Influence of oil and gas fuels on the exploitation of boilers

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

Abstract

Nowadays, most of world's industries still depend on fossil fuels. Governments and non-governmental organizations are tackling the problem of emissions and global warming, successively promoting renewable energy sources and introducing new technologies as replacement for the old ones. Parts of the world are still operating using coal and oil in a significant percentage, as solutions like concentrated solar systems or biofuels technologies are lacking efficiency and are not profitable. Due to this, for many industry sectors worldwide, this is economically impossible to implement completely environmentally friendly units. Entrepreneurs in Poland that are required to come across European Union requirements, are implementing other solutions, which are change of the type of fossil fuel with a modernization of the exploiting units. First part of the Thesis presents current European energy situation and European Union energy policies, with focus on the Polish industry sector and challenges that are needed to overcome towards system's decarbonisation. Second part contains overview of current technologies and fuel types used in oil and gas sector, ready to be implemented in the Polish industry in a larger scale than renewables. The last, experimental part covers real case study of the boilers and fuel change's research for the powdered milk factory in Poland, in a form of performance, environmental and economic analyses, finished with development of energy strategies for Laktopol. The Thesis is presented in a form of case study, supported by the model creation and then simulations of the heat and power production processes, using IPSEpro and Excel software.

Index terms - energy efficiency, fossil fuels, case study, oil&gas, powdered milk factory

Resumo

Hoje em dia, a maioria das indústrias a nível Mundial, ainda depende de combustíveis fósseis. Governos e organizações não governamentais estão a enfrentar o problema das emissões de gases com efeito de estufa e do aquecimento global, promovendo com sucesso fontes de energia renováveis e introduzindo novas tecnologias para substituir as antigas. Muitas zonas do mundo ainda operam usando carvão e petróleo numa percentagem significativa, pois soluções tais como sistemas de energia solar concentrada ou tecnologias baseada em biocombustíveis carecem de eficiência e não são lucrativas. Por isso, para muitos setores da indústria em todo o mundo, é economicamente impossível implementar unidades integralmente amigas do ambiente. Os empresários polacos, que são obrigados a cumprir os requisitos da União Europeia, estão a implementar outras soluções, baseada na mudança do tipo de combustível fóssil utilizado, com a modernização das unidades em exploração. A primeira parte da tese apresenta a situação energética europeia atual e as políticas energéticas da União Europeia, com foco no setor da indústria Polaca e os desafios que são necessários superar para assegurar a descarbonização do sistema. A segunda parte contém uma visão geral das tecnologias atuais e dos tipos de combustível utilisados no setor de petróleo e gás e que estão em condições de serem implementados na indústria Polaca numa escala maior do que as energias renováveis. A última parte, experimental, cobre o estudo de um caso real onde se investigam as caldeiras utilizada e a possibilidade de substituição do combustível utilizado numa fábrica de leite em pó na Polónia, sob a forma de uma análise de desempenho, ambiental e economica, finalizando com a apresentação de possíveis estratégias energéticas para a Laktopol. A Tese é apresentada na forma de um caso de estudo, apoiada na criação de modelo e posteriormente em simulações dos processos de produção de calor e energia, utilizando IPSEpro e software Excel.

Palavras-Chave - eficiência energética, combustíveis fósseis, estudo de caso, óleo e gás, fábrica de leite em pó

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List of Acronyms

OECD	The Organisation for Economic Co-operation and Development Or
GDP	Gross Domestic Product
EU	European Union
LNG	Liquified Natural Gas
CNG	Compressed Natural Gas
CCUS	Carbon Capture Utilisation and Storage
H&C	Heat and Cooling
FED	Final Energy Demand
IEA	International Energy Agency
ECCP	European Climate Change Programme
EC	European Commission
EU ETS	European Union Emissions Trading System
GHG	Greenhouse Gases
BAT	Best Available Techniques
PV	Photovoltaics
REACH	Regulation, Evaluation, Authorisation and Restriction of Chemicals
ECHA	The European Chemicals Agency
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
API	American Petroleum Institute
NOX	Nitrogen Oxides
PGNiG	Polskie Górnictwo Naftowe i Gazownicze SA
PKN ORLEN	Polski Koncern Naftowy ORLEN
PN	Polish Norm
AFR	Air-Fuel Ratio
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
AR	Assessment Reports
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
FAME	Fatty Acid Methyl Esters

List of Software

SimTech	IPSEpro version 7.0
Microsoft Office	Excel Application, version 365

1. Introduction

Facing a vast development that is happening in the world, led by the non-OECD countries, the concerns about the problem of Global Warming and environment grows every year. The change towards green energy and Paris Agreement fulfilment is being the priority when it comes to new energy policies establishment in the countries that belong to the Organisation for Economic Co-operation and Development. To meet the requirements stated in *2050 long-term strategy* and reach net-zero carbon emission goal, each Member State of European Union developed the roadmap for economy decarbonisation. For Poland this goal is more difficult to fulfil due to the current reliability on fossil fuels, particularly on coal. In addition, industry in Poland is still operating on the old technologies, in the significant share from before year 2000, which is extremely energy-intense, as the remains from communist times. As the requirements introduced by European Union and then by Polish government, are the tough challenge to overcome by Polish industry sector, entrepreneurs seek support in the strategy development to minimise the costs connected with energy in line with the other connected costs, like EU Emission Trading System allowances' buyout. Polish energy system has a number of challenges to overcome to reach full decarbonization in next 30 years, and the major ones are: Polish landscape is not feasible for renewable energy sources implementation – e.g. relatively low number of sunny days or constantly changing wind velocity and direction; the economy would not stand the instant turnover and going fully renewable or that there is a huge social aspect, as the mining industry only employs nearly 200 000 people (directly), that would be left without a job.

The purpose of this Thesis was to show the realities of the current European energy system, with the focus on Polish industry sector, and develop the short-term and long-term strategies for the powdered-milk factory – Laktopol. The company operated on the relatively old heat and power production installation sourced with heavy oil. The manufacture of 200 tons of powdered milk per day from nearly 1,5 million litres of milk requires significant capacity of energy, particularly heat for the drying and evaporation processes in a number of 2 MW. The electricity is produced as a byproduct from the heat production with the capacity of 1,8 MW to run the Laktopol's offices and devices on the production lines. The company wants to investigate the possibility of changing the primary source of heating from heavy oil into light oil or natural gas, depending on their performance, environmental impact and economics of operation. The respective analyses were conducted with a support of heat and power production installation modelling in the IPSEpro software and conducting the calculations in MS Excel software, finally developing the recommendation for the company based on their current energy situation, in the light of the variety of regulations and laws targeted in the energy system.

In Chapters 2 and 3 the energy situations on the World's, European Union's and Polish levels are presented, with the focus on the industry segment, including the most important Regulations, Directives and Programmes that are developed and affect the country economy. The theoretical introduction for the fossil fuel options and heating systems abundantly used in the Polish industry is presented in the Chapters 4 and 5. Next the descriptions of the company itself and the installation that is already installed in the facility are shown in Chapter 6 with the characterization of the IPSEpro software and properties of devices and fuels that were introduced into the model. Chapters 7 and 8 shows the outcome of the simulation of different boiler – fuel combinations with the analysis outcome performed in MS Excel software in the aspects of performance (combustion process efficiency, fuel usage), environment (exhaust fumes, CO_2 and other pollutants production) and economics (fuel costs, investment costs of LNG regasification station, EU ETS). The Thesis is finished with strategies development presented in Chapter 9 and final conclusions in Chapter 10.

2. World, European Unions' and Polish energy situation

In the present times, a great focus is given to the global warming problem. Governments and non-governmental organizations across the world are introducing programs and regulations to limit greenhouse gasses and other emissions in each country and to promote using different sources of energy like renewables, rather than keeping with the old technologies in all the sectors – residential, industry, transportation, services and others. As we are facing rapid development in all sectors and more energy is needed to power this change. Most important factors that influence world energy demand are increasing living standards, increasing population and emerging economies development. The biggest contributors to this change are going to be countries that are not members of The Organisation for Economic Co-operation and Development (OECD). According to the U.S. Energy Information Administration's forecast world energy consumption will rise nearly 50% in the years 2018 – 2050 [1], and this change will be driven mostly by non-OECD countries, which are home for almost 2/3 of world's population (India, China, other Asia, Africa and Russia). In the mentioned regions of the world another indicator that influences the change is the significant economic growth – the average annual percent change in Gross Domestic Product is assumed to be around 4%, where in comparison in OECD countries GDP growth is only at 1,5% level. The better standards of living, connected with immense and still rising population, have consequences in much higher energy demand every year. To fulfil this energy consumption expectations, the non-OECD regions are predicted to use mostly liquid fuels. In 2050 world crude production increases to about 100 million barrels per day, from circa. 80 million barrels per day in 2018 [1]. The change is forced by non-OECD countries, as 45% increasement in liquid fuel consumption is expected, comparing to 4% loss in the OECD member countries [1].

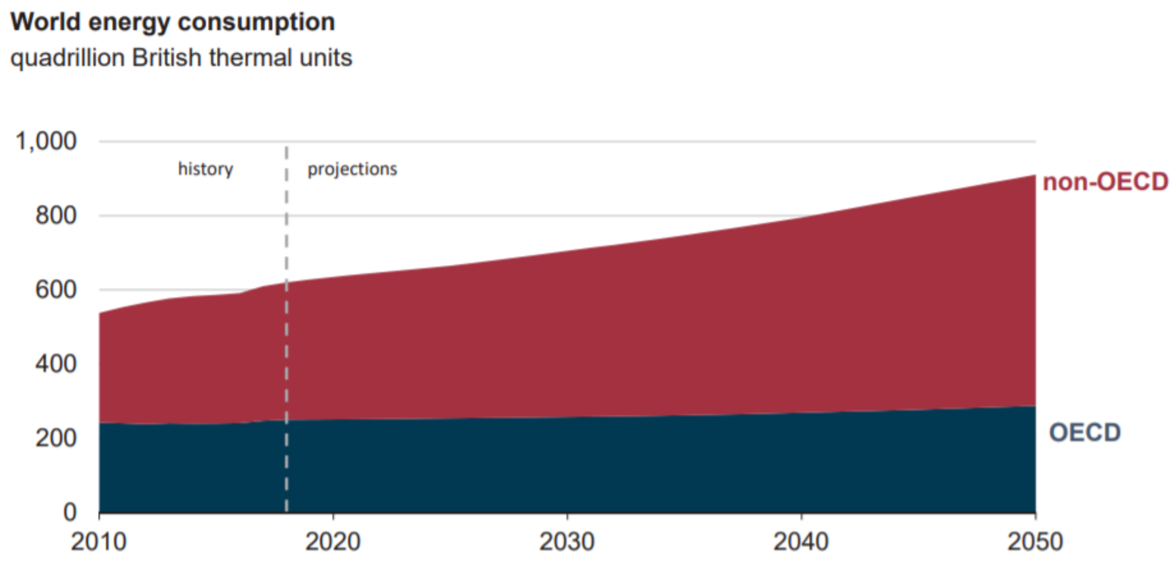


Figure 1. World energy consumption forecast [1]

As presented in the Fig. 1, non-OECD countries energy consumption rate is expected to rise by nearly 70%, where growth in OECD should remain at the level of 15% [1]. The slower growth rate is caused by relatively smaller increasement in population and economic growth, connected with improving energy efficiency and stagnating in energy-intensive industries, additionally powered by renewable energy sources. This immense expansion, mostly in the regions of China, India and Africa is going to cause a significant amount of CO_2 and other pollutants emission, as fossil fuels will remain their primary energy source. As it is presented in the Fig. 2, non-OECD countries have a significant growth tendency in the carbon dioxide emission between years 1971-2017, with a forecast to grow continuously, where member countries remain stable through the period.

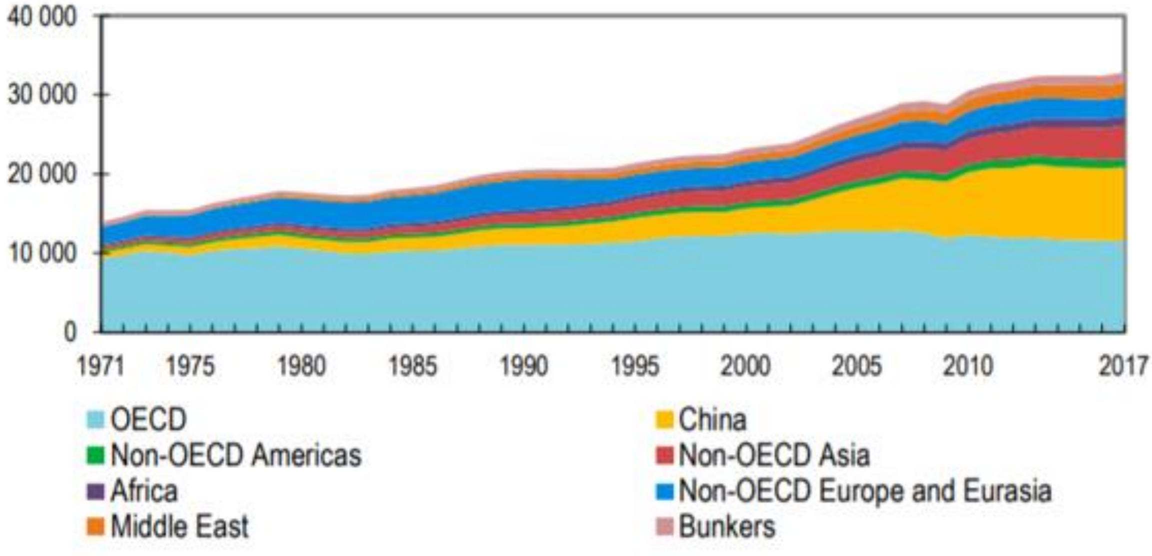


Figure 2. World CO_2 emissions from fuel combustion from 1971 to 2017 by region in Mt of CO_2 [2]

To face mentioned challenge and to visualize a danger, the International Energy Agency (IEA) elaborated a set of possible scenarios with a list of actions to be taken by the governments into energy transition [3]. These scenarios are:

- The Current Policies Scenario – the world continues the present path, without policy changes. Demand rises 1,3% every year till 2040, along with energy demand, where is no regulations when it comes to energy efficiency and transition. Emissions from energy sector are relentless, as well as destabilization of the energy security.
- The Stated Policies Scenario (formerly New Policies Scenario) – only already announced policies are going to be introduced in next years, without any flexibility to the possible changes in the future. Energy demand rises 1% every year till 2040 with photovoltaics leading to supply more than half of this growth, supported with expansions in natural gas and liquified natural gas (LNG) trade. Some countries undergo rapid transformations with limiting demands for coal and oil. It is expected that it only slows down the rise in emissions, but the world is far from completing shared sustainability goals.
- The Sustainable Development Scenario – it visualizes the path to fulfil sustainable energy goals in line with the Paris Agreement – keeping global temperature rise below 1,5°C, additionally outcoming with the universal energy access and cleaner air. This scenario requires vast changes within all energy system sectors with strong cuts in emissions possible by new, efficient and cost-effective technologies [3].

