9.	Economizer KDE CEG	2017		1.8					
1.10.	Turbo generator	1957	1998						
			Total:	291.8	150	24	210	272.8	18

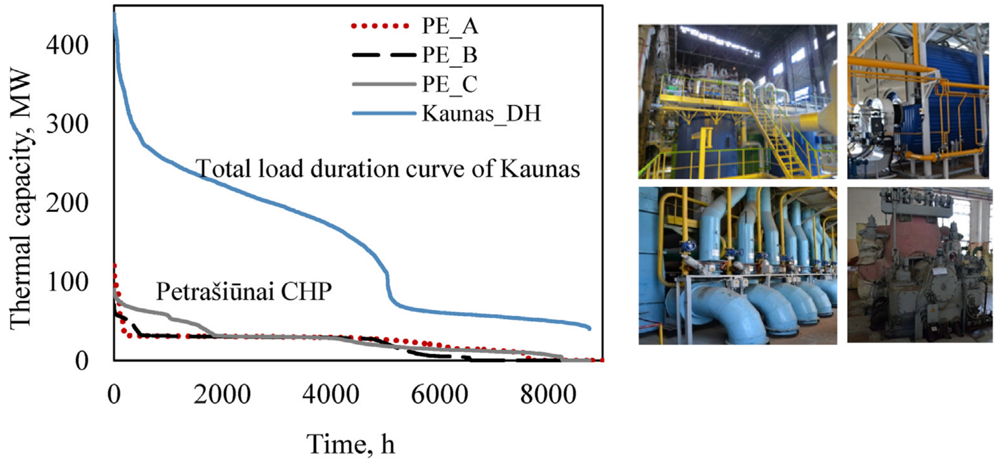

Fig. 4. Annual heat production demand at Petrašiūnai power-plant (provided by JSC Kauno Energija).

2.5. Product output capacity by integrating the FLEXCHX concept

Considering that the Petrašiūnai CHP requires a very flexible operating mode, and that the FLEXCHX concept aims to optimize the use of energy resources, the capacity range of the gasifier should cover the fluctuation range of the thermal power. In addition, considering the typical load duration curves, the capacity ranged from 30 to 120 MW during the winter season, although the more intense capacity variation can be set in the range of 40–70 MW. Based on this condition, the limits of the analysis were defined, and it can be said that the optimum capacity of the gasifier may be in the range of 10–40 MW. Based on the FLEXCHX basic process concept (base scenario A) and CHP plant capabilities, the product outputs (Fig. 5) are presented considering the capacity of the gasifier and the different concept cases. The biofuel selected for the analysis was residual wood&bark with a moisture content of up to 50%. The net calorific value (LHV) of this biofuel was set at 8.7 MJ/kg. Due to the very high moisture content of biomass waste, it needs to be dried to a nominal moisture content suitable for gasification (around 10%). would be ensured by low-temperature waste steam. This has been taken into account and this heat content is not included in the product outputs. The need for electricity depends on different scenarios, and this will be discussed in detail in the economic evaluation section.

It is worth mentioning that the analysis of the selected potential site data and FLEXCHX concept integration is based on actual capabilities, that is, it is limited by real parameters such as capacities, streams, heat, and power production. Given that the annual load duration curve (Fig. 2; PE_B) represents the workload scenario, it was used as the base curve for the calculations. In addition, it is necessary to note that the accepted maximum heat demand is 172673 MWh regardless of the heat source used.

The following conditions were assumed for the technical assessment, which affected the calculation results:

a) The flexible working mode of the gasifier was adapted to ensure fluctuations in the heat capacity when the required load was over 30 MW. To cover the fluctuations of the heat demand, the syngas might be supplied directly to the CHP plant to maximize the heat and power production rapidly, thus by-passing the synthesis unit (scenario B). The maximum capacity of the gasifier is 40 MW to achieve independence from fossil fuels.

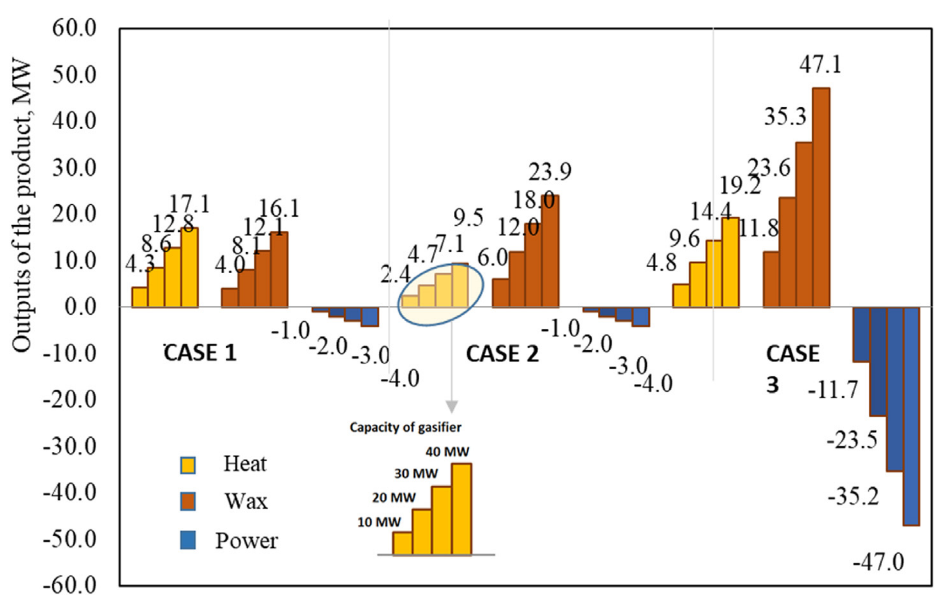

Fig. 5. The capacity of product outputs (provided by VTT Technical Research Centre of Finland).

b) Low-calorie gas (as the waste gas) can be burned in the natural gas boilers using the existing burners, which should be adopted for burning these gases when the hat demand is over 30 MW. If the required total heat demand from customers is less than 30 MW, the waste gas can be directly supplied to the biofuel furnace for burning. It can partly substitute the biofuel used for heat production in the existing biomass boilers, but the biomass savings have not been assessed.
c) If the economic assessment reveals that the use of syngas to ensure power fluctuations (by scenario B) would not be economically viable, then the syngas supply option for unexpected heat demand would be considered ineffective. In this case, the output of the FT products and by-products would be generated evenly throughout the year.

In order to make efficient use of waste energy sources, it is necessary to take into account the ratio between the waste stream generated Q_{gen} (potential) and the waste stream consumed Q_{consum} (used). The efficiency criterion of waste stream integration Q_{efect} can be calculated using equation (1),

$$Q_{efect}=Q_{gen}/Q_{consum} \tag{1}$$

where Q_{consum} is the consumed waste stream, in MWh, and Q_{gen} is the generated waste stream, in MWh.

3. Results

3.1. Technical assessment of waste streams integration possibilities

The technical capabilities considering the product outputs (Fig. 5) were evaluated to integrate the waste streams into the CHP plant. This assessment allowed us to understand how the heat production in the individual heat generation facilities would change by integrating the waste streams into the Petrašiūnai CHP. For example, waste gases with low calorific value can be utilized in three separate options: 18 MW gas boilers, 116 MW gas boilers, or 12 MW biofuel furnaces. The utilization of gases in the biofuel furnace when gaseous recirculation products are directly supplied together with low calorific value gases is a low-price alternative that provides unrestricted realization of waste streams. However, the use of gas boilers for the combustion of waste gases requires large investments because reconstruction of the burners is needed. In addition, consideration of the maximum and minimum permissible load capacity of the boiler is required. Because the possibility of syngas usage is considered and the power plant has gas boilers, it is much more favorable to adapt the gas burners. The exploitation of the biofuel furnace is still considered an option in situations where very small streams are generated and the gas boilers are lightly loaded. However, regardless of the selected alternative for gas utilization, an automated gas management system must be installed in the entire power plant. It would be counted as an additional cost for plant development in order to implement the FLEXCHX concept. If the option of utilizing waste gas in the natural gas boilers is chosen, the burners must be adapted to the combustion of waste gas and syngas after assessment of the additional investments required.