Achieving the goals (primarily to reduce greenhouse gasses emission which are energy-related) contained in the third scenario is mostly possible by accelerating low-carbon energy sources – a quick progress in using of Carbon

Capture, Utilization and Storage is expected between 2025 and 2030, reaching installed capacity of 130 GW (comparing with 0,2 GW in 2017 [4]). Oil which currently is the most used fossil fuel will be partially substituted with natural gas (buildings and transportation sectors) and biofuels (transportation and industry sectors). The most rapid growth is expected in the area of renewable energy sources, excluding bioenergy and hydropower generation. It is predicted to have 18% of total electricity production from solar and 12% from wind by 2030 [4].

2.1 Energy mix in Europe

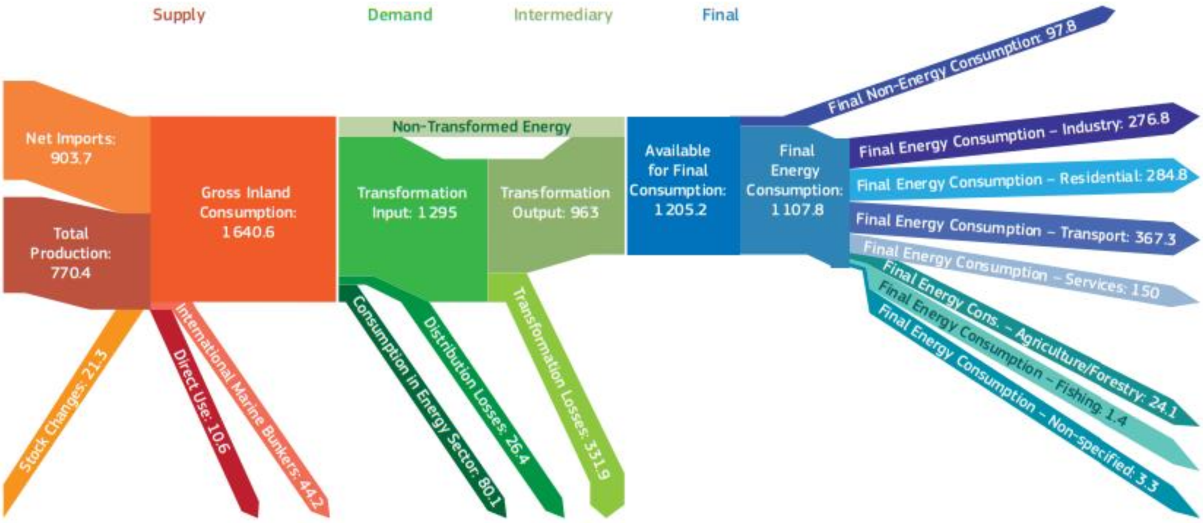


Figure 3. EU-28 Energy Flow in 2016, Mtoe [5]

When total worlds' energy production in 2016 was on the level 13 764 Mtoe which is more than 4 500 Mtoe more energy produced than in year 1995, Europe particularly, had a noticeable declining tendency when it comes to this indicator. Since mid-90' of 20th century the old continent had limited production of energy from 967 Mtoe to 759 Mtoe in 2016, which is only 5,5% of worlds total. When it comes to the gross energy consumption benchmark the change is not so significant. EU-28 countries were only achieved a 49 Mtoe of reduction, from 1 648 Mtoe in 1995 to 1599 Mtoe in 2016 [6]. European Union (27 countries from 2020) imports around 1 308 Mtoe of energy annually [7], where most of it are fossil fuels. Based on Eurostat data in 2018 from the total, not-transformed energy imported (1 350,484 Mtoe), 64% were oil and petroleum products, 24,4% was gas, 7,8% were solid fuels (coal), when only 3,8% was imported in a form of electricity and renewable energy [8]. The Sankey diagram Fig 3 shows European Union's energy flow with the losses during a transition till final energy consumption and division per sector. The biggest share in EU energy mix has transportation sector with 33%, followed by residential and industry sectors with around 25% of the total share each. Rest 17% is divided between services sector (150 Mtoe), agriculture and forestry sector (24,1 Mtoe), fishing sector (1,4 Mtoe) and non-specified (3,3 Mtoe).

The European Union's energy mix (2017, 28 countries) in the total energy available (gross inland consumption, around two thirds are consumed by end users) was mostly powered by petroleum products (fossil fuels, usually in a liquid state, include crude oil and all products that derive from it – motor gasoline, diesel and fuel oil, etc.) – 36,5% and natural gas – 23.1%. Solid fossil fuels (various types of coal and solid products derived from them) have 14,5% of the total share, followed by constantly increasing 13,6% share of Renewable energy (biogases, biofuels, renewable waste, hydropower, geothermal, wind, solar, tide-wave-ocean energies) and 12,2% of nuclear energy in a share, finished with the other sources that are determined as only 0,1% [9].

2.1.1 Dependence on the fossil fuels in the European Union – heat and electricity production

The European Union and the members countries itself had introduced various actions towards diminishing CO_2 and greenhouse gases emission with promotion of using renewable energy sources (within all sectors) and increasing energy efficiency. In 2016, 28 member countries produced 210,7 Mtoe of energy from renewable energy sources, which states for 27,4 % in a total production share that year [5]. Despite of the fact that every year the share of renewable energy production increases European Union still is mostly dependent on the production of electricity and heat from fossil fuels. As it was mentioned in the previous subsection, even when member states have significant amount of energy produced from renewables (circa. 30%), that in the total energy consumption benchmark it is not so stately. Every year Europe imports around 1 308 Mtoe of energy, from which more than 95% in a form of fossil fuels. Most of it is imported for usage by the transport sector, and the rest of the sectors still at least partially relies on oil, coal and other non-renewables consumption, lowering the share of total energy consumed from renewable energy sources to around 13% in comparison of how much is producing [6].

The 44% of the electricity consumed in the European Union comes from the powers stations that burn fossil fuels. We can observe disproportions across EU member states, which is caused by personalized access to the natural resources like oil and coal, variety of economic and social situation or simply geological position. Despite of it, the big moves in front of renewable energy production are shown, as 31% of this share comes from renewables in the whole European Union [9].

Heating and cooling sector in Europe have a huge potential for improving its energy efficiency with an integration with renewable energy sources. In the H&C are included: space heating, process heating, hot water, space cooling, process cooling and other heating. The highest final energy demand for heating and cooling belongs to the residential sector – 2,845 TWh, which is followed by industry sector – 2,388 TWh and the rest of the sectors combined – 1,119 TWh. H&C in European Union is very important, as it stands for around 50% of total energy demand across the members countries (which was 6350 TWh in 2015), especially a space heating which is 53% of end-use final energy demand (FED) for heating and cooling and it is followed by 32% in process heating [10].

The proportion of energy carriers used for the heating and cooling varies across the European Union's member countries (EU-28). For example, Netherlands' and United Kingdom's this sector is mostly powered by gas boilers, where in others is supplied by electricity (in Cyprus and Malta), or by coal boilers (Poland, Slovakia, Czech Republic). As presented in a Figure 4, the biggest share in heating and cooling still belongs to fossil fuels (>65%), additionally district heating and electricity accounts for ~ 20%, where their production is also based mostly on fossil fuels. Renewable energy share is on a level of around 15%, where majority of it is produced by biomass; heat pumps, geothermal and solar thermal heat productions are still marginal in most of the EU-28 countries.

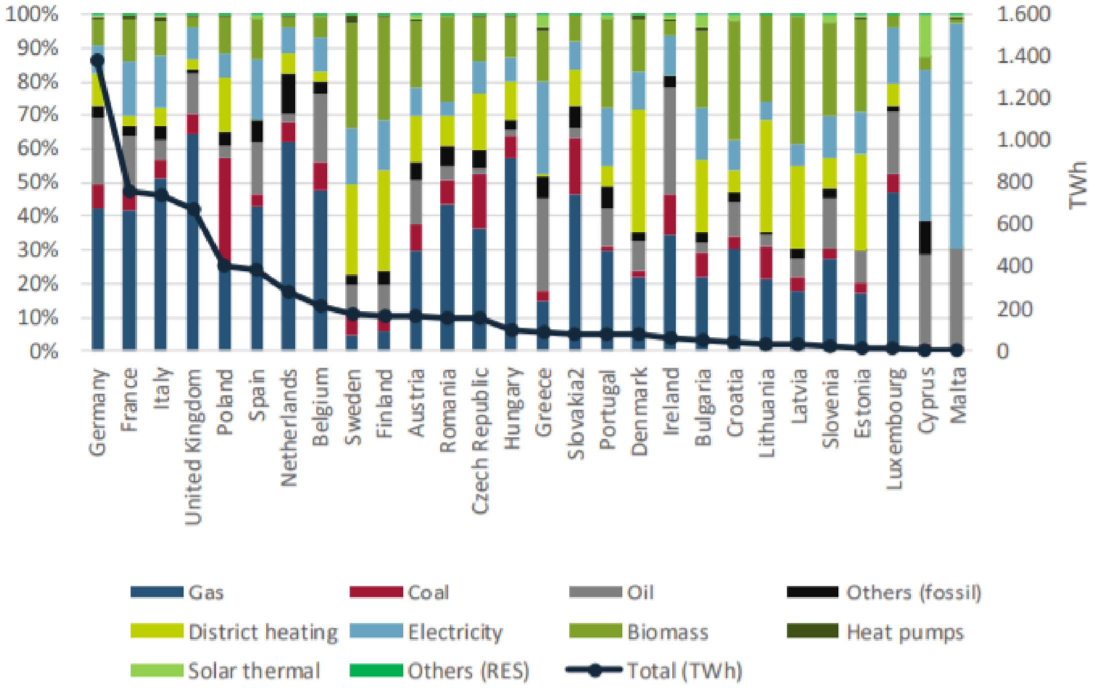


Figure 4. Share of energy carrier for the final energy demand for heating and cooling by country, for all sectors in 28 European Union countries in 2015 [11]

Despite of growing share in renewable energy sourced in total energy consumption for European Union member countries, electricity and heat production still relies and will be relying mostly on using fossil fuels to generate them. To reduce total energy consumption the biggest actions are targeting residential sector, as it is the most receptive sector for the change across the whole Europe, which is also connected with cutting the one of the biggest shares in emission of CO_2 and greenhouse gases in the private households. The methods are: introduction of new district heating systems and modernizing an old one, in most of the countries promotion and co-financing using renewable energy sources like photovoltaic panels, solar thermal energy or heat pumps by individuals.

2.1.2 Industry sector in Europe

The innovations within all sectors are driving Europe towards better energy efficiency, including industry sector which is responsible for a quarter of the total energy consumption in the European Union. This sector specifically faced overall decline in the mentioned benchmark by 14,1% in years 2007 – 2017, where another three biggest sectors either had small reduction (transport by 2,9%), or even a rise (households' energy usage raised by 0,2% and services by 9,3%). Such significant improvement within industries was possible by a shift toward service-based economy and implementing less energy-intensive methods in manufacturing. Other indicators which are influencing the change are application of more energy-efficient solutions and closure of the units that are inefficient, in the matter of both – energy consumption and economics [12]. The industry sector is leaning more towards improving its operational efficiency, by introducing new technologies and changing fuel sources, instead of going fully renewable. As it was mentioned in the subsection 1.1.1, industry sector's energy mix contains only about 15% of renewable's share and almost all of it is based on the biomass combustion which additionally is used largely in inefficient boilers and stoves [11]. In this matter, sources like photovoltaics and solar thermal energy and heat pumps are not sufficient enough, due to its high price of the implementation and low-efficiency when it comes to this manufacturing sector.

Similarly, to the total energy consumption benchmark, greenhouse emission production fell down mostly within the industry (~35%, which stands for decrease of around 476 million of tones of CO_2 alone [13]) and energy supply sector, where emissions produced by residentials, faced positive trend in years 1990 to 2017. The change was mostly possible not by using renewable energy sources, but by new technologies introduction, which led to the energy efficiency improvement – less fuel is used and by the change of the burning fuel type – for example change from the oil-based fuel to the gaseous one, which is more environmentally friendly, as it produces less emissions.

2.2 Energy mix in Poland

Poland in comparison with other European Union's member countries has relatively small gross inland energy consumption per capita, when EU's (EU-28) average is 137,1 GJ per capita in 2017, in Poland it was 115,9 GJ [14]. From 2007 to 2017 it is estimated that mentioned indicator had been rising on the annual average 1,4%, due to dynamic increasement in the energy consumption connected with the vast economic growth in recent years. In Poland the structure of the final energy consumption per carrier is mostly determined by the natural resources that occurs in the country. Even that the primary Polish resources are hard coal and lignite, they are classified on the third place in the presented structure, which noticed a decrease in its usage from 19% in 2007 to 16% in 2017. The third position is caused by the presence of heat and electricity in the structure, which are primarily produced from coal and lignite. The most important carriers in 2017 were liquid fuels, and their share was on the level of 36% in the total structure (increase of 3% comparing with 2007), followed by electricity – 17% (16% in 2007), natural gas – 13% (15% in 2007), heat – 9% (10% in 2007) and others 9% (7% in 2007) – mostly renewable energy sources [15].

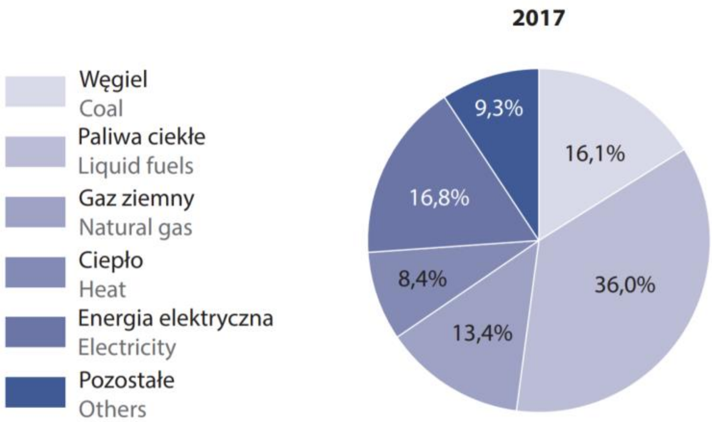


Figure 5. Structure of final energy consumption by carrier in 2017 in Poland [15]

Energy structure in Poland in latest years has been undergoing serious changes to maximize its energy efficiency and limit produced emissions, as the country mostly operates on "dirty" energy sources and its geolocation is not in favour to implement renewable energy sources that are economically and energy efficient (e.g. not sufficient river's slopes to introduce efficient hydro power plans or not significant amount of sunny days to invest in the photovoltaic or solar thermal energy systems). The Polish energy mix changed since 2007 mostly within transportation sector which rose 6,49% to 2017 (31,5%). Share of the rest of the sectors was either stable or declined, when comparing years 2007 and 2017: Industry sector -2,21% to 22,8% in 2017, Households -3,69% to 28,54% and Agriculture and Services sectors were stable with around 6% and 12% shares respectively [15].

Figure 6. The structure of the final energy consumption by sector in Poland in 2007 and 2017 [15]

Power plants and combined heat and power plants that operate in Poland, are using fossil fuels as the primary resource – in majority coal, lignite and natural gas. In 2018 electricity produced in mentioned facilities was at the level of 140 TWh and it stated for 82,3% of the total electricity production (rest belongs to the independent facilities and to the ones with the industrial purposes) – primary resources used in its generation were coal, which share was 47,8%, followed by lignite with a share of 29,0% in 2018. Since 2010 the share of renewable energy sources in the total electricity production had rose by 5,8%, to 12,7% in 2018 – the most important resource was wind energy with biomass and biogas, with photovoltaics having the smallest share, but it had been noticed that is the fastest growing section. Even with the relatively small impact of the renewables on the Polish electricity generation, and with the more than three quarters still produced from fossil fuels, since last decade the vast increasement in the energy efficiency had been observed within the sector, with an increase of 56,3% in 2018 [16]. According to statista.com [17] in 2019 the electricity production in Poland decreased by around 10 TWh from 2018, containing important aspect – lowering the share of fossil fuels in electric power generation in favour of continuously rising share of renewable energy sources in the structure, with the wind energy growing the most.

Similarly, to electric power production, heat production in Poland mostly runs on fossil fuels. In 2018 Polish plants produced 294,4 PJ of heat in total, which was 2,4% less than in a previous year and around 15% less than in 2010. Unfortunately, this change is also driven by the less intense winters caused by Global Warming effect. The biggest share in the mentioned benchmark belongs to public power plants, heat only boilers and public heat plants, where rest (auto-producing power plants, non-public heat plants) produced only 21,3 PJ in total in 2018. Its energy efficiency obtained in the production of commercial heat varies across the years 2010-2018 between around 75% to 82% [16]. Renewable share in the heat production is relatively small, and majority of the heat produced is by using biomass as the primary resource.

In addition, according to Eurostat data, Poland is dependable for the import of the crude oil almost in 100% and of the natural gas in around 80%, the same time being an exporter of the solid fuels, which is below 0% (it has been varying in between around -20% to 0% during the last decade). It gives the overall energy imports dependency on the level of around 40%, which is rising due to the closures of the old energy blocks which were run mostly on coal, switching the fuel source from coals to others like natural gas, and smaller coal extraction, which is main export product. In comparison European Union's average import dependency presents like this: solid fuels ~ 45%, natural gas ~ 75% and crude oil ~ 85%, which gives in total ~ 55% EU-28 dependency on the energy import [7].

2.2.1 Industry sector in Poland

Poland is mostly dominated by the small industries that employ less than 50 employees - 74% from all Polish manufacturing companies, where medium sized companies stand for around 20% and large sized enterprises for only 6%, having most of the production in the largest, Masovian Voivodeship. Polish industry consumes mostly natural gas (around 26% of total energy consumption in 2015), followed by electricity and hard coal (19% and 11% respectively). Poland is operating mostly in energy-consuming branches of the industry like manufacturing of coke (more than two thirds of the European Union total added value), petroleum products, chemicals and non-metallic mineral products. Similarly, to EU structure, industry is the third biggest sector in the energy consumption – after transport's and households' sector [18].

Although the share of the industry in a total energy consumption mix decreased to 23%, its energy consumption rose from 13 Mtoe in 2009 to 15,8 Mtoe in 2017 due to economic growth in every sector. Manufacturing sector since years have been undergoing radical changes by introduction of new technologies and constant investments towards better energy efficiency supported by changing the primary source of the used fuel. The biggest decrease (years 2007-2017) was in the liquid fuels' usage, which diminished by 50,2%, followed by fall in the heat and coal usage by 33,2% and 13,3% respectively. On the other hand, consumption of different types of carriages faced the increasement, the electricity consumption for industrial purposes by 20,3%, gas consumption by 3,2% and the other carriages by 141,9%.

The structure of Polish industry sector was largely stable within last years, having only few meaningful changes in the branches of: wood (from 4,4% in 2007 to 6,9% in 2017), paper (from 8,2% to 11,6%), chemical (from 20% to 17,7%) and primary metals (from 19,9% to 16,2%) in a total industrial energy consumption structure.

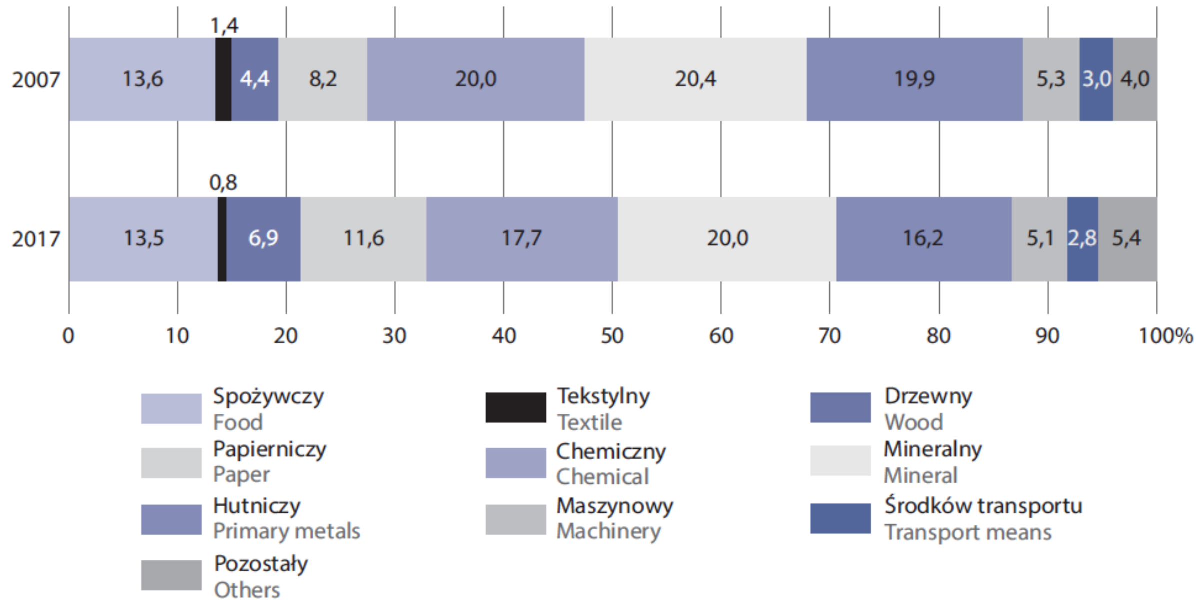


Figure 7. Structure of final energy consumption in manufacturing by branch in 2007 and 2017 [15]

The three branches are dominating in the Polish market when it comes to the energy usage – primary metals, chemical and mineral. Their combined energy consumption in 2017 represented 54% of the total usage for the industry sector. Additionally, food and paper industries crossed the line of 10% share each, in the energy consumption for the industry structure. Only production of steel, concrete and paper was responsible of the 34% energy usage in 2017. Due to investments in the energy efficiency and new regulations introduction in the recent few years, all branches of the industry noticed a positive change in their energy intensity rate, which, on average decrease by 2,2% annually. The biggest changes were directed to the primary metals branch, as the most energy intensity one. Since 2007 till 2017 it faced the change from 1,6 kgoe/EUR to 1,1 kgoe/EUR [15], having significant improvement at the level of around 40%.

3. Polish industry situation to the European Union regulations

To reach the goals stated in the Sustainable Development Scenario prepared by International Energy Agency real, governments and organizations across the globe are cooperating and taking actions individually to limit bad influence of the industry sector and others and face the danger of continuous global warming effect and stay below 2°C of the raised Earth's average temperature. The European Union is one of the organizations, counted with 27 member states countries (28 members till 2020) that have been tackling the problem by introducing restrictions and co-financing various actions in partnership countries with an introduction of the continent-sized plans that each country agrees to fulfil. The aim is to limit emission produced in Europe with improving overall energy efficiency with significantly bigger share of the renewable energy sources in each country's energy mix to fulfil statements of the Paris Agreement. During every energy production and consumption, the environmental impact exists, that is why both energy and climate/environmental policies are linked together, and during the introduction of the new laws, regulations or actions for one site, it immediately affects the other. One of the first such actions was the European Climate Change Programme [19] (ECCP) established by the European Commission in 2000, to ensure that the European Union would reach the goals stated under the Kyoto Protocol. Programme was created to analyse and to find the most cost-effective and most environmentally friendly policies to be taken in Europe (on both – EU and each country level) to limit emissions of greenhouse gases and other pollutants and improve energy efficiency. Later it dovetailed with another Programmes and Strategies that were developed within time like EU's Sixth Environmental Action Programme, which operated in years 2002 – 2012 or Sustainable Development Strategy. Both, the First and the Second ECCP explored various options to optimize in various areas like transportation (aviation, marines, road transportation), agriculture, energy supply and demand, emission trading or industry. Actually, the main goals are set to both 2020 and followed by goals to reach by 2030 regarding 3 main areas: improving energy efficiency, increasing share of renewable energy sources and to cut the emission production across the European Union Member States.

3.1 European Union regulations

Since the beginning of the European Union, institution had introduced various regulations, directives and laws that each Member State country need to respect individually (each ordinance may be personalized for each country in respect of its capabilities and its means to reach established goal, based on their primary and final energy consumption, energy savings and energy intensity). The main directives, regulations and programmes in the area of energy, climate and environment are:

- *2020 climate & energy package* – as a set of legislations (set by EU leaders in 2007 and legislated in 2009) that are linked together to make sure that the European Union meets targets for 2020 in the areas of energy and climate, having 3 key goals: 20% decrease in greenhouse gases emission, comparing with a state from 1990; share of 20% total energy from renewable energy sources and improvement of 20% in overall energy efficiency [20]. The main aspects of the package are:
    - Energy Efficiency Directive 2012/27/EU [21] set the target to improve European's energy efficiency by 20% until 2020, that time comparing with the projected energy usage for 2020. As the change must be economically feasible, the European Union's measurements focused on the, for example buildings and residential sector, where both savings and possibilities were the greatest. Behind Energy Efficiency Directive there is a number of others tackling different sectors of widely understanding energy sector, examples are Energy Performance of Buildings Directive 2010/31/EU [22], amended later by Directive 2018/844/EU [23] setting next step for the sector as a part of Clean energy for all Europeans Package [24] or Ecodesign Directive 2009/125/EC [25].
    - 20% of the share of renewable energy sources in the energy consumption structure by 2020, on the power of the Renewable Energy Directive 2009/28/EC [26]. The target to reach is independent for every European Union's country due to different economic position and their starting points in a share of renewable energy sources in the country's energy structure – as the example with the end of 2020 share of renewables in Malta should be at the level of at least 10%, when in Sweden the borderline is set at the level of 49%. Effect of the introduced actions should benefit with at least 20% of renewable in the whole EU structure and 10% share of renewables in the sector of transportation [20].
    - To cut the greenhouse gas emissions by 20% by 2020 in EU a bunch of restrictions and tolls were introduced. The key toll for cutting emissions of the greenhouse gases was the European Union Emissions trading system, which covers ~ 45% European Union's total emissions, as well as targeting the danger using The Effort Sharing legislation [27] (part of 2020 climate & energy package), which targets remaining ~ 55% of emission. Based on the country's national wealth the target to cut the emission is different – it varies from 20% cut in the richest countries to staying below 20% increasement in the least wealthy countries [20].
- *2030 climate & energy framework* [28] is basically what *2020 climate & energy package* is, with the more ambitious plans and it was adopted in 2014, then revised in 2018. The Framework targets key changes for the period of 2021 – 2030:
    - Minimal improvement of 32,5% in energy efficiency
    - Minimum 40% cut in the emissions of greenhouse gases (comparing with the level from 1990)
    - Share of the renewable energy o the level of minimum 32%
- *2050 long-term strategy* [29] - a step further from the *2030 climate & energy framework*, where the European Union is aiming to be climate-neutral by year 2050, extending plans adopted for both, *2020 package* and *2030 framework.* This strategy is targeting all economic and society sectors to fulfil the statements of the Paris Agreement and the European Green Deal. The main statement is to create an economy-wide the net-zero greenhouse gas emissions. Every EU country is obligated to establish national

long-term strategies, in them it is stated what actions are to be made to fulfil their Paris Agreement's commitments with European Union's requirements and objectives. The vision of the EU in cutting greenhouse gas emissions is based on the improvement in the seven strategic blocks: energy efficiency; deployment of renewables; clean, safe and connected mobility; competitive industry and circular economies; infrastructure and interconnections; bioeconomy and natural carbon sinks; tackling the remaining emissions with a carbon capture, utilization and storage [30]. To enhance the progress to be made, in March 2020 the European Commission proposed the first European Climate Law aiming to ensure that every European Union's current and future policies will contribute to completing the goal stated in the European Green Deal mainly by decreasing the emissions level, by the investments into new green technologies and environmental protection. The main statements present in Proposal are: setting the long-term direction of work travels – meeting especially, monitoring the current situation and the progress made and new strategies adaptation to strengthen Member State's resilience.

- The European Union emissions trading system (EU ETS) was established to fight against the climate change as a one of the key tools in the cost-effective reduction of greenhouse gas emissions. It was set to life in 2005 as the first carbon market and it still remains as the biggest one. EU ETS operates also in Iceland, Norway, and Lichtenstein, apart from EU; the obligatory participants are more than 11 000 power stations, industrial plants and airlines that operates in mentioned countries, being categorized as heavy energy-using installations [31]. The system proved working successfully cutting the emissions from variety of installations, by putting a price on them, operating on a 'cap and trade' system. Installations in a system are up to produce an only certain maximum amount of emissions, limited by a "cap", which is being reduced annually to decrease a total emission production across Europe. The system not only limits the GHG emission, but also promotes investments into clean technologies and puts forward into energy transition. The EU ETS market works on a principle of buying and selling emission allowances, which indicates how much pollution the company can emit each year, and in case of crossing that limit, heavy fines are enforced. Overall goals for this system are to cut emissions from the installations by 21% (comparing with 2005) by 2020 and later by 43% by 2030 [32]. It covers carbon dioxide, nitrous oxide and perfluorocarbons production from various branches of the industry.
- In addition to EU ETS system, The Effort Sharing [33] legislation was introduced. When the European Trading System bands together installations responsible for circa 45% of total emissions, the legislation concerns the remaining ~ 55%, produced from transport, agriculture and buildings sectors with a waste segment. Comparing with 2005 emissions level, The Effort Sharing targets to limit them by 10% by 2020, followed by 30% by 2030 from mentioned sectors. It covers six different types of greenhouse gases stated in Kyoto Protocol: carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O, hydrofluorocarbons HFCs, perfluorocarbons PFCs, sulphur hexafluoride SF_6 and nitrogen trifluoride NF_3 [33].
- Linked with Energy Efficiency Directive 2012/27/EU [22] is Energy Performance of Buildings Directive 2010/31/EU to increase buildings' energy performance and towards decarbonization, being an essential sector, not only to increase citizens' living standards, but also being the most cooperative sector to introduce wide spread solutions towards boosting energy efficiency and renewable energy sources usage by both – services and residential dwellings. New goals for the both Directives were later stated as a part of Clean energy for all Europeans package [24], especially for the second one amended by Directive

2018/844/EU [23] stated new regulations regarding buildings' modernization and renovations with introduction of new available technologies. Both, original and amended Directives include policies that Member States are obligated to introduce towards: renovation strategies setting the milestones for each decade by 2050 – it aims mostly in decarbonization; new constructions being nearly zero-energy buildings from the end of 2020 or introduction of obligatory energy performance certificates; all mentioned is supported with constant introduction of new technologies available on the market. It is essential to target buildings sector, as being responsible for ~ 40% of total European Union's energy consumption with ~ 36% of the total CO_2 production [34]. In EU almost three quarters of existing buildings is energy inefficient and relatively old (around 35% of them is more than 50 years old).