The heat production in different heat generation sources was recalculated for three different cases with different gasifier capacities, and the results are presented in Table 2.

According to the results obtained (Table 2, Fig. 6), the amount of waste energy streams depends on the FLEXCHX unit capacity, which also impacts the heat generation in the other sources. Although the changes in the cost of heat will be noticeable, and they will be lower than the market price, the biggest advantage of this project is that it involves sustainable energy, which is strongly related to the 4th generation DH approach. The fact that primary energy sources are not used for energy production and secondary by-products are used leads to savings of natural resources and contributes to climate change mitigation.

After evaluation of the technical capabilities to vary the heat generation operating modes by changing the feeding of different primary and secondary energy sources, it was concluded that implementation of the concept in the power plant within the set limits of the plant is technically feasible. However, to achieve effective utilization of waste energy sources with optimum facility loads depending on the consumer demand curve, it is also necessary to consider the value of the generated waste stream (potential) and consumed (used) waste stream. This efficiency criterion of waste stream integration Q_{efect} is calculated by equation (1). The results are shown in Table 3. The closer the value of this ratio is to 1, the greater the amount of waste stream consumed. This criterion can also affect the selection of the capacity limits of the gasifier to obtain the greatest economic returns when the efficiency of the utilization of waste energy sources is the highest.

Table 2
Heat production by heat generation sources at Petrašiūnai power-plant.

Heat sources	Actual data		Gasifier 10 MW		Gasifier 20 MW		Gasifier 30 MW		Gasifier 40 MW	
	MWh	%	MWh	%	MWh	%	MWh	%	MWh	%
Total heat production	172672	100	172672	100	172672	100	172672	100	172672	100
CASE 1										
Nat. gas boilers (PTVM)	8559	**5.0**	5087	**2.9**	1523	**0.9**	78	**0.05**	–	**-**
Nat. gas boiler (GM - 18 MW)	2085	**1.2**								
Waste gas/waste heat	–	**-**	27720	**16.1**	52737	**30.5**	75953	**44.0**	98292	**56.9**
Biofuel boilers	162028	**93.8**	133436	**77.3**	108419	**62.8**	85204	**49.3**	62864	**36.4**
Syngas	–	**-**	6428	**3.7**	9993	**5.8**	11437	**6.6**	11516	**6.7**
CASE 2										
Nat. gas boilers (PTVM)	8559	**5.0**	5087	**2.9**	1523	**0.9**	78	**0.05**	–	**-**
Nat. gas boiler (GM - 18 MW)	2085	**1.2**								
Waste gas/waste heat	–	**-**	15535	**9.0**	30949	**17.9**	45018	**26.1**	58330	**33.8**
Biofuel boilers	162028	**93.8**	145621	**84.3**	130207	**75.4**	116138	**67.3**	102826	**59.6**
Syngas	–	**-**	6428	**3.7**	9993	**5.8**	11437	**6.6**	11516	**6.7**
CASE 3										
Nat. gas boilers (PTVM)	8559	**5.0**	5087	**2.9**	1523	**0.9**	78	**0.05**	–	**-**
Nat. gas boiler (GM - 18 MW)	2085	**1.2**								
Waste gas/waste heat	–	**-**	33885	**19.6**	63516	**36.8**	91409	**52.9**	118145	**68.4**
Biofuel boilers	162028	**93.8**	127271	**73.7**	97640	**56.5**	69748	**40.4**	43011	**24.9**
Syngas	–	**-**	6428	**3.7**	9993	**5.8**	11437	**6.6**	11516	**6.7**

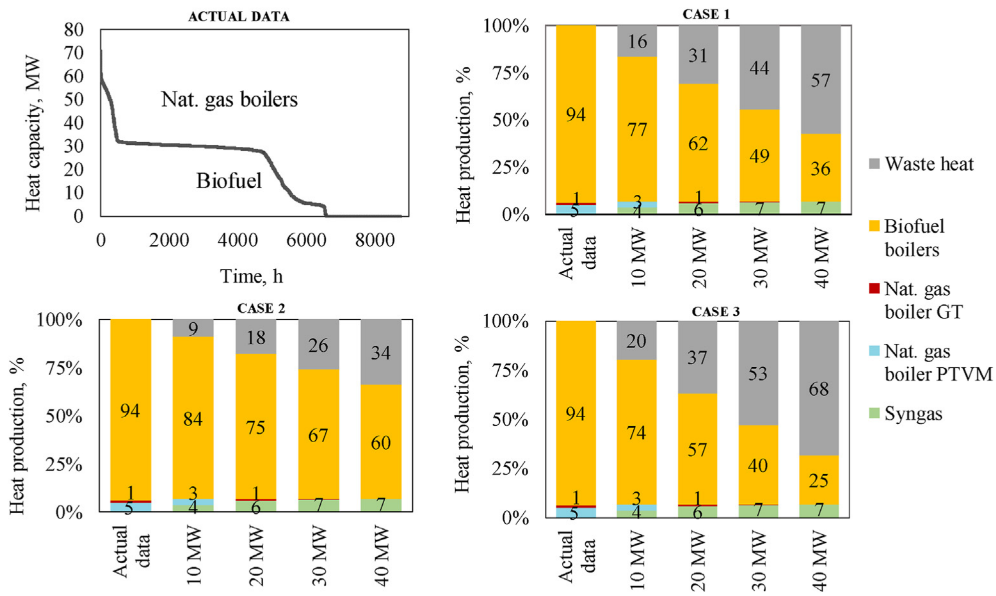

Fig. 6. Waste heat distribution depending on the gasifier capacity.

Table 3
Volumes of waste streams integration into CHP.

Gasifier capacity	Waste heat capacity	Heat potential	Used heat	Efficiency
MW	MW	MWh	MWh	MWh/MWh
Case 1				
10	4.27	37440	28018	0.75
20	8.55	74880	53251	0.71
30	12.82	112320	76690	0.68
40	17.10	149760	99243	0.66
Case 2				
10	2.37	20716	15535	**0.75**
20	4.73	41432	30949	**0.75**
30	7.10	62148	45018	**0.72**
40	9.46	82865	58330	**0.70**
Case 3				
10	5.20	45541	33885	**0.74**
20	10.40	91081	63516	**0.70**
30	15.60	136622	91409	**0.67**
40	20.79	182162	118145	**0.65**
Actual data				
Total heat production to CHP – 172672 MWh.				

Because the heat demands of consumers change during the year, the waste energy stream consumed in the evaluation of the power plant was based on the annual load duration curve (Fig. 6), as presented in Table 3.

During the summer season, the heat demand is significantly reduced because most boiler houses are often switched off. Therefore, the use of waste heat streams may be ineffective if the initial capacity of the gasifier is excessively high. The heat utilization efficiency (Table 3) of waste streams was calculated in the analysis and for this particular case, it was between 0.75 and 0.65. To achieve a price of the integrated heat that is competitive in the heat market, the efficiency would reach 1 and heat production would be increased by 35% of the total heat. Competition, which dictates the market conditions, is one of the advantages of a large number of small heat producers in the DH network. Therefore, the possibility of using waste streams at the CHP plant would mostly depend on the heat price in the market.