- Excise Duties on Energy are the rules that cover energy products that are used for electricity and heat production and transport. Two main directives are: Energy Tax Directive 2003/96/EC [35] that covers taxation rules for the electricity and energy products; and Council Directive 95/60/EC [36] which covers fiscal marking of gas oils and kerosene. Both legislations established the minimum rate of excise duty for the Member States.
- Industry sector is one of the most impactful ones when it comes to the environment, as it not only affects the air, but also water and soil, and generates significant number of wastes. In addition to the previously mentioned directives, regulations and programmes there are ones that regulate industry sector more directly, rather than targeting overall of the energy sector. The main legislations are [37]:
    - Directive 2010/75/EU [38] on industrial emissions – the core rules and principles to control large-scale industrial installations, with usage of the BAT (Best Available Techniques) applications to reach the level of possible maximizing the environmental protection with maximum available cost and energy efficiency.
    - Directive (EU) 2015/2193 [39] on medium combustion plants – it gives regulation on the pollutant emissions like: nitrogen oxides (NOx), sulphur dioxide (SO_2) or dust, produced in a combustion process in medium-sized plants 1 – 50 MW thermal.
    - Directive 1994/63/EC [40] and Directive 2009/126/EC [41] on petrol storage and distribution – both directives regulate measurements performed on the petrol distribution and storage to limit volatile organic compounds emission to the air.
    - Regulation 166/2006 [42] on the European Pollutant Release and Transfer Register – around 30 000 companies in European Union are obligated to give detailed information on the pollutants and waste off-site transfers and on the emissions for the free public address.
    - Energy Efficiency Directive 2012/27/EU [21] - is a main legislate that is tackling not only industry sector, but all of them. In this context of the industry, it amends the Directive 2004/8/EC [43] about cogeneration to lower greenhouse emission and boost energy efficiency by combining power plants where electricity is producing with a heat production, by this overall efficiency can reach approximately 90%, by using waste heat from electricity generation. Promoting cogeneration is able to decrease level of the greenhouse gas emissions even by 250 million tonnes till the end of 2020 [44].

3.2 Actions in Poland toward fulfilling the regulations

Poland, and likewise all other 26 Member States (formerly 27, before 2020) is obligated to fulfil the requirements stated in the *2020 energy & climate package*, which will be continued by *2030 climate & energy framework* with the more ambitious goals. In the package is stated that Poland due to its previous economic, social and energy situation is obligated to have 15% (EU target is 20%) share of renewable energy sources in a total energy structure by 2020. Nevertheless, relatively small share of renewables in comparison with other European Union's Member States to fulfil till the end of year 2020, Poland is obligated to develop long-term strategy (for the 2050) by the end of 2020, that supposed to be integrated with the national energy and climate plans, which were developed for the years 2021 – 2030. Two pressures that are present on the Polish market are now making this relatively rapid change over the next decades possible – first one is the significant drop in the costs for the renewable energy sources and second one is constantly increasing prices for the CO_2 emissions. The government have not yet introduced its *2050 strategy* (as of 05 March 2020 [45]). The WiseEuropa (Warsaw Institute for Economic and European Studies) had prepared two possible scenarios for Poland in the spectrum of the Europe's climate neutrality by 2050 and the Paris Agreement statements fulfilment [46]. Based on the created MEEP model (specially created by WiseEuropa), both pathways need gradual and deep transformation, with technological diversification containing a dominant role of the renewable energy sources and a share in nuclear power (which is currently absent in Poland) and new technologies implementations as e.g., Carbon Capture and Storage et al. In the first one Poland set its goal to cut the emissions by 80% by structural changes in the Polish energy system and its national economy. The second one country bases on the vast fuel and energy sectors' restructuration, diminishing the gap between the Poland and the other Member States in 15 years.

3.2.1 Change towards renewable energy sources

Poland is a country where it is relatively hard to replenish a significant amount of renewable energy sources, as the current overwhelming majority in its total energy consumption or production structure belongs to the fossil fuels. One of the main aspects working versus renewables is the political situation before 1990, when country's industry sector was dominated by heavy industry. Manufacturing was performed using obsolete technologies, which were not only energy inefficient but also emitted enormous amount of greenhouse gases and other pollutants. Polish geolocation is also not in favour for implementation of the cleanest technologies. Nevertheless, even with all the mentioned obstacles, Poland was obligated to fulfil 15% of the renewable share by 2020, 21-23% by 2030 and more in the distant future.

- The main Polish renewable energy source are biofuels, having around 70% of share in the total energy production from renewable energy sources. Despite being the most used carrier from the group of renewables, and even considering that the energy produced from them through years is stable, its share in total energy production from renewables is decreasing. This is caused by the total energy consumption increase and covering the created gap by other new investments, especially in the wind energy technologies. Biofuels are the easiest kind of renewable carriers to implement, especially due to its relative abundancy comparing with others and being able to use in the already existing infrastructure, installations and machines without major modifications – especially when it comes to the industry sector.
- Poland has relatively flat surface and it is almost impossible to build a significant number of big hydropower plants, mostly due to relatively low inclination of the Polish rivers. It is also connected with

the high investment cost and relatively low amount of energy generated from such power plants when considering Poland's terrain. Currently Polish government and individual investors plan only invest into small and medium hydro power plants, which their installed power is maximum 1 MW and 1 – 10 MW respectively.

- Photovoltaics and solar thermal energies are currently being much more accessible across all sectors, due to continuously lowering prices of the installations. Few years ago, PV or solar thermal installations were not economically feasible due to high prices, combined with relatively low number of solar days across the country. Residential and services sectors are the most targeted by both, Poland and European Union, as the most sensitive for a change towards renewable energy sources, especially, by promoting photovoltaics. The PV panels are now much more accessible because of the EU's and government's financial support for the individual investors, as the home installation for the private usage or to power service sector like office areas or even churches. Solar thermal and photovoltaic energies possess relatively low energy efficiency, which connects with a significant area that they need to cover to create meaningful amount of energy
- In addition to co-financing solar energy installations, European Union and Polish government are supporting the topics of thermo-modernization (mostly insulation of the building) and heat pumps investments for the individuals for residential purposes. By using such methods, it leads to making the building considered as the zero-energy or passive building and ensuring that self-production of energy from renewables will be enough for the detachment's energy demand. Yet heat pumps usage cover mostly only residential sector having even less than 1% in the total primary energy production from renewables structure in 2018. Technology is considered as a best installation, that makes the building self-sufficient as zero-energy or passive, creating a surplus of energy.
- Through last decades wind energy was also considered, as a not so good option due to the very high investment cost, huge land area to be taken, relatively low energy efficiency with problem of energy storage and distribution, lack of social approval and high law regulation barrier. Currently, across Europe the significant investments are being proceeded, especially in the topic of offshore wind energies, also in Poland at the Baltic Sea shoreside areas. The share of the wind energy in the electricity and heat production increased rapidly through last decade – only in the electricity production the share increased by 66,7% in years 2014 – 2018 [47].
- Geothermal energy, as in most of the other countries, still remains marginal source of energy generation, due to low efficiency and weak economic feasibility. In years 2014 – 2018 energy consumption from geothermal sources increased by 17,0 %, which is remarkable, nevertheless comparing it with total energy consumption it is really small percentage.

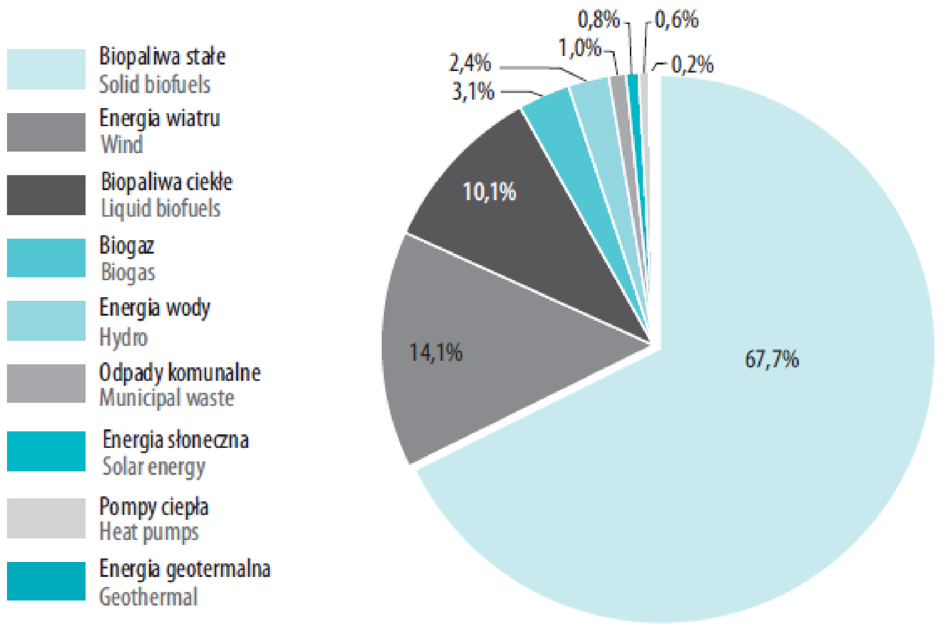


Figure 8. Structure of primary energy production from renewable energy sources in 2017 in Poland [48]

3.2.2 Continuity of operations based on fossil fuels

As it was mentioned before, Poland is operating in drastically majority on fossil fuels – mostly coal and lignite. More and more concentrated restrictions introduced by European Union are forcing Polish government and entrepreneurs to take actions towards cleaner future. The main problem is connected with the European Union's emission trading system and its diminishing amount of emission's production allowance. Polish industry in a relatively immense percentage is operating on the old technologies powered by fossil fuels. In many situations cutting of emission of greenhouse gases and pollutants is equal to shutting down the company as it is economically impossible to completely switch from fossil to renewable energy sources. In addition, using less clean technologies allow to uphold continuity of work in the whole spectrum of the industry, where on the other hand renewables are not so reliable, mostly because of the energy storage problems. Many factories are using clean technologies to support current ones, to lower pollutants production, but to still being able to operate basing on previous methodology and currently implemented installation. Other commonly used method is a simple change of the used fuel for cleaner one – for example from heavy oil fuel to natural gas – this allows to limit emissions and keep operating using existing infrastructure, with relatively small modernizations. This solution lets on savings and drastically lowers initial investments cost, when comparing to switch to renewable energy sources. The bottleneck of this solution is the cost of alternative source of energy, when comparing to the new one. Nevertheless, many entrepreneurs add some percentage of clean solutions to their energy structure, but more as a form of additional electricity or heat source to the current ones, rather than completely relying on them, when it comes to the industrial production processes, which usually are high energy intense. Even when it is connected with significantly higher cost of used fuel, it is still much better economical option to implement in the Polish industry sector to keep on working on the current technologies rather than going fully renewable and environmentally friendly.

4. Description of the main properties of the fossil fuels

One of the reasons in favour of the global trend of renewable energy investments is that fossil fuels are not unlimited, contrary to the energy from the sun or wind (skipping the fact of the life cycle of the renewable installation - e.g., photovoltaic panel ~ 25 years of the efficient lifetime – and mankind possess limited resources from which installations are made from e.g. Silicon). It is estimated that with the current energy consumption from oil, gas and coal, fossil fuels will deplete in next 50 years (natural gas and oil) to around 100 years (coal). Even that the number of each carrier is significant, their stocks are diminishing relatively rapidly – having hundreds of billions of tons of coal distributed across the world is expressing, but even a medium sized coal power plant is burning a few millions of tons of coal annually. The process of fossil fuels creation from organic matter takes dozens or even hundreds of millions of years, by the sedimentation processes under no air presence and high pressure under the surface level, that is why there is no possible chance to recreate them when the deposits will be depleted. The sufficiency of world's natural resources is strongly rounded up, due to number of investments in renewables and continuity of new technologies introduction, which is decreasing energy consumption level produced from fossil fuels.

Table 1. Advantages and disadvantages for the primary energy carriers' conversion into final energy form [49]

Energy carrier	Advantages	Disadvantages
Hard coal	Abundance, national security, easy in transport and storage, rich deposits, relatively cheap	Causing CO_2 and pollutants emission, with lignite are the least clean energy carriers
Brown coal and lignite	Abundance, relatively cheap	Causing CO_2 and pollutants emission, difficult to transport and store, with coal are the least clean fuels
Oil	Relatively cheap, almost no substitutes in the transportation sector usage, convenient in usage	Causing CO_2 and pollutants emission, strong market price fluctuations, sensitive for the political situation, deposits are concentrated in the certain parts of the world
Gas	Convenient to use across all sectors, efficient	Causing CO_2 and pollutants emission, expensive and dangerous in transportation and storage, market price fluctuations, deposits are concentrated in the certain parts of the world, special infrastructure is required to operate

In 2006 The European Parliament and the Council had introduced unified Regulation concerning the Regulation, Evaluation, Authorisation and Restriction of Chemicals [50] (REACH) as an action to improve health and environmental protection from the chemical pollution. It also regulates the competition in the Europe's market, covering all kinds of chemical substances – not only industrial ones, having impact at almost all European companies. The main Directive 1907/2006/EC, had faced a number of smaller and bigger amending regulation across the years, tackling different areas of the chemical trading and manufacturing. The REACH obligates companies to conduct tests and research to investigate and identify hazards and later manage with the risk identified. The European Chemicals Agency (ECHA) is the institution that gathers and controls the suggested procedures, followed by their evaluation – in case of the non-manageable risk, the Organisation is in power to limit the usage of the particular substance, leading to substitution of it with a better, more safely choice in a future. The addition to the REACH, The European Parliament and the Council introduced Regulation 1272/2008/EC [51] coming out with a new classification, labelling and packing system of the chemical substances and mixtures. Mentioned regulation is an implementation of the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) managed by the United Nations into European's Law (replacing previous systems contained in the 67/548/EEC Dangerous Substances Directive and 1999/45/EC Dangerous Preparations Directive). The Directives and Regulations implemented into the European's Law the strict ways how to determine the hazard of the substance and the risk that it takes with it and put specified ranges for the chemical and physical properties of the particular substance or mixture in the manner of classification of them, followed by directing them for a certain usage in particular industries, being cognizant of its possible consequences in a matter of health and environment.

4.1 Crude oil

This is "a complex combination of hydrocarbons consisting predominantly of aliphatic, alicyclic and aromatic hydrocarbons. It may also contain small amounts of nitrogen, oxygen, and sulphur compounds" – different types of oil have different amounts of each type of hydrocarbon [52] and in addition crude oil possess in its mixture suspended water (trace amounts), sedimented inorganic elements and dissolved gases. According to American Petroleum Institute crude oil contains on average approximately: 84% of carbon, 14% of hydrogen, 1-3% of sulphur, 1% of nitrogen, 1% of oxygen and 0,1% of minerals and salts [53]. The classes of compounds in the range of types of crude oil are generally the same, but they vary widely in the aspects of physical and chemical properties, dividing it in the industry analysis into: asphaltenes, resins, aromatic hydrocarbons and saturated hydrocarbons. Depending on the composition of the crude oil mentioned before its properties vary significantly, these properties are: density, viscosity, flash point and adhesion as the main ones; and is divided to light or heavy (size and volume of hydrocarbons dependency – API index) and sweet or sour (sulphur content dependency – sweet when less than 0,5% of sulphur). It is commonly stated that the most desirable crude oil products, are those with the shortest hydrocarbon chains. Usually, the oil types are possessing the API index in the range of 10-70 (the higher API index, the lighter oil is). In addition to high API index, the sulphur content and viscosity properties are almost equally important, as the lighter, the sweeter and less viscous the oil is, the easier and cheaper it is to recover the lighter oil fractions, which are the most desirable, especially diesel and petrol for the purpose of transport system. The resins and asphaltenes are usually undesirable compounds in the crudes, due to its high content of minerals and longer hydrocarbon chains, which lowers its properties and making them more difficult to conduct refining process. Industrially the refining process is ongoing in the refineries, where in the special fractionating columns, the crude oil is split, step by step, until receiving the desired product. As the first fraction the heavy oils are received, later followed by the lighter fractions as a product. The products of the refining are petrol, light and medium oils, diesel, paraffins, grease, petrolatum, heavy oils and asphaltenes. The range of another products is also present as the side effect of refining, with the presence of polymers production, placed usually next to refineries.

Table 2. Percentage of weight of the major classes of compounds in the crude oil of the various samples coming from different wells [54]

Type of crude oil	Saturated hydrocarbons	Aromatic hydrocarbons	Resins	Asphaltenes
Light crude (Scotia Light)	92	8	1	0
Medium crude (West Texas Intermediate)	78	75	6	1
Heavy crude (Sockeye Sour)	38	29	20	13
Diluted Bitumen (Cold Lake Blend)	25	22	33	20

The origin of a crude oil comes from the thermal and biochemical transformations of the animal and plant's organic matter. Oil through decades has been the most unstable resource when it comes to its price and availability, due to its limited locations of occurrence. The richest regions are Venezuela and Middle East with Saudi Arabia at the top, followed by Iran and Iraq, Canada, USA and Russia. These regions throughout the years were the various nations' conflict territories and each conflict affected oil price on the global market, yet it eases in usage in majority of sectors (mostly in transport sector) is making the whole world depending on the mentioned carrier, despite its instability in the matter of energy security, price and availability on the market.

The heavy oil is the one mostly used in the various industries and in face of the Regulation 1907/2006/EC the refined product must fulfil certain requirements in the manner of classification and its purpose. Usually the country (in Europe) does not specify additional regulations complying to the European Union standards. In the table below are presented the ranges for the classification of the few examples of the oils used in the industry (refined by the ORLEN company, PL).

Table 3. Normative requirements and properties of heavy oil of type 1E [55]

Property	Regulated requirement for the type 1E	Regulated requirement for the type 0,5E	Regulated requirement for the Ekoterm
Density in 15°C [g/cm^3]	Min. 0,8901	Min. 0,8901	Max. 0,86
Ignition Temperature [°C]	Min. 62	Min. 62	Min. 56
Distillation under lowered pressure, up to 350°C distils [%(v/v)]	Max. 29	Max. 29	-
Flow temperature [°C]	Max. 40	Max. 40	Max -20

Kinetic viscosity in 100°C [cSt]	Max. 25	Max. 25	Max. 6 (in 20°C)
Calorific value [MJ/kg]	Min. 40	Min. 40	Min. 42,6
Water content [%(v/v)]	Max. 0,20	Max. 0,20	Max. 0,02
Ash [%(m/m)]	Max. 0,20	Max. 0,20	-
Sulphur content [%(m/m)]	Min. 0,51 – max 1,00	Min. 0,10 – max 1,5	Max. 0,1
pH	neutral	neutral	-
Solid contamination content, extraction method [%(m/m)]	Max. 0,30	Max. 0,30	Max. 0,0024%
Vanadium content [mg/kg]	Max. 150	Max. 150	-

4.2 Coal

The process of creation of bituminous coal takes around 200-300 million of years as a formation from organic compounds by two main phases – first biochemical one that transform plant materials to peat and later to lignite, followed by second geochemical phase that transform lignite to bituminous coal and then to anthracite. Each type of coal is structured by three main ingredients: organic matter (especially carbon, hydrogen, oxygen, sulphur, nitrogen and lead), which is combustible, mineral matter and moisture. The structure of each coal type varies strongly across the world, as each deposit underwent different processes over the millions of years. Its composition determines coal's quality, especially in aspects of the energy production and greenhouse gases and pollutants emission that comes from the combustion processes. The main benchmarks are its calorific value, moisture, volatile matter content and its mineral and organic matter. Depending on the mentioned indicators the coal is classified for the specific usage for the technology that is going to be used – especially the furnace type, as the pyrolysis' thermal decomposition temperature varies between 300 and 600 °C. The primary characteristics for the Polish bituminous are [56]:

- Lower calorific value 18 – 25 MJ/kg
- Mineral matter 7 – 25 %
- Sulphur content 1,2 %
- Nitrogen content 0,6 – 2,8 %
- Moisture ~ 10,2 %
- Ash content ~ 21,75 %

Despite of the common European stereotype that Poland is overwhelmingly rich in the natural resources – especially in coal, it is not true, having only small percentage of this resource in a world's scale. The main location rich in the carrier is USA, with resources equal to around 300 billion of tons, followed by Russia and China with around 100 – 200 billion of tons and Australia with around 75 billion of tons.

4.3 Brown coal and lignite

Brown coals are classified as the soft and the hard ones or by the diameter of the one seed (7 classes). Due to its moisture and relatively high ash containment, it is hard to transport lignite using roads or rails. During the transportation it transform into a hard mass, difficult to unload with the problem of freezing when cold temperatures occur. That is why usually power and heat plants, which use lignite as a primary carrier, are built in a near presence of the mines, allowing to quick transportation – usually via treadmills – directly to the power plant. Similarly, to hard coal its characteristics strongly varies across the world, depending on the region lignite is extracted. Based on the average characteristics for Polish lignites are [56]:

- Lower calorific value 5,6 – 11,7 MJ/kg
- Mineral matter 4 – 25 %
- Sulphur content 0,2 – 1,7 %
- Nitrogen content 0,6 – 2 %
- Moisture 49,6 %
- Ash content 10,63 %

Brown coal and lignite are less favourable source of energy production than hard coal, especially due to its transport limitations mentioned earlier and significantly higher emissions productions, connected with its moisture indicator. The more the coal is contaminated with moisture, the more pollutions are emitted to the atmosphere, when vaporization occurs – harmful particles and elements are not being transferred to the ash, from where its utilization is easier.

Table 4. Approximated characteristics of the organic fuels [56]

Fuel	Carbon content [%]	Hydrogen content [%]	Oxygen content [%]	Nitrogen and Sulphur content [%]	Volatile Matter content [%]
Wood	50	6	43	1	75
Peat	58	5,5	34,5	2	65
Lignite	70	5	24	0,8	50
Hard coal	82	5	12	0,3	35
Anthracite	94	3	3	trace	5

4.4 Natural gas

Is a colourless, flammable gas without any odour. Its main compound is a CH_4 – methane, with minor fractions of ethane, prophane, butane or other organic and mineral matters. Two specific types are distinguished in the matter of chemical and physical properties, high methane natural gas, which contains more than 85% of the methane, and nitrogen rich gas, which contains the methane in range of 30 to 80% in its composition. In the matter of natural gas' composition, two categories were derived, a dry gas that has over 95% of total methane and ethane content in its composition, and wet gas with the significant part of heavier hydrocarbons, but less than 30% of them in the natural gas' composition.

Natural gas occurrence is strongly connected with the occurrence of the oil due to the chemical and physical processes that had targeted both during years of creation. That is why, similarly to oil and coal, natural gas is mostly extracted in the Russia, Iran, Saudi Arabia, Venezuela, USA or Nigeria, but it is also occurring separately, without the co-presence of crude oil or coal deposits. Different types of gas reservoirs and their classification are present: conventional and unconventional, with the variety of methods to extract the gas from them; or associated – natural gas coexist with oil in the wells, and non-associated, where natural gas is produced by natural gas wells. The former type of deposits are geoformations where the fluid-like properties of the reservoir, allow to non-problematic flow of hydrocarbons through the drilled well. It is estimated that around 50% of total resources of gas are present in the conventional reservoir. The unconventional deposit is the type of geoformation, where the porosity and permeability properties are significantly low, blocking in a certain manner its flow through the drilled well. The extraction of the natural gas from the unconventional formations requires usage of the special engineering technologies, like hydraulic fracture stimulation (into well the pressurized water, chemical additives and sand are injected into well to stimulate the process by the rock fractures' increasement and maintenance) and horizontal drilling.

In addition to the Regulation 1907/2006/EC, Polish government introduced a Norm PN-C-04750:2011 [57] classifying various types of natural gas into families, followed by the groups varying on their origination, Wobbe Index, gross calorific value, basic hydrocarbons content [58].

- Family I - gases extracted using industrial methods and gaseous mixtures with air:
  - "Sn" low-calorific gases, gross calorific value $H_s < 9,4$ MJ/m^3
  - "Ss" medium-calorific gases, gross calorific value $9,4$ MJ/m$^3 \leq H_s < 28,5$ MJ/m^3
  - "Sw" high-calorific gases, gross calorific value $28,5$ MJ/m$^3 \leq H_s < 37,9$ MJ/m^3
- Family II – natural gases:
  - Nitrogen-rich "L" and Methane-rich "E" basing on their Wobbe Index
    - "L_m" $23,0$ MJ/m$^3 \leq W_s < 27,0$ MJ/m^3
    - "L_m" $27,0$ MJ/m$^3 \leq W_s < 32,5$ MJ/m^3
    - "L_m" $32,5$ MJ/m$^3 \leq W_s < 37,5$ MJ/m^3
    - "L_m" $37,5$ MJ/m$^3 \leq W_s < 45,0$ MJ/m^3
    - "E" $45,0$ MJ/m$^3 \leq W_s < 56,9$ MJ/m^3
- Family III – Liquified gases $C_3 – C_4$
  - "B" technical butane $C_4 \geq 95\%$ [mol/mol]
  - "B/P" propane – butane $18\% \leq C_3 \leq 55\%$, $C_4 \geq 45\%$ [mol/mol]
  - „P" technical propane, $C_3 \geq 90$ % [mol/mol]
- Family IV – biogas – gas not connected with the families mentioned above:
  - "BG" – biogas, 55 – 85% of methane, 15 – 45% CO and less than 3% of hydrogen sulphate content

4.5 Biofuels

Biofuels are the fuels derived from the organic matter of the plants and animals that can be combusted in their initial, neat form or combusted as the blends with the other types of fuels. Six main types of biofuels are: wood, biogas, biodiesel, ethanol, methanol and butanol; and they are divided by generations:

- 1st generation: fuels made from starch, sugar, animal fats or oil from vegetables, using conventional technologies; usually the products are fermented grains (high in starch or sugar) – bioethanol, or pressed seeds into vegetable oil
- 2nd generation: fuels made from e.g., cellulosic biofuels or waste biomass, like stalks of corn, wheat or wood; non-food crops
- 3rd generation: fuels produced from algae using extraction methods – the most promising generation, due to low-cost production and significantly higher energy density than the ones from the 1st generation.
- 4th generation: basically, divided into solar fuels – synthetic chemical fuels that are produced from solar energy – converting light into chemical energy; and electrofuels – electrical energy stored in liquids' or gases' chemical bonds

As the biofuels are grouped as a renewable energy source, they are considered as the more favourable source of energy generation, than the fossil fuels. Their advantages are lowering the level of pollution and greenhouse gases (in the matter of so called self-sustained system) or increasing economic and energy independency, but as a drawback with the biofuels production comes significant production cost. The main problem in the matter of using them is that the plant's growth (especially on the industrial scare) requires relatively high amounts of energy, which is generated (with a significant share) from the fossil fuels, causing industrial pollution. Even considering the self- sustained system (CO_2 produced during the bio-fuel production is used for the crops' growth) the carbon emission in total is not that low, as it could be imagined, when treated biofuel as the renewable energy source. There is a need to introduce more effective manners of plant's production to increase the effectiveness of the biofuel industry, which in the current state is not so promising. The next disadvantage of mentioned carrier's type usage is the water pollution, connected with a need of fertilizer management, which contains a significant amount of the nitrogen and phosphorus, which could be even more harmful that CO_2 emission into atmosphere, when using common fossil fuels.

5. Description of the types of industry boilers used for the water and steam preparation

Steam and water boilers' usage is widespread in the industry across all of its branches, especially in the energy branch and others, where is a need to provide heat in a form of steam. The boiler is the device to convert chemical energy that the carrier contains, into the working medium (hot water or steam) in a form of heat. The medium is then transported to the place of usage – turbine, particular technology or in the purpose of central heating systems. Boilers are working in the closed circuit, where the medium is directed back to the boiler, or in the open circuit, where the medium is lost. Industrial boilers find a purpose not only to power production processes in the factories, but also works similarly to the residential sector's usage – to generate energy for the central heating and domestic hot water preparation. Usually, it is possible to use different kind of fossil fuels for the one device, allowing for bigger number of possibilities in the matter of savings, energy efficiency and emission production.

5.1 Flame and smoke tube boiler

This type of boiler is characterized with a combustion chamber in a form of a tube with a significant diameter (flame tube), and with smaller tubes (smoke tubes) where the smoke flows from the combustion chamber to the exhaust. The overall of tubes is immersed in the water, that takes the heat from the hot smoke. This kind of steam boiler is the most commercialized one on the present market, as they are able to perform under low pressure, as well as under the high one – usually the maximum pressure does not exceed 40 MPa and maximum efficiency is at the level of the 50 t/h of steam produced [59]. Usually, the construction of the device consists of a flue tube and two exhaust ducts, creating a three-pass boiler (Figure 19). They are more expensive than the two-pass ones, but they mark out with more valued efficiency and lessened NOX emission. Usually, an integrated part with the boiler is the burner. Depending on a power need and the available carrier type, they can be sourced with natural gas, liquified natural gas or light and heavy oils. The particular types of the device allow to burn different resources, without the change of the burner itself.