The main highlights of this technical assessment are as follows:

- The capacities of the gasifier are within the range of 10–40 MW, which was selected based on the heat demand fluctuations.
- The gasifier might meet a peak demand for thermal power by directly utilizing syngas in the boilers. Peaks account for just 6% of the total demand; therefore, FT product production would not be significantly affected. The FLEXCHX concept allows a more flexible and faster response to changes in consumer heat demand compared with biofuel boilers, and it would provide independence from fossil fuels by using biomass.
- Waste streams can be used all year round, which would also provide the possibility of a flexible response to minor power fluctuations. The potential ranges from to 5–20 MW depending on the installed gasifier capacity.
- To ensure the operation of the gasifier, an additional power input is required.

3.2. *Economic assessment of waste streams integration possibilities*

This research presents studies on the integration of waste streams into the Petrašiūnai CHP in Kaunas City, Lithuania. It is essential to design a coherent production concept for cost-effective tri-generation of FT products, heat, and power. On this basis, the economic attractiveness was assessed in terms of operating modes, preliminary process management schemes, by-products and FT product streams, electricity and heat markets, and other surrounding conditions. In addition, we qualitatively assessed the various potential DH applications in the Petrašiūnai CHP, where the waste streams could be integrated considering the conditions of the process. Undoubtedly, this research aims to prove that the dependence on fossil fuels can be reduced in heat generation sources such as boiler houses and CHP plants by integrating the FLEXCHX concept. This option is offered by combining the operation of a syngas conversion unit (FT synthesis) with a sudden demand for heat. Integrating the concept into the CHP plant (the same situation might also occur in boiler houses) would eliminate the use of natural gas in heat production, replacing it with syngas. An economic assessment was performed to determine whether synthetic gas would be economically attractive to cover heat demand fluctuations. However, it should also be understood that the use of syngas is directly dependent on the operation of the FT unit because it reduces the production of the FT product (alternative renewable fuels for transport) as a basic product and consequently, the waste streams.

The economic evaluation was performed considering the conditions presented in the technical assessment, such as working modes, yields of by-products, and main FT product streams obtained through the FT reaction. Investments in the complex FLEXCHX were assessed according to the literature [41], where the average investment value of similar technologic components is described. These investments were recalculated by adopting scale factors (SF = 0.8) [42] for the respective chosen capacity. To reduce the investment value, the possibility of FLEXCHX unit integration in the present Petrašiūnai CHP with a well-developed industrial infrastructure (biofuel supply system, DH system, and a great industrial location) was considered. According to the listed assumptions, investments for realization of the FLEXCHX concept amounted to 2.02 M€/MW per biomass input. In addition, when calculations were made, it was confirmed that the direct capital costs (see Table 4) are the same for both Case 1 and Case 2.

In terms of the operating mode of Case 3, the direct capital costs are significantly higher compared to those in the cases mentioned above, because the additional investment in the electrolyzer block was included in the evaluation. It is no secret that the green hydrogen extracted by means of electrolyzer blocks can ensure decarbonization in the industrial sector; moreover, it has been observed recently that costs have decreased dramatically along with the growing assets of renewable energy. The investment cost in the electrolyzer was obtained based on a comparative analysis carried out by Saba et al. [43] by reviewing the advantages and disadvantages of polymer electrolyte membranes (PEMs) and alkaline electrolyzer equipment. On this basis, the cost of the electrolyzer was assumed to be 500 €/kW. The direct capital cost data are presented in Table 4.

According to the economic evaluation, the manufacture of liquid biofuels such as FT products has a relatively high cost. Shale oil fracking [40] is a much cheaper process and therefore it would pay back more rapidly; however, this technology poses many threats to sensitive lands that are too wild to drill. In the search for more sustainable technologies, it can be said that FLEXCHX stands out for its potential of application in various fields, and therefore, it allows the achievement of sustainability in different industries simultaneously (heat, power, steam for industry, refinery). Owing to the complex technologies used, which require high investment, it may be necessary to obtain state support (state subsidy) to justify the FT product. This is significant not just because innovative technologies that use renewable energy sources are developed, but also because they contribute to solving national challenges and have global importance in the environment.

Based on the state support model discussed above, economic calculations were performed to evaluate the financial attractiveness when support was received (up to 25%) compared to when it was not. In addition, it is worth mentioning that the investments in base scenarios A and B (Fig. 2) are the same. Furthermore, in both scenarios, the additional cost of the FLEXCHX unit integration into the CHP plant is included. The direct capital costs of all the discussed scenarios (base scenario A and scenario B), operating modes (Case 1, Case 2, Case 3), and capacities of the gasifier (in the range from 10 to 40 MW) are presented in Table 4.

It is known that costs consist of fixed and variable parts. The operating expenses (OPEX) were estimated taking into account the potential variable costs to ensure the ongoing processes, and the fixed costs were assessed to cover the costs of continuous operation. The variable costs are those incurred for the use of fresh and waste water, gas cleaning, electricity cost, maintenance materials, troubleshooting, and biomass costs. These costs are constantly variable, depend on the technology used and capacity of the equipment, and can fluctuate significantly over the years.

The annual variable production costs for 1 MW of gasifier capacity are presented in Table 5. It is necessary to mention that in all calculations, it was assumed that the operating time of the plant was 20 years, and the discount rate was 0.05 (5%). It was also assumed that the working time of the FLEX unit would be the maximum, which means that the equipment will work without interruption for 8760 h per year. All production costs (for water, gas cleaning, maintenance materials, electricity) are based on the actual consumption of the 1 MW pilot version of the SXB gasifier depending on the prices in Lithuania on 2021 01.

In terms of fixed production costs, it was assumed that they did not change for a gasifier capacity in the range of 10–40 MW. These costs include staff salaries, their training for the first five years from the start of implementation, and insurance costs. The fixed production costs are presented in Table 6.

To be competitive in the heat market, it is important to maintain the price of heat in a low position. This possibility can be offered by the FLEXCHX concept, which allows for a more flexible response to the changing demands of heat consumers and for more sustainable heat production methods using waste sources. One of the advantages is that when there is high competition, waste heat can be offered at a price lower than the market price. Conversely, when competition is low, waste heat can be sold to consumers at market prices. Considering the above discussed circumstances in which it is difficult to estimate dynamic changes in the heat price, it was assumed in the economic calculations that all heat would be sold at a market price of 3.71 €/MWh [44] (2021, Kaunas city, Lithuania) for the entire assessment period. The heat price in Kaunas is quite low because there are many heat producers (more than ten) in the DH system, and the installed capacity of heat sources exceeds the demand of consumers, which results in strong competition. For these reasons, offering a low price of heat is a priority for all heat producers.

Assessing the waste heat potential, it was found that the efficiency of waste heat integration in the Petrašiūnai CHP is approximately 70%–75%. It was also determined that the surplus waste heat, if any, would be directed to the steam turbine (8 MW) at the

Table 4
Direct capital costs according to cases (suitable for both scenarios), support, operating modes, and capacities of the gasifier.

Gasifier capacity, MW	10	20	30	40
Case 1, Case 2				
Direct capital costs without support, M€ (scenario A and B)	26.7	46.4	64.2	80.8
Direct capital costs with support, M€ (scenario A and B)	20.0	34.8	48.1	60.6
Case 3				
Gasifier capacity	10	20	30	40
Direct capital costs without support, M€ (scenario A and B)	31.7	56.4	79.2	100.8
Direct capital costs with support, M€ (scenario A and B)	23.7	42.3	59.4	75.6

Table 5
Variable production costs (€/MW) per year.

Relation		Costs, €/MW (Case 1, Case 2)	Costs, €/MW (Case 3)	Annual price increase, %	Notes
Variable production costs	Fresh water	23 750	25 486	1% annually	Cost increased
	Waste water				
	Gas cleaning utilities				
	Maintenance materials			0.5% annually	
	Electricity for gasifier			–	Usage of surplus electricity
	Water suitable for electrolysis	–		–	No changed
	Electricity for electrolysis	–	617 009	Pessimistic/optimistic scenario	From grid 0–70 €/MWh
	Biomass feedstock	95 370		3% annually	Biomass price 11 €/MWh
Total variable production costs, €/MW per year		119 120	737 865	–	The cost trend is upward

CHP plant to generate electricity. It can also be mentioned that higher priority was given to heat energy than to electricity, in line with the 4th generation system in DH networks. Therefore, part of the electricity demand of the gasifier will be met by surplus resources.