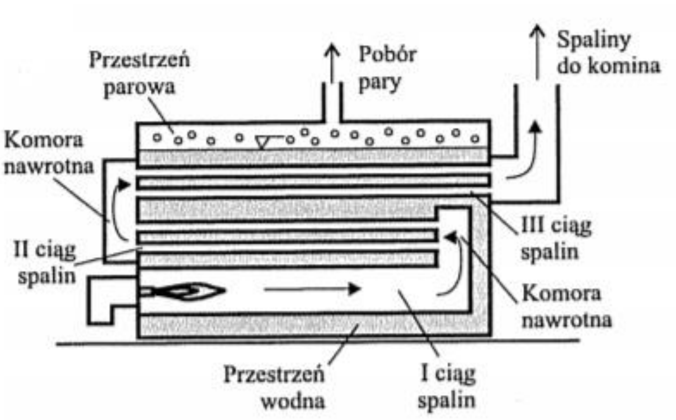


Figure 9. Three-pass boiler with a turnback chamber (cooled by water) [59]

For the work of the flame and smoke tube boiler, a huge impact has to do with its water and steam capacities. The installations with larger steam and water volumetric capacities are characterized with lesser vulnerability for the sudden changes in the steam production and changes in the volume of that steam to be used; increased heat accumulation in comparing with boilers with small steam and water capacity; and it is more secure in exploitation with less automatization devices needed to control the whole process. To the basic drawbacks of this kind of technology we include a long time of launching from the cold state, significant losses when the work is stopped, and immense mass and volume of the device. On the opposite the flame and smoke tube boilers with small water and steam capacities are more compact, with lesser heat losses when stopped working and are much easier to launch quickly when needed, but they need a number of control and automatization devices through whole installation. The major drawback of the technology with small water and steam capacities is the contamination of the steam with water drops, when the level of water is not controlled precisely, which is lowering the efficiency significantly [59].

5.2 Fluidized bed boiler

In a recent decade this kind of technology is getting more and more attention in the energy sector, having a new energy blocks with even 800 MW of installed capacity. The specification of fluidized bed allows to use not only a variety of typical fossil fuels or biomass, but also to burn other energy carriers and wastes. The high oxidation of the fuel's particles, presence of Calcium and relatively low combustion temperature (~850-900 °C) are leading to small amount of pollutant and greenhouse gases emission into atmosphere and high energy efficiency in comparing to other technologies widely used in the commercialized energy sector. The desulphurization is at the level of 95% and NOX emission reduction at the level of 50-80%. By the process of turbulence mixing and a long time that fuel's particles are present in the combustion chamber, the fuel's burning efficiency is at the level of even 99% [60]. The boiler allows to use a range of carriers which calorific values varies between 4 000 and 36 000 MJ/kg [61]. The amount of ash produced in the combustion process is higher than when using traditional pulverized bed boilers, due to Calcium's additives, followed by their reactions with sulphur oxides and burning low calorific fuels (mostly wastes). The advantage in sake of the significant fluidized ash amount is that it can be reused in combustion process (depending on its chemical and physical properties) to enhance efficiency of the fuel or limestones and their reaction with sulphide oxides. The burning leftovers (mostly coal and its derivatives) can be used e.g., also in the mining industry, building material's production or can be deposited safety without harming the environment (petrification or vitrification processes). To other advantages of the technology, we can include relatively lower costs, in comparison with pulverized bed technology, e.g., by the crushing of the carrier rather than grinding it (exploitation cost) and by compact size (investment cost).

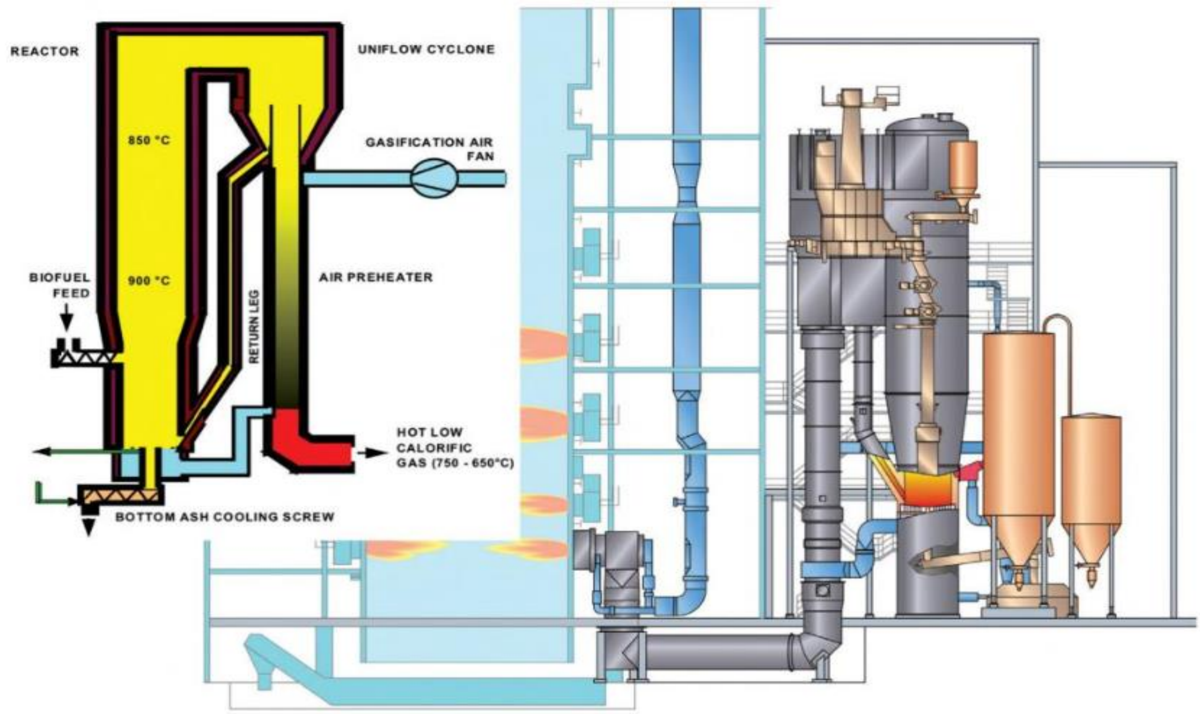


Figure 10. Example of Circulating Fluidized Bed boiler scheme in Lahti, FI [62]

5.3 Pulverized fuel-fired boiler

The technology is the most commonly used one in the energy production branch, when it comes to the solid fossil fuels combustion. The carrier needs to be conducted under grinding process first, as this type of boiler need to be sourced by the smallest granulate as possible in a sake of efficiency. Pulverized fuel-fired boilers are highly effective, but the cost of fuel preparation might be relatively high, depending on their original state (granulate size max. 200-300 μm and a moisture content). The mills and grinders as additional devices are rising up both, the exploitation cost and the investment cost. The boiler is able to reach heat power from 50 MW_t (in medium sized ones) to even 2 000 MW_t (in big ones).

5.4 Stoker – fired boiler

Similarly, to the pulverized fuel-fired boiler, stoker-fired boiler is widely commercialized. It allows to use a solid fossil fuel carrier with a diameter up to 25 mm. The stoker might be stable or moving with the air sourced from the under of it. To maintain combustion, process the incendiary vault is used, replacing the typical launching burners used in the pulverization technology. The ignition, degasification and combustion of the fuel works using a radiation generated from the incendiary vault.

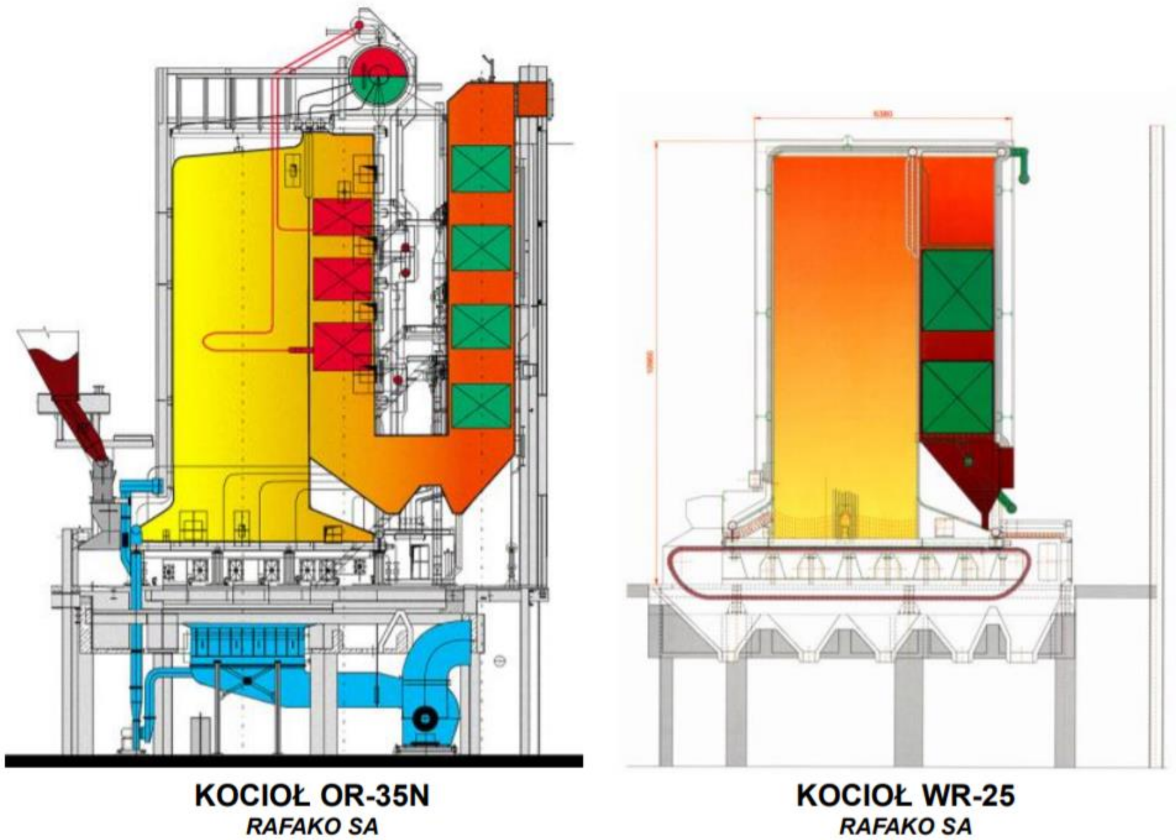


Figure 11. Examples of the stoker – fired boilers located in Combined Heat and Power plant in Cieszyn, PL (OR-35N) and Power Plant Czestochowa, PL (WR-25-014S) [63]

5.5 Steam generator

The steam generator usually has a construction made from the water tubes, which are washed by the hot smoke. A medium (in this case water) is flowing through a very long coil and is heated to boil and to the temperature of the saturation, dictated by the given pressure of a steam. Then a steam is pushed forward into the steam tubes. The coil itself has relatively low volumetric capacity, and the volume of an evaporation is unable to be determined directly, due to changing evaporation point. The small water capacity allows for a vast water heating and then steam generation, leading into only a few minutes in needed for a full launch of the device. A small diameter of a coil is leading to a need of being sourced by the high-quality water. This is a prevention from the limescale, which might lead to tightening, already small tube and even clocking. Similarly, to flame and smoke tubes boiler, the burner is usually an integrated part with steam generator, basing on the carrier source. The particular burner can be sourced with natural gas, liquified natural gas and light or heavy oil, depending on the needs.

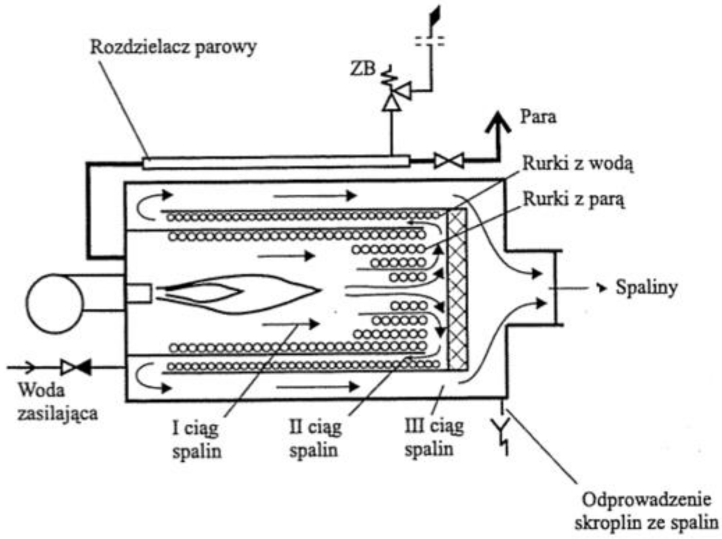


Figure. 12. Example of the steam generation with a three-pass scheme of the smoke exhaust [59]

6. Laktopol powdered-milk overview

The aim of the case is to develop strategies for the Laktopol company and give recommendations, which to follow. The company contacted the consultant to investigate the possibilities of the change of the source of energy currently used in the facility, within the boundary of keeping the existing infrastructure installed in years 1990' and 2000'. Laktopol possess the full installation (presented later in Chapter 6 in details) with three independent boilers ready to be operated separately at any time (steam generator and two flame and smoke tube boilers). In line with the 2050 target to become net-zero emission and continuously increasing fossil fuel prices and also emission allowances prices creating significant added value, the company wants to develop operational energy strategies for the next decades. The final choice is divided into the short-term strategies (up to 15 years forward) and long-term (to reach 2050 net-zero carbon emission target). The division of proposed final scenarios is strongly bound to subsequently decreasing share of the fossil fuels in the energy mix (regional, countrywide and worldwide) and actions towards limiting pollution. The main indicator, forcing the industry to establish strategies for a few decades forward, are rapidly rising prices of the EU Emission Trading System and new taxations introducing, or to be introduced on the fossil fuels. The main goal of such actions taken by the governments (in this case – Polish Government in line with European Union) to increase the total costs of operating on fossil fuels, that switching to low-emission or renewable technologies becomes much more profitable, than sticking to the current option.

The Laktopol's needs for heat are around 2 MW (milk drying process in driers and evaporators to produce powdered milk), and for the electricity (devices in the office and at the production lines) are 1,8 MW. The facility runs its production 24h, 7 days per week, and the energy load is stable around the year. There are no plans to increase the energy demand level in the future for both – heat and electricity productions.

6.1 Factory and problem description

Polindus-Laktopol is a company specialized in a dairy products production founded in 1989. The whole spectrum of the capital group goes from the milk purchasing, through its manufacturing and final products production, ending with the domestic and international distribution. The main offerings in Laktopol's portfolio are: fatless powdered milk, powdered whey protein and Fat Filled Milk Powder Instant (milk-fatty mixture). On the way of their development strategy realization Polindus-Laktopol launched one of the biggest and the most modern evaporate-dryer installation in their factory in Suwalki, North-East Poland. The investment allowed to enhance the production to the level of 200 tons of the milky powders from around 1,5 million litres of milk per day. The company's brand is present around the world, having distribution in the UE, Asia, Americas and Africa.

The main purpose of installation at the Laktopol's facility is to generate heat directed primarily to the driers, where the essential processes of powdered milk production happen. The cow's normalized or skimmed milk first needs to be pasteurized for the sake of elimination of harmful bacteria and enzymes, then it is followed by vacuum drying in evaporators to receive state of condensed milk with up to 50% of water content less in a product. The condensed milk is directed into the ending stage, treated with the air of the temperature of around 200°C in a spray-driers. In the machine milk is sprayed to the form of small particles, and then treated with a high temperature, allowing the quick water evaporation from the milk particles creating a milk in powdered form. After such a treatment the final product has a satisfactory water content of around 15%. The water content can be later lowered (to around 2%) by using drying and cooling vibrofluidizers.