In terms of electricity, it can be said that the FLEXCHX unit itself is also a consumer of electricity. Therefore, to ensure the operation of the gasifier, most of the surplus electricity is consumed by the unit itself for its own demands. However, sometimes, the demand may not match the volume of electricity produced. Thus, the economic calculations assumed that, if electricity is not used, the surplus electricity could be sold to the grid at a price of 66 €/MWh [45]. Conversely, if there is a lack of energy, electricity would be purchased from the grid to ensure the operation of the FLEXCHX unit.

In terms of turbine capability, it was determined during the technical assessment that the turbine has sufficient capacity to pass the surplus steam flow; therefore, there are no technical obstacles to its use. In the economic calculations for Case 1 and Case 2, it was assumed that the electricity sold would cover the cost of the electricity purchased. Another part of the electricity demand will be generated using surplus energy; therefore, the additional costs of electricity were not assessed in these cases.

However, the assessment of electricity demand was performed differently in Case 3. Given that the electricity demand in Case 3 is significantly higher because of the electrolysis unit, and the waste heat streams, including the surplus heat, are also higher, the purchase of electricity from/to the grid was assessed. Regarding the electricity market in general, the forecast of price changes reported in study [46] was taken into account when assessing the price of electricity. This study revealed that the price of electricity should become more competitive as we approach 2050, with an increasing amount of surplus free electricity. Based on the forecasting in the study report [46], as well as in the national legislation [47] and the National Energy and Climate Action Plan of the Republic of Lithuania [9], it can be argued that the share of electricity produced from renewables should increase, which may lead to surplus free electricity. With this in mind, two forecast scenarios of electricity price were selected for the analysis: pessimistic and optimistic (see Table 7). Table 7 also shows the electricity cost (MW) of the electrolysis unit.

The difference between the optimistic and pessimistic forecast scenarios in the electricity market suggests that the electricity costs can differ by one-third (up to 30%). How this affects the price of the FT product will be discussed later in the calculation results.

All of the above assumptions affect the prime cost of the underlying product in one way or another. Of course, it can be argued that the positive effect of revenue from waste heat or surplus electricity was estimated in the prime cost of the FT product. However, the economic assessment also analyzed a less economically attractive scenario B with a priority to use syngas for heat production. The calculations in scenario B took into account that the FT product output decreased from 1% to 6% depending on the operating modes of the different cases and gasifier capacities. However, a new product, syngas, is emerging in the market (Fig. 2). This gas is taken by bypassing the FT synthesis reactor and is directed to the CHP plant for heat and power production, thus generating additional revenue for the heat energy produced. Revenues from syngas were estimated taking into account the amount of heat produced and the heat price in the market (3.71 €/MWh).

Considering all the accepted assumptions and evaluating the gasifier operating modes and power limits, concept scenarios, primary and secondary product outputs, electricity and heat prices, state support, CHP plant technical capabilities, etc., the prime cost of the FT product was obtained, and the results (Fig. 7) were summarized for the operating mode of Case 1.

The base case with biomass alone, enriched air gasification, and once-through FT synthesis revealed that the lowest prime cost of the FT product would be 0.88 €/kg (at 40 MW gasifier capacity) considering state support. The average cost in the same case over the entire period is equal to 0.97 €/kg. Assessing the rise in variable and fixed costs (Tables 5 and 6), the prime cost of FT products is forecasted to increase by 5%–23% over a 20-year period in different scenarios. It was observed that state support allows the price of FT products to be reduced by approximately 13% from the average price. In addition, the results revealed, as expected, that scenario A would lead to lower FT product prices compared to scenario B. Nevertheless, it was shown that with the use of syngas as an

Table 6
Fixed production costs (€/a).

Relation		Fixed costs, €/a (Case 1, Case 2, Case 3)	Annual price increase, %	Notes
Fixed production costs	Operating labor and supervision	262 800	Salaries increase after 5 years by 10%, after 10 years - 20%	–
	Training	100 000	–	The first 5 years
	Profit tax	0	–	Not appreciated
	Insurances and taxes	500 000	Insurance costs decrease 5% annually	–
Total fixed production costs, €/a		**862 800**		

Table 7
Forecasting of annual electricity costs through 1 MW of the electrolyser.

Case 3	Unit	Price level in the market				Total
Market factors		Surplus	Low	Medium	High	Average
Price	€/MWh	0	30	50	70	0–70
Pessimistic evaluations						
Operating time per year	%	0	10	30	60	100
	h	0	876	2628	5256	8760
Costs for electricity	**€/MW**	**0**	**26 280**	**131 400**	**367 920**	**525 600**
Optimistic evaluations						
Operating time per year	%	25	22	18	35	100
	h	2190	1927	1577	3066	8760
Costs for electricity	**€/MW**	**0**	**57 816**	**78 840**	**214 620**	**351 276**

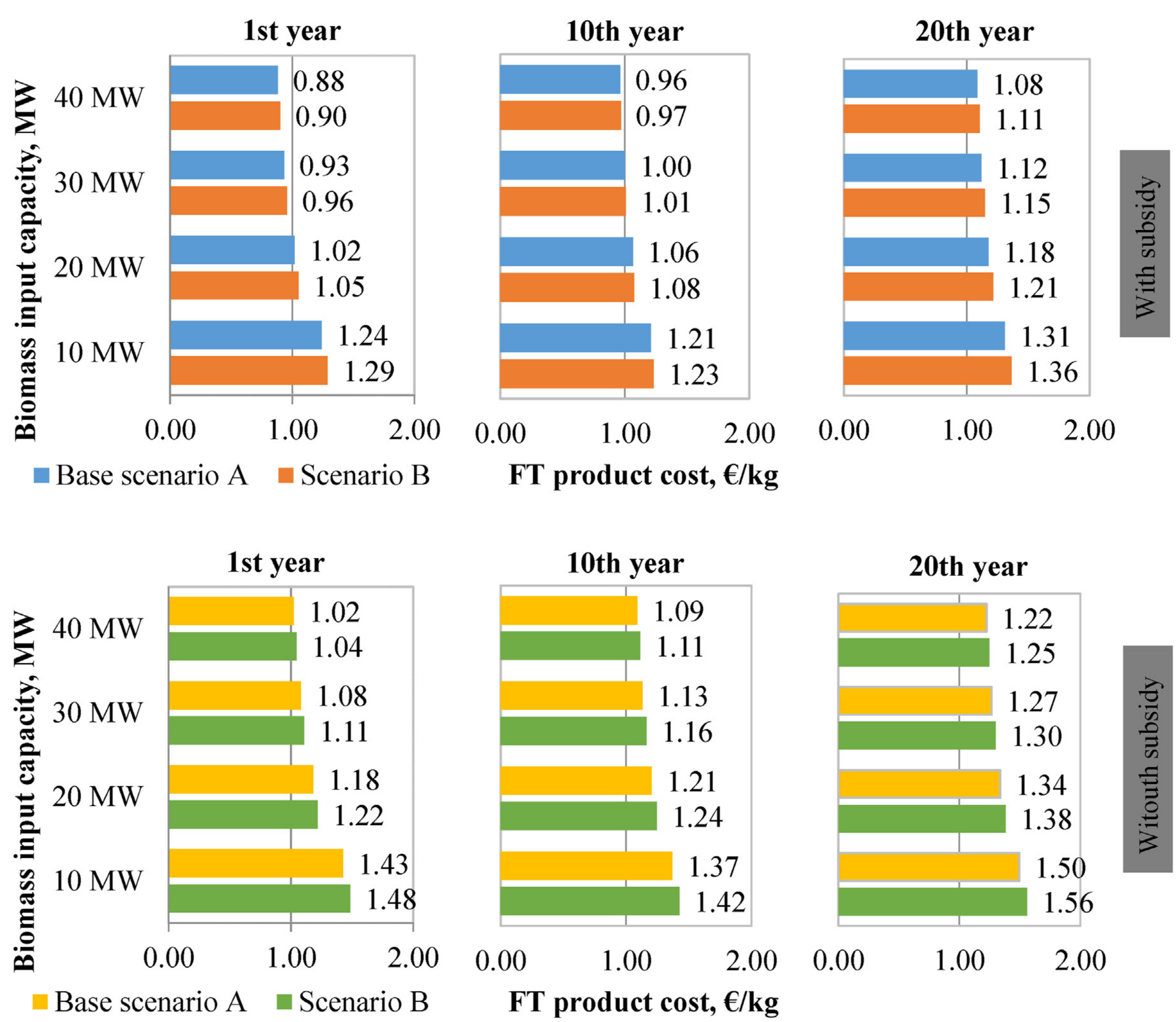

Fig. 7. Prime cost of FT product when the FLEXCHX unit is operated in Case 1.

alternative for heat production, the prime cost of the FT product increased insignificantly, that is, only 2%–4% (0.02–0.05 €/kg) from the average price. It was also found that the difference in FT product price between scenarios A and B decreased when the nominal capacity of the FLEXCHX unit was higher. From a sustainable energy perspective, the goal of becoming energy-independent from fossil fuels has a high level of adaptability, and the price differential is so small that the goal may be achieved. However, it must be emphasized that if the use of syngas for heat production increases, the economic attractiveness could deteriorate as it depends on the scale of heat demand fluctuations. The Petrašiūnai CHP is not only one of the heat producers in Kaunas but it also balances heat production; therefore, it must ensure that a sudden demand for thermal capacity could be met, and then scenario B could be considered suitable for the analyzed CHP. The fluctuations of thermal power do not constitute a decisive part of heat production (only 6%); therefore, the syngas alternative fits perfectly in this particular case.

The prime cost of the FT product when the FLEXCHX unit was operated in Case 2, is shown in Fig. 8.

In Case 2, when the FT synthesis unit was operated with a recycle loop to further improve the FT product yield, excellent results were obtained. It can be stated that the lowest price can be reached in scenario A when including state support, which is 0.61 €/kg at a gasifier capacity of 40 MW. In the same case, the average price over the whole assessment period would be 0.67 €/kg (maximum of 0.74 €/kg). The prime cost of the FT product in Case 2 is forecasted to increase by 5%–23% over a 20-year period in different scenarios. The subsidy reduces the prime cost of the FT product by 13% of the average price.

It is clear that a higher capacity unit makes it possible to reduce the prime cost of the product because of the fixed production cost component. It has been observed that although a lower capacity plant allows for a more efficient use of the waste heat, it provides lower economic benefits than a higher capacity one owing to the lower yields of the FT product. Therefore, it can be argued that a 40 MW gasifier is a more favorable alternative than a lower capacity unit. In addition, a 40 MW gasifier can reliably achieve fossil fuel independence conditions using the syngas option (scenario B). As for the alternative of using syngas in scenario B, the cost of the FT product operating in Case 2 mode would also increase insignificantly, that is, only 3%–6% (0.01–0.06 €/kg) of the average prime cost.

The prime cost of the FT product, with electrolysis-assisted FT production targeting the maximized conversion of biomass to FT hydrocarbons, is shown in Fig. 9.

The FLEXCHX unit operating in Case 3 produces twice the yield of FT product and generates twice as much waste heat compared to Case 2. However, the size of capital investment in Case 3 is larger, with an increase of 18%–24%. Operating in this mode for an entire year, according to the generated waste streams and capabilities of the CHP, large amounts of surplus heat are generated. If the consumer heat demand decreases, this can be easily solved by directing the waste heat to produce electricity. After the capital investments and operating expenses are estimated, the lowest prime cost of the FT product was obtained, which is equal to 1.04 €/kg (at 40 MW gasifier capacity) in scenario A. In the same scenario, the FT product average prime cost is projected to be 1.07 €/kg during the entire period considering state support. However, if state support is not included, the prime cost would be 6% higher. In Case 3, the average prime cost of the FT product is forecast to increase by 2–6% over a 20-year period in different scenarios. It was observed that the FLEXCHX concept operating in Case 3 can offer the lowest FT product price if a 40 MW gasifier is installed. With respect to syngas usage in scenario B, the FT product average cost will also increase slightly by 1%–2% (0.01–0.03 €/kg).

Fig. 9 presents the results payback period calculations for the for the three different cases: Case 1, Case 2, and Case 3, and with four more separate conditions (price with subsidy under scenario A, price without subsidy under scenario A, price with subsidy under scenario B, and price without subsidy under scenario B). As discussed in the Methodology section, the calculations assumed that the price of the FT product to the refinery would be 850 €/t (0.85 €/kg).