Figure 13. Polindus-Laktopol's factory in Suwalki, PL [64]

Due to the European Union's directives, projects and Emission Trading System more restrictive every year, the company is considering change in the currently used carrier – heavy oil. Laktopol asked for consultation in the matter of switching the fuel to natural gas to lower its impact on the environment, improve the boiler's exploitation and boost its cost effectiveness. The facility does not possess a secured connection with the gas pipelines and the forms of gas taken for the examination are Liquified Natural Gas and Compressed Natural Gas, which can be transported to Laktopol using other means of logistic than a gas pipeline. The modelling and the analysis are conducted using SimTech's IPSEpro software supported by the Microsoft Office Excel software. In Chapters' subsection from 6.4.1 to 6.5.3 the information about the current infrastructure is gathered and presented. The properties for each device are delivered by Laktopol from each device's manual and chemical and physical properties per each energy carrier are delivered either by the Laktopol or taken from the official producer's website.

6.2 IPSEpro software

IPSEpro is a comprehensive and flexible environment used for the modelling and analysing purposes, finding application majorly in the energy and chemical engineering fields. The software has been designed to serve the purpose of problem-solving, representing by the network of the components and connections between them. IPSEpro is using the build-in libraries with the prepared components and allows to create new ones that would suit the design of the project working on; the mentioned assessment introduces a significant amount of flexibility, when it comes to the process modelling of the complex schemes (e.g., a heat and power plant), that uses unique components. The Process Simulation Environment, apart from the Component Level flexibility, offers a second level of it, at the Process Level. It introduces a freedom in the order arrangements of the components, by the graphical user interface and environment, to represent process scheme, that would reflect reality the most and would suit the modelling and analysis purposes (e.g., when investigating the processes that occur in power plant with a variable data) [65].

The processes in the IPSEpro are to solve frequent mathematical models that exist in the previously designed model's structure, per each component and in total. The whole structure is set to be a mathematical behaviour descriptor in the terms of the parameters and variables (per each component e.g. – fuel composition, certain device parameters, used medium) that have been inputted and on the embedded equations loaded into the software. The final solution is calculated numerically in the iteration process, based on the set of initial values (that are constant), and calculating the rest that are set on the estimation, that the whole cycle (structure) is closed.

Program approaches all solution methods as the non-linear equation, that are bases on the initial values' iteration. Using the two-step approach, IPSEpro solves the modelled system, firstly analysing the system itself, by checking the order of the calculations that need to be performed and order based on input variables' treatment. Secondly, in the numerical solving phase, the software groups the existing variables to optimize the numerical methods suited for each group, followed by the calculation of the numerical solutions describes for the system. The methodology used for the numerical solution is the Newton-Raphson. The methodology begins from the starting values and approximates the system functions, using the starting value's linearization. It is followed by the calculating a new starting value, basing on a new linearized system created. This is repeated to reaching a point that solution is sufficiently accurate. IPSEpro allows to introduce a dumping factor α ($0 < \alpha \leq 1$), having the calculations the same as when using undamped method, only with an additional factor. The dumped methodology is used when, using undamped method fails, and the number of errors increases over every next calculated iteration. The value of Δx is the difference between the starting value and linearized solution of the system that is calculated. In order to receive a new starting value for the followed step of iteration, Δx is added as a correction to the starting value [66].

6.3 Laktopol's installation

The installation present at the production site is the one that can be compared to the heat and power plant's, but on significantly lower scale. The cycle's purpose is to fulfil only the house load of the facility in Suwałki for heat and electricity. The heat is used is significant load in powdered milk drying process and during winter for a central heating, capacity of both combined is estimated as 2 MW. The electricity's load is dedicated to power additional production devices and for daily usage, like powering the office, estimated at the level of 1,8 MW.

The main elements in the installation:

1. Boiler:
    - Clayton E-604 – steam generator
    - Babcock Omnical – OMNIMAT 33 HD 7.0 – 18 – flame and smoke tube boiler
    - LOOS – flame and smoke tube boiler
2. Back-pressure reduction micro-turbine, 2-step by GESTRA
3. DNA coat and tube heat exchanger by Secespol
4. Deaerator
5. Condenser
6. Generator
7. Pumps
8. Exhaust

In Romanian number the respective steps of Clausius - Rankine

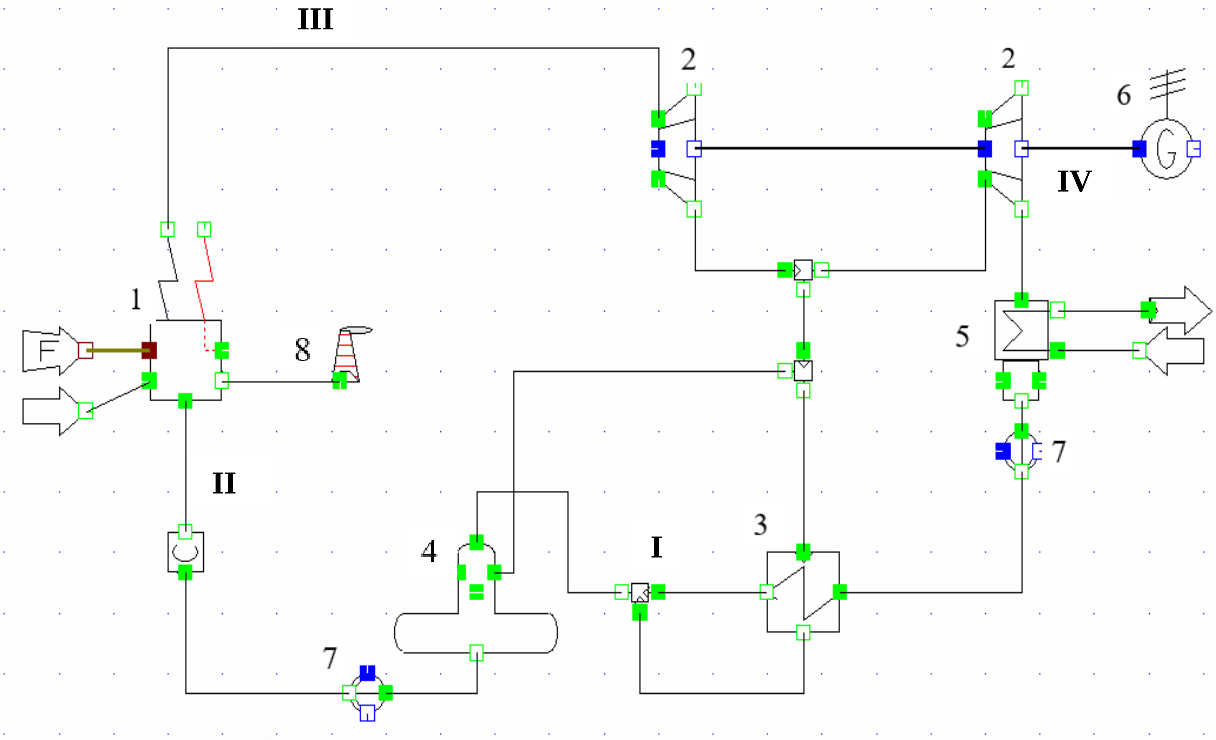


Figure 14. Scheme of heat and power generation installation at Laktopol production facility, designed in IPSEPro

The data that was introduced into the model is gathered into the Tables 5 -15 that are presented further in the Thesis with a respective device (mechanical properties for combustion and cycle operation) or fuel (chemical composition and chemical and physical properties) description (Chapters from 6.4.1 to 7.0 included).

IPSEpro software model uses build-in modules of particular devices that works mostly basing on the principles of the Clausius-Rankin cycle and heat and mass balances to resolves the equations and calculations. Each component is connected and rely on each other to close the cycle and calculate by iteration the respective variables that originally are uncertain. The modules and connectors have imbedded physical and chemical equations and IPSEpro simulates the respective reactions and corelation between them. The software creates the possibility to investigate how the process and respective devices behave in each step of the heat and power production process, by implementing a number of known input and output variables, supported with the boundaries or known parameters for each device, like max. pressure that can be present in the combustion chamber or the Temperature of the steam that is defined for the powdered-milk production in this respective case study. The additional aspect to be introduced into the program was chemical composition of each fuel that was investigated, as on this data relies the outcome in a form of elementary composition of exhaust fumes or even the amount of heat produced basing on the percentage share of carbon element per fuel.

6.4 Overview of installed technology at Laktopol production site

Laktopol's facility in Suwałki possesses three other steam boilers in their equipment, all three developed by different producers, allowed to work separately. Each one is able to be supplied by other kind of fuels – in the considered case, heavy oil and natural gas. All three boilers are able to provide enough energy for the facility's operational purposes alone., which is estimated to be around 2 MW. The steam produced is used for the facility's production purposes – evaporators, and electricity generation simultaneously as a by-product. The basics of operation of the installation in the Laktopol's facility is Clausius-Rankine Cycle, where high pressurized steam of high temperature is produced by the conversion of chemical energy from the fossil fuels into thermal energy. The energy is transferred into the working fluid (usually water), that passes the boiler by the means of steam production. Produced steam then passes one or series of steam turbines – high- and low-pressure – to power electric generator, converting steam's energy into mechanical shaft. At the last stage of the turbines' series, the steam is directed into condenser, which product is then pumped-back to the initial stage of the Rankine Cycle – boiler, closing and repeating cycle. Work of basic Rankine Cycle is presented below:

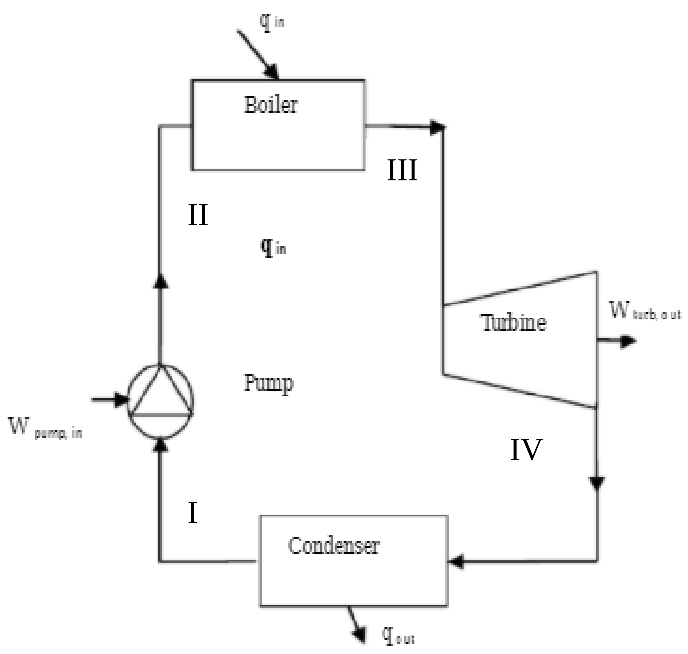


Figure 15. Clausius – Rankine scheme [67]

- Step I - II: isochoric pump of condenser in a pump
- Step II - III: isobaric heating of the liquid (usually water), its evaporation and overheating of produced steam in a steam boiler or steam generator
- Step III - IV: isentropic (adiabatic) decompression of steam in a turbine
- Step IV - I: isobaric condensation of decompressed steam and heat extraction in condenser

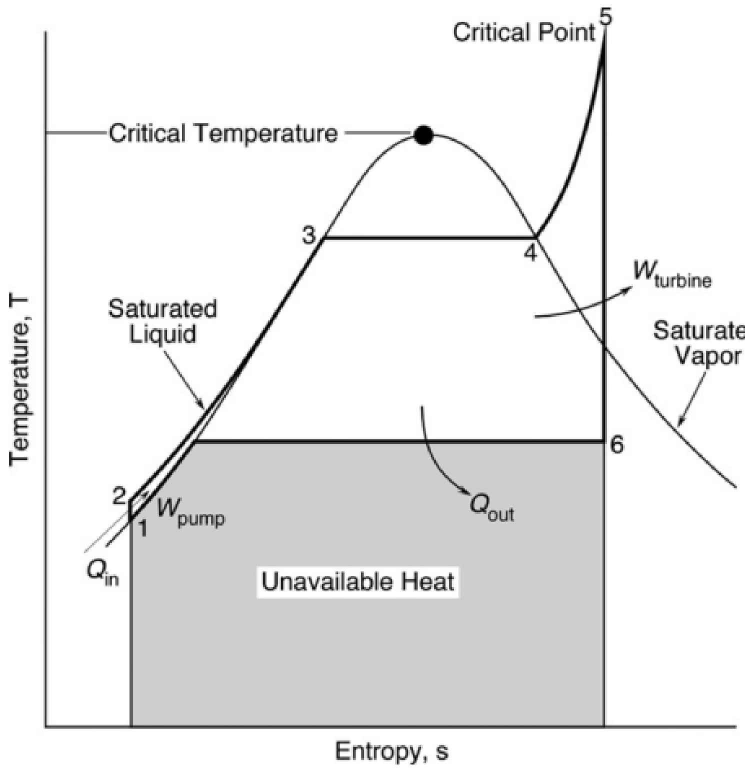


Figure 16. Temperature – entropy diagram of the ideal Clausius – Rankine cycle [68]

- Step 1-2: Working fluid is compressed, pressure is changed from low to high
- Step 2-3: Liquid at high pressure state enters boiler, where heated at the constant pressure, state is changed to compressed liquid
- Step 3-4: Compressed liquid forms two-phase mixture (usually water and steam)
- Step 4-5: Superheating of the medium
- Step 5-6: Expansion of steam through turbine and power generation
- Step 6-1: Expanded medium (vapor) enters a condenser at decreased pressure and temperature; it becomes a saturated liquid

6.4.1 Clayton E-604 – steam generator

Steam generator, according to the data provided by the producer, generates best quality steam in the amount scripted in the technical specification, with up to 1% of the water in it. In 5 minutes from the starting point, it can reach its maximum rated pressure. The machine is equipped with additional devices to control and secure: the installation from the emergency water input cut, burner breakdown, pressure level or electricity overload. In addition, automation devices regulate feed water flow or flame height in accordance with the current need for the steam.