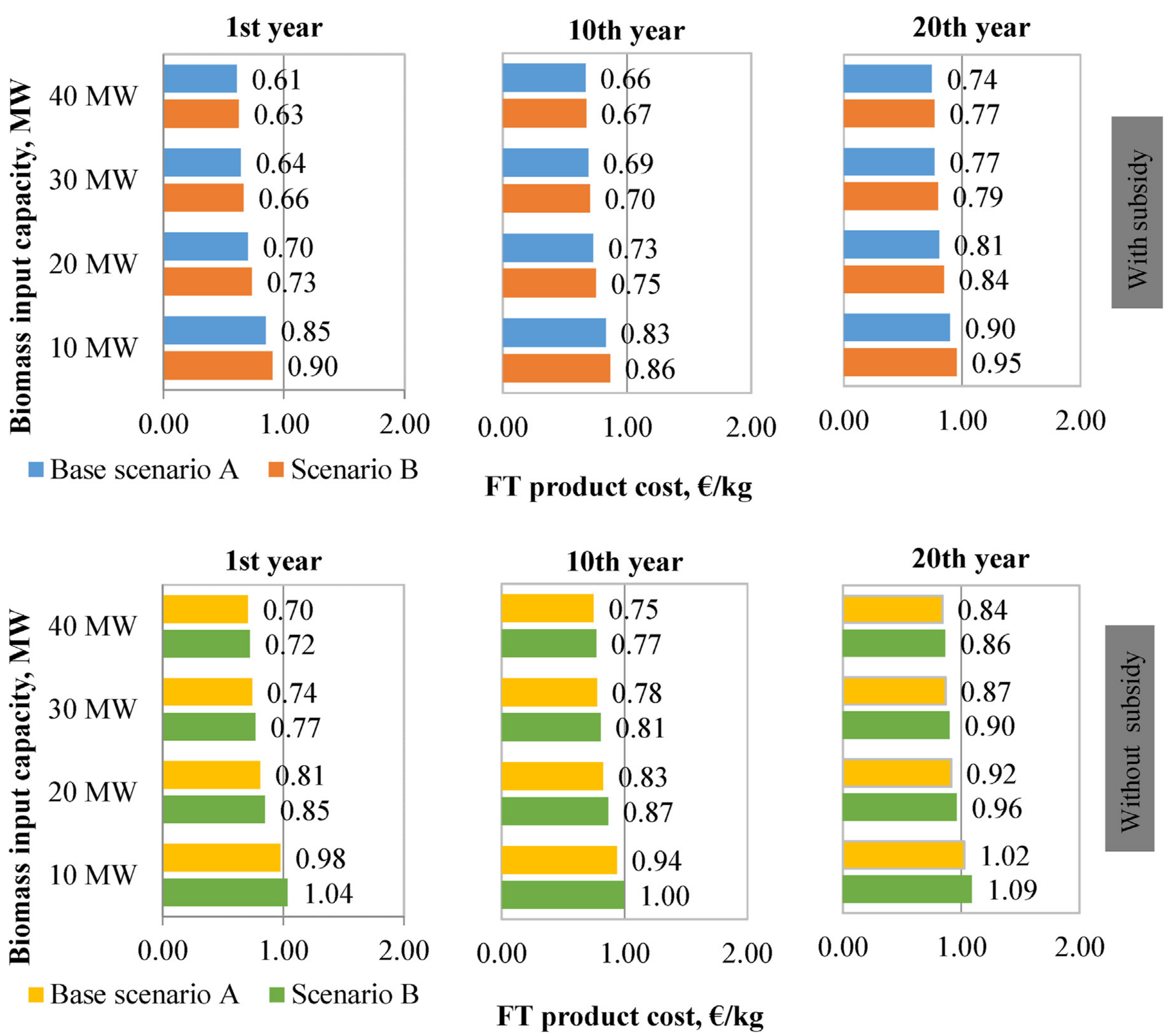

Fig. 8. Prime cost of FT product when the FLEXCHX unit is operated in Case 2.

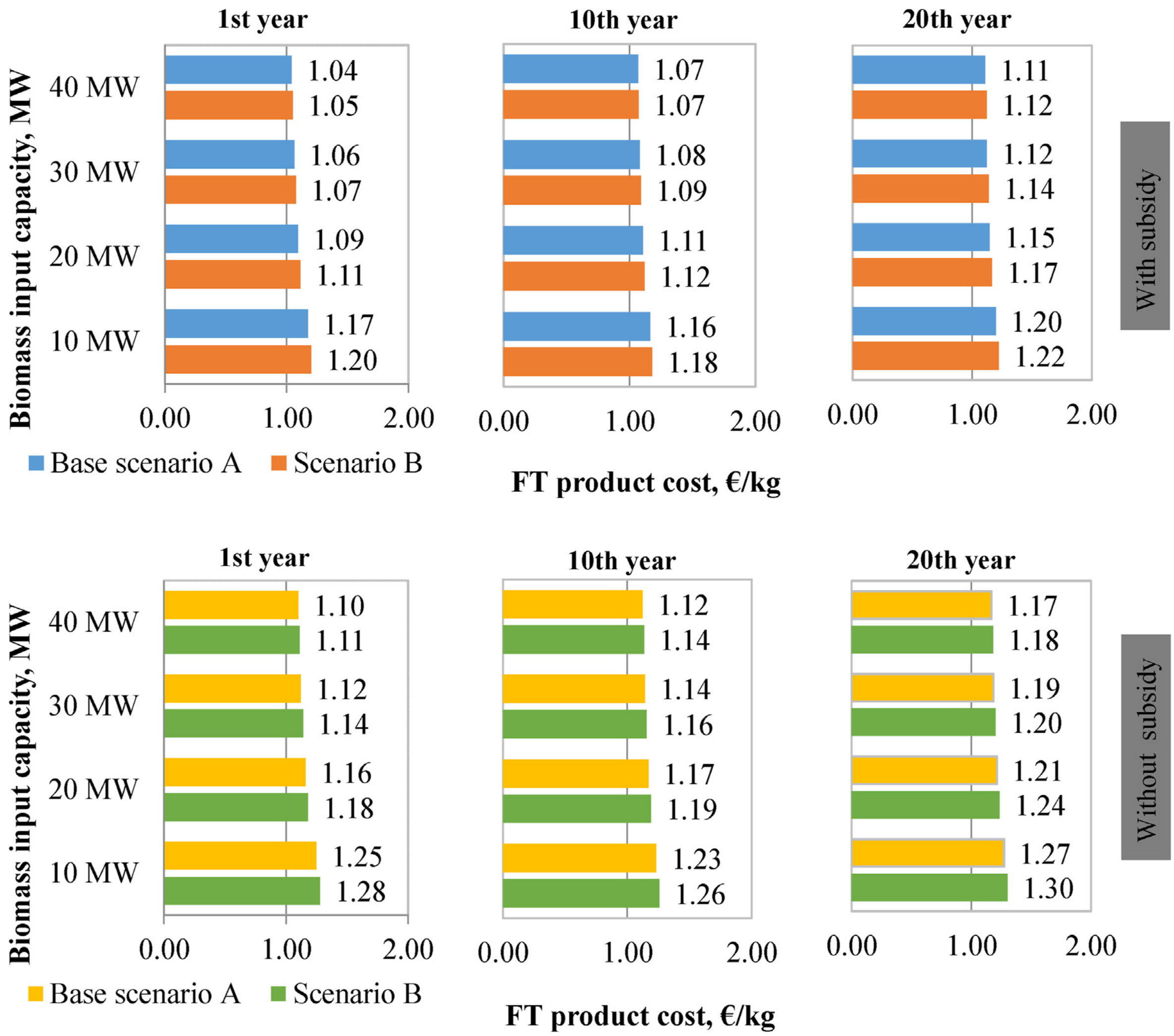

Fig. 9. Prime cost of FT product when the FLEXCHX unit is operated in Case 3 according to the pessimistic electricity scenario.

The economic assessment was limited to the production process of the FT product (from biomass to the production of the FT product), and the integration possibilities of the FT product at the refinery were not assessed.

The internal rate of return (IRR) is closely related with the payback and the attractiveness of the project. The trend of the IRR change (Fig. 10) depends on different cases.

The results of the economic evaluation (Fig. 10) showed that the integration of the FLEXCHX unit is more realistic in the operating mode of Case 2 owing to the lowest resulting FT product cost, 0.67–0.78 €/kg, and the shortest payback period, from 6 to 9 years, with a gasifier capacity of 40 MW. The IRR of Case 2 (Fig. 11) was the highest, thus exhibiting an advantage over other operating modes of the FLEXCHX unit. It can be concluded that the FLEXCHX concept is attractive when the FT product cost up to 1.07 €/kg (Fig. 11) and IRR >0. Below this threshold, it is difficult to expect a return on investment. Therefore, in Case 3, when electrolysis-assisted FT production targets the maximized conversion of biomass to FT hydrocarbons within the accepted conditions, it is not profitable. The situation could be improved by the emergence of surplus electricity in the market, as discussed under the optimistic scenario (see Table 7), which would reduce the prime cost of the FT product by 24%. On this basis, the attractiveness of the project would be in the range of -0.03 < IRR <0.07.

The study at the site level revealed the possibilities of FLEXCHX integration and proved that it can be economically attractive in today's market by operating in Case 2. This concept would allow heat producers to save energy resources and compete with low-cost biomass biofuel boilers while becoming energy-independent from fossil fuels.

4. Discussion

The challenge of combining the transport sector with a DH network and the power grid is presented in this article by discussing the operating modes of the gasifier, output of FT product and waste stream generated after the synthesis reactor, preliminary process management schemes, market factors, and economic attractiveness. In addition, this research focused on the integration of waste streams into local heat and power production plants, which is essential in the design of a coherent production concept for cost-effective tri-generation of FT products, heat, and power. To highlight the applicability of the FLEXCHX concept, existing CHP plants in Lithuania that could become potential sites for industrial and demo plants were selected.

Considering that by-products obtained after technological processes can become potential energy sources, it was determined during the research that the formed waste heat ranged from 21 to

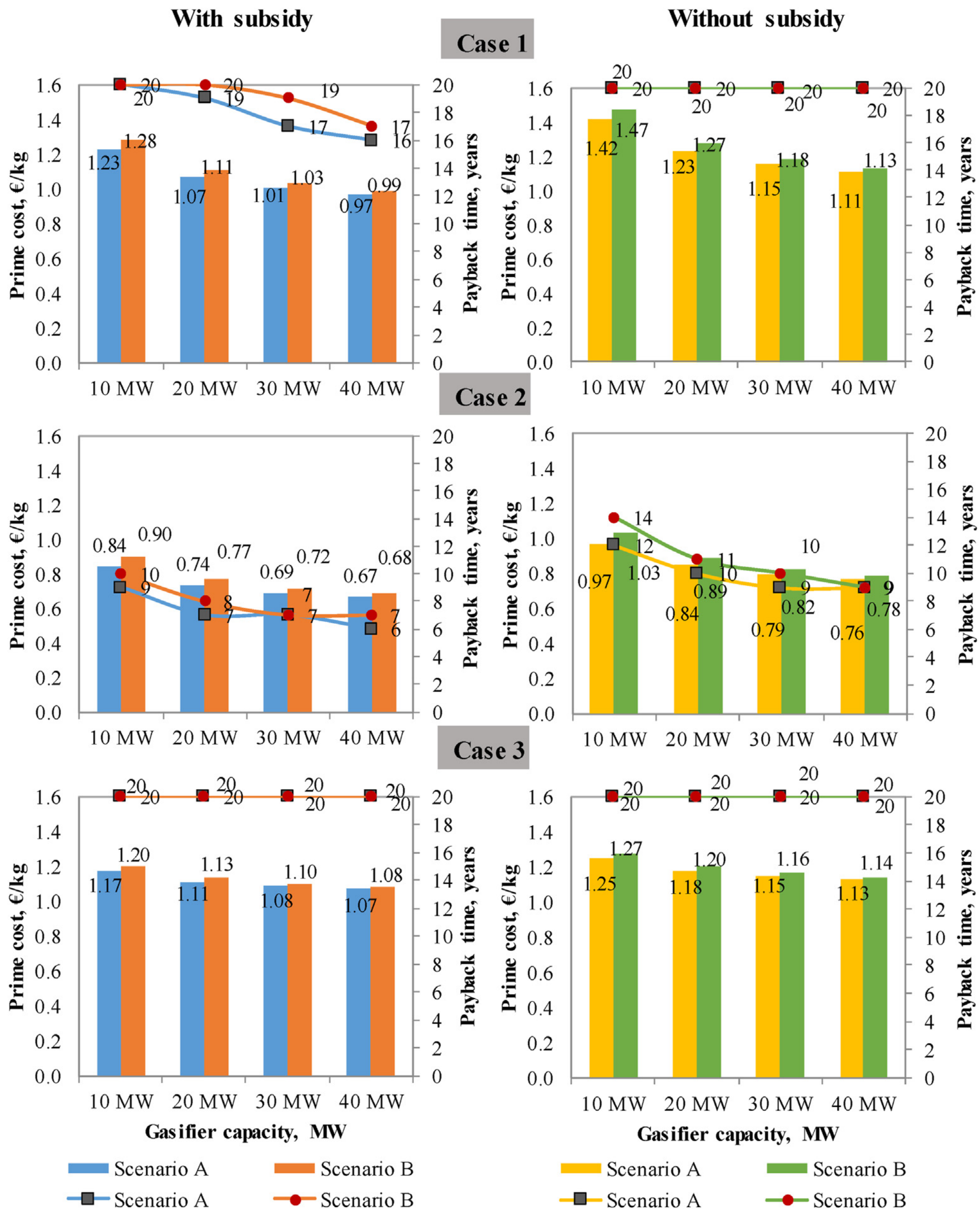

Fig. 10. Variation in prime cost depending on surrounding conditions.

182 TWh at different capacities and operating modes of the gasifier. It is believed that the integration of the FLEXCHX concept is related to the efficiency of waste utilization and depends on the CHP level in the system and operation regime. It was determined that a larger power plant could serve a higher capacity FLEXCHX unit. Therefore, the waste heat generated through the gasification process could be used as efficiently as possible and produce FT products at a lower price, thus creating stronger competition between heat producers. As the energy demands of consumers change throughout the year, the consumption of waste heat in the power plant was estimated based on an annual load duration curve (the calculations were adopted under conditions where the consumption could not exceed the annual demand curve). The calculations showed that the waste heat utilization efficiency was between 0.75 and 0.65 (Table 3). After evaluating all the technical capabilities (heat capacity, type of operating mode, activity and responsibility of the operator, assurance of reserve capacity, location), the integration of the FLEXCHX concept into the Petrašiūnai CHP requires a gasifier capacity of between 10 and 40 MW to achieve maximum efficiency. The analysis of economic attractiveness according to scenario A revealed that the FLEXCHX concept is more realistic for the operating mode of Case 2 because it leads to the lowest average cost of the obtained FT product, which ranges from 0.67 to 0.97 €/kg depending on the gasifier capacity. It was proven that the 40 MW gasifier is the most economically attractive option owing to the lowest average price of the FT product, which is 0.67 €/kg. For the same case, the economic calculations, which considered the planned amendments to the RED II Directive to promote them, showed that the payback period is 6 years and the IRR value is 0.13 (at 40 MW of gasifier capacity) assuming market price of liquid biofuels at the level of 0.85 €/kg. The other gasifier operating modes analyzed showed 30%–60% higher prime cost of the main FT product, ranging from 0.97 to 1.42 €/kg (Case 1) and 1.07 to 1.25 €/kg (Case 3). The IRR value based on the assumed price of liquid

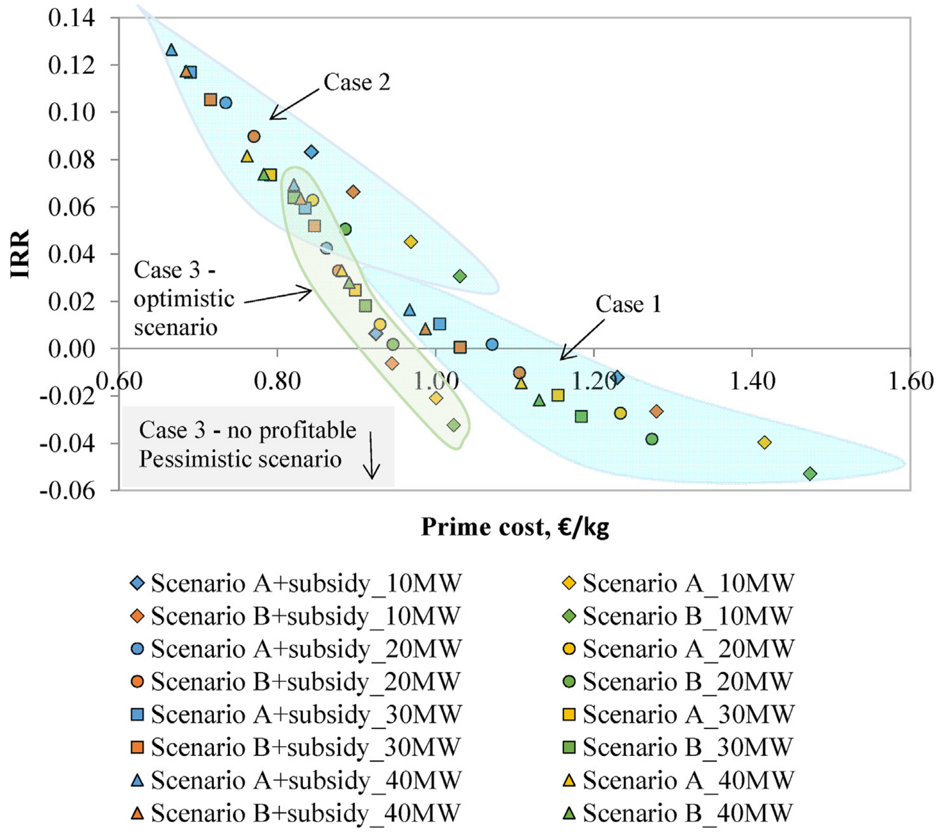

Fig. 11. IRR value depending on product cost.

biofuel (feedstock suitable for refinery) was almost always negative in Case 1 and Case 3 (pessimistic scenario), making payback impossible in the calculated period. The main difference between Case 2 and Case 3 is that the unit operating in the latter mode produces twice the output of the FT product and generates twice as much waste heat. However, the required investments are up to 24% higher, and additional costs for electricity purchase have been estimated. For these reasons, the average prime cost of the FT product was the highest and was equal to 1.07 €/kg in scenario A (at 40 MW gasifier capacity). The significant changes in the energy market that will be effective from 2030 will allow the use of surplus electrical energy to ensure the operation of the electrolysis device and the operation of a gasifier. It was determined that the prime cost of the FT product could become more competitive and approximately 30% lower, reaching 0.82 €/kg in the same scenario, with a gasifier capacity of 40 MW. The payback period would change to 10 years, and the IRR return value would be 0.07.

In addition, it was proved that the hybrid FLEXCHX technology in scenario B using renewable energy sources (syngas produced from biomass) may ensure independence from fossil fuels (natural gas) for energy production by flexibly responding to the changing demand of heat consumers. On this basis, heat producers such as the Petrašiūnai CHP with operator status may use syngas to cover the capacity in the event of a sudden increase in heat demand, thus eliminating the use of traditional fossil fuels, that is, natural gas. From a technical perspective, biofuel, syngas, and waste heat could account for 100% of the total energy in the heat production balance. It should be emphasized that during the FLEXCHX activity period, the production of FT products is negligibly affected. On this basis, a sudden increase in heat demand or other significant fluctuations should not account for a large share of heat production. Conversely, if the heat production is essentially monotonic and remains significantly unchanged over the years, the use of syngas for heat production in boiler houses would not be appropriate, as it would have a significant impact on the production of FT products and would not be economically viable (no cost-effective). In the analyzed Petrašiūnai CHP, the sudden fluctuations in heat demand reached no more than 6% of the total demand, which led to insignificant changes in the level of economic attractiveness compared to that in scenario A. The results of the economic attractiveness assessment revealed that scenario A offers lower FT product prices compared to those in scenario B. Nevertheless, the use of syngas as an alternative for heat production has shown that the cost of the main product increases insignificantly, that is, only 1%–6% (0.01–0.06 €/kg) of the average value (Cases 1, 2, and 3). It was also found that the difference in FT product cost between scenarios A and B decreased as the nominal capacity of the unit increased. From a sustainable energy perspective, the goal of becoming energy-independent from fossil fuels has a high level of adaptability, and the prime cost differential is so small that the goal may be achieved. However, it must be emphasized that increasing the syngas amount for heat production can lead to a deterioration in economic performance; therefore, it is necessary to assess the extent of heat demand fluctuations. It was established that a gasifier of 40 MW may be the optimal choice in Case 2, when the average prime cost of the FT product under scenario B (0.68 €/kg) is insignificantly higher than that of scenario A (0.67 €/kg). The payback period is equal to 7 years, and the IRR is 0.12 (in scenario A it was 0.13). With the use of electrolysis (Case 3) in the optimistic scenario, the prime cost of the FT product could reach 0.83 €/kg. The payback period would be equal to 10 years and the IRR would be 0.06.

5. Conclusions

Based on the targeted hybrid process, the following conclusions are drawn from the **techno-economic analysis:**

1) In future energy markets, the role of fossil fuels will be minimized and the entire structure of DH systems would become more efficient through the use of waste streams. It can be argued that the hybrid FLEXCHX concept is suitable for Lithuanian DH systems because the by-products obtained after the technological processes are potential energy sources. It was established that if the FLEXCHX concept is installed in the Petrašiūnai CHP, the streams of waste heat under the study conditions would be between 21 and 182 TWh.
2) Considering that the Petrašiūnai CHP requires a very flexible operating mode owing to the need to balance heat production in the DH network of Kaunas City, a technical feasibility assessment was performed for determining the suitability of the FLEXCHX concept. The investigation revealed that the capacity range of the unit should cover the fluctuation range of thermal capacity by increasing the use of renewable energy sources such as syngas. It was determined that the integration of the FLEXCHX concept into the Petrašiūnai CHP requires a gasifier with capacity between 10 and 40 MW.
3) It was proved that the FLEXCHX concept with a unit capacity of only 40 MW can help create independence from fossil fuels with 100% not intermittent renewable energy. The use of syngas as an alternative for heat production according to scenario B has shown that the cost of the main product increases insignificantly, that is, only 1%–6% (0.01–0.06 €/kg). However, it is necessary to mention that in the analyzed Petrašiūnai CHP, the sudden fluctuation in heat demand was equivalent to no more than 6% of the total demand.
4) The economic evaluation showed that the concept is profitable when producing FT products at a prime cost of no more than 1.07 €/kg according to Case 1 and Case 2. However, various scenarios have shown that the prime cost of the FT product could be 0.67–1.47 €/kg for gasifier capacities ranging from 10 to 40 MW. The payback period was equal to 6–20 years. The project was not profitable if the payback period was equal to 20 years or more.
5) The study revealed that the integration of an electrolysis unit (Case 3) into the FLEXCHX concept as an additional component increases the prime cost of the FT product by 30%–60% when assessed under the current electricity market (in the pessimistic scenario) as it requires an approximately 24% higher investment and higher electricity costs. The prime cost of the FT product was found to be 1.07–1.25 €/kg. In this case, because the IRR was below 0, the concept could be considered not profitable. In addition, the payback period was more than 20 years.
6) The significant changes in the electricity market expected from 2030 onwards will lead to the use of surplus energy in a proportion of up to 30%. Thus, in the case that included an electrolysis device (Case 3 in the optimistic scenario), the prime cost of the FT product could become more competitive, approximately 30% lower, reaching 0.82 €/kg at a gasifier capacity of 40 MW. The payback period would be 10 years.
7) It was determined that the 40 MW gasifier is the most economically attractive option as it results in the lowest average prime cost of the FT product, 0.67 €/kg (Case 2). With this gasifier, the payback period is six years and the IRR is 0.13.

In overall, it was established that the hybrid FLEXCHX concept might be suitable for the Lithuanian market, but certain restrictions and exceptions apply until implementation. Nevertheless, it can be said that the FLEXCHX concept can help create independence from fossil fuels, allowing the use of syngas to ensure the reserve capacity to face a sudden increase in heat demand, whereas the analysis of economic attractiveness has shown that the price difference is not significant. Considering the obtained results, it can be concluded that the data on the FLEXCHX concept presented in this work could be applied to CHP plants in Lithuania. However, to apply this concept in other countries, it would be first necessary to examine the surrounding conditions, such as the existing national laws, existing directives, state support mechanisms, whether or not there is a difference in policy, the level of competition between heat producers, etc., as they may affect the economic attractiveness.

CRediT authorship contribution statement

R. Skvorčinskienė: Conceptualization, Data curation, Investigation, Formal analysis, Writing – original draft, preparation, Writing – review & editing. **N. Striūgas:** Investigation, Writing – review & editing, Data curation. **A. Galinis:** Investigation, Data curation, Software, Formal analysis, Validation. **V. Lekavičius:** Investigation, Data curation, Software, Formal analysis, Validation. **E. Kurkela:** Funding acquisition, Supervision, Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Validation, Writing – review & editing. **M. Kurkela:** Project administration, Data curation. **R. Lukoševičius:** Resources, Formal analysis, Investigation, Editing. **M. Radinas:** Resources, Formal analysis, Investigation, Editing. **A. Šermukšnienė:** Resources, Investigation, Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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