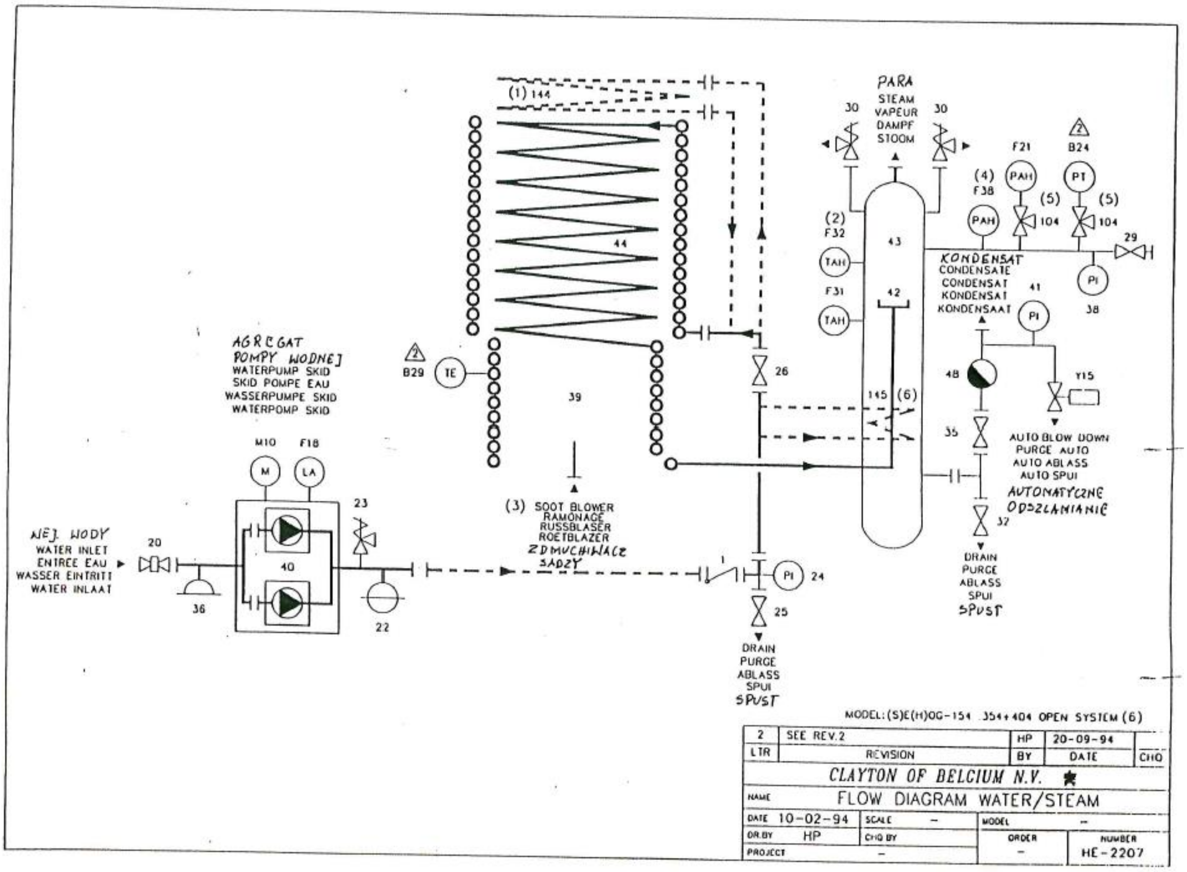


Figure 17. Scheme of the installation with Clayton's E-604 boiler – Flow diagram water/steam [69]

Table 5. Technical specification of Clayton's steam generator type E-604 [69]

Property	Unit	Value
Capacity installed	kW	5885
Steam generation (at p = 1 bar and feed water temperature T = 100 °C)	kg/h	9388
Max working pressure	bar	28
Heavy oil usage with its specific weight of 0,85 kg/l and its calorific value of 42 700 kJ/kg – 100% workload	l/h	675
Gas usage with its calorific value of 31 666 kJ/Nm^3 – 100% workload	Nm^3/h	756
Min. gas' pressure - input	mbar	350
Max. gas' pressure - input	mbar	500

6.4.2 Babcock Omnical – OMNIMAT 33 HD 7.0 - 18 – flame and smoke tube boiler

The second boiler installed in the facility is the boiler of the flame and smoke tube type, produced by Babcock Omnical company. The medium is the saturated steam, and the main components of the instalment are the main boiler, the reversable flame tube to create better optimization when combusting, turbulence pipes multiplying a heat transfer coefficient and improving a pollution's drainage, and combustion chamber with built water heater. To meet up-to-date standards the whole appliance is insulated and equipped with the additional control and automatization devices. The oil burner is produced by Weishaupt, type RL 50/2-A.

Table 6. Technical specification of Babcock Omnical flame and smoke tube boiler – OMNIMAT 33 HDA 7.0 [70]

Property	Unit	Value
Capacity installed	kW	4560
Steam generation (at p = 1 bar and feed water temperature T = 100 °C)	kg/h	7000
Max working pressure	bar	18
Water capacity	dm^3	8,5
Fuel usage	kg/h	175 - 658
Min. gas' pressure - input	mbar	100
Max. gas' pressure - input	mbar	5000

6.4.3 LOOS - flame and smoke tube boiler

The boiler with a significant water capacity to produce saturated steam, produced by the company LOOS. The installation is able to be sourced by oil and gas as well, with the less than 0,2% sulphur contamination. 2-3% water content (moisture) in the steam is the normal occurrence during the optimal workflow of the boiler. The installation is equipped with the additional control and automatization devices. The boiler's set-up has the burner installed – type RGMS70/1-A, produced by Weishaupt.

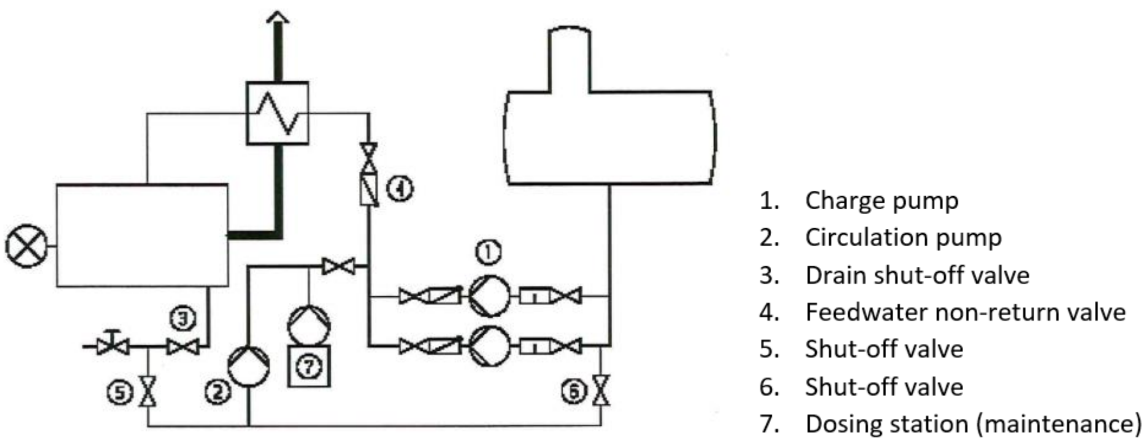


Figure 18. Simplified scheme of the LOOS boiler [71]

Table 7. Technical specification of LOOS flame and smoke tube boiler [71]

Property	Unit	Value
Capacity installed	kW	8050
Steam generation (at p = 1 bar and feed water temperature T = 100 °C)	kg/h	12000
Water capacity	m3	0,279
Max. pressure	bar	22
Max. Temperature	°C	219
Fuel usage	kg/h	190 - 934
Min. gas' pressure - input	mbar	100
Max. gas' pressure - input	mbar	5000

6.4.4 Back-pressure reduction turbine - GESTRA

Considering steam turbine's choice that would match working conditions and properties of three different heating sources, additionally powered by different types of fossil fuels is a challenge. The turbine's market operates with the devices working on higher pressures and with much higher installed capacity, comparing with those at Laktopol's production site. The main issue regarding the respected case was relatively low maximum working pressure which varies from 18 bar to 28 bar. The turbine's installation was added to deliver electricity generated as a by-product of the generated heat that is indispensable in large amounts for the powdered milk production purposes.

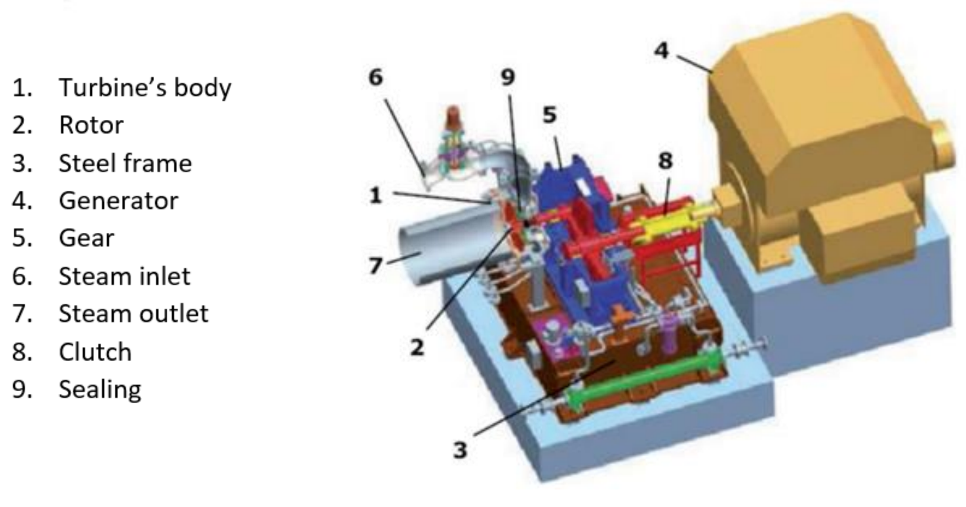


Figure 19. Back-pressure reduction turbine – scheme [72]

Steam turbine installed at Laktopol's site is micro-turbine produced by German company GESTRA that operates strongly on Polish market. Exact type of the device offered by producer is the back-pressure reduction turbine, that reduces steam pressure, produced in the steam boiler, to the pressure required by the production specification of the certain company. In addition, it provides ability of electricity generation for the company's own purposes. The operation of the back-pressure reduction turbine is based on the same methodology, as the reduction valve – with additional energy conversion of reduced steam into electricity. Main advantage is that micro-turbine does not use the steam, but it reduces steam pressure, that is later used in company's production process.

Exact turbine that is used at the production site is a 2-step steam turbine. Installed technology allows for the high temperature drops and for mid-step steam extraction. Usually used to power generators.

Table 8. Properties of back-pressure reduction micro-turbine, 2-step, operational ranges given by producer – GESTRA Polonia [72]

Property	Unit	Value
Capacity	kW	150 – 2000
Steam flow	t/h	4 -30
Steam pressure – inlet	bar	6 – 63
Steam pressure - outlet	bar	0,5 – 10
Max. working temperature - inlet	°C	300

6.4.5 Additional devices

- **Pumps**

Due to significant pressure drop causing a drop in mass flow of the medium after the elements: condenser, deaerator, there is a need to install water pumps to enhance mentioned parameters and force the circulation of the condensate. The implementation of water pumps has the purpose to boost up the mass flow rate within the whole installation, make the medium movement even over the cycle, and to prevent significant efficiency losses and clogging.

- **Deaerator**

The device is introduced to the cycle to serve a purpose of elimination of dissolved gases in a feedwater that is directed to the boiler, with a focus on the oxygen contamination removal. Dissolved O_2 in feedwater causes significant corrosion damage, by attaching to the boiler walls and metal equipment, forming oxides. In addition, dissolved carbon dioxide, also may cause serious corrosion, as the gas combined with water forms carbonic acids. The implementation of such device is essential for the proper workflow, prolonging the life of the whole installation and lowering the risk of leakage or other serious damages, caused mainly by occurring corrosion.

The pressure in Laktopol's deaerator is set to be 10 bar.

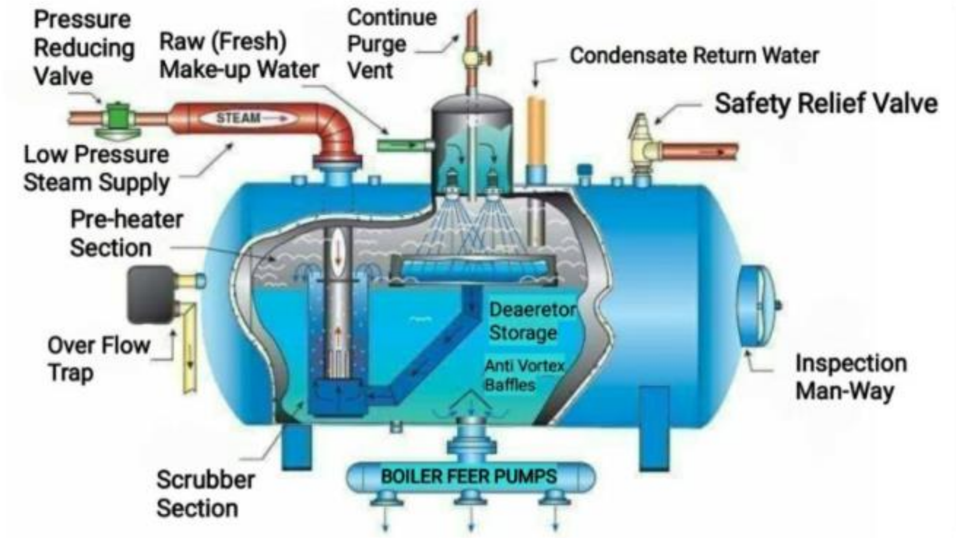


Figure 20. Deaerator – working principle [73]

- **Condenser**

Condenser is a device, which main purpose is to convert the medium from gaseous state into the liquid one. It behaves with a same manner as heat exchanger, taking the heat from the gas stream, using the cooling medium (water in this situation) that circulates through the pipes of the condenser.

- **Generator**

Generator's working principle is to convert mechanical energy into electricity. Firstly mechanical, then electric energy is produced as a by-product of the steam production for the production purposes (drying) and used to power electric devices in the heat and power generation installation, other devices over facility and its offices. To fulfil the company's needs it is estimated to produce 1,8 MW of electricity, with the exceptional overloads being covered by the energy provided by the grid, operated by the regional Distribution System Operator of North-East Poland. The whole facility could be electrified from the grid, although when having significant needs for heat production (~2MW), it was much more effectible to invest into generator's placement and use produced heat in the turbine to generate electricity as a biproduct, from economical point of view and providing independency from the grid for the Laktopol's facility.

- **Heat exchanger Secespol DNA 273.10.S151**

Heat exchanger of shell and tube type is characterised by a significant area of heat exchange. It is built from a cylindrical shell, which contains a number of tubes with thin walls. This type of heat exchangers is the most abundant in the industry, due to its high range of utility.

The model installed at the Laktopol's facility is produced by the company Secespol, characterized with used technology called DNA. The company produces such types of devices, that can be used in the food industry, possessing the sanitary attestation. As a main advantage this technology allows to receive higher area of heat exchange, comparing with the standardized models common within the industry. Spirally made tubes, inside the shell, are forcing turbulent flow of the medium, doubling the heat exchange coefficient, additionally lowering the weight and size of the device, making it much more compactable, when comparing with other models. The DNA heat exchanger is adapted to work with a range of mediums (e.g., fumes, heated air, low-pressurized steam) still receiving satisfactory level of heat exchange. [74]

Figure 21. Shell and tube heat exchanger – type DNA, by Secespol [75]

Table 9. Characterization of DNA shell and tube heat exchanger by Secespol [76]

Work coefficients	Coat	Max. Pressure	10 bars
		Max. Temperature	200°C
	Tubes	Max. Pressure	16 bars
		Max. Temperature	200°C
Tube diameter [mm]			10
Area of heat exchange [m2]			15,1
Tubes' volume [l]			33,3
Coat's volume [l]			78,1

6.5 Fuels' properties

The boilers presented in the paragraph 5.3 are able to be sourced by the different carriers – oil and gas. The model's analysis is based on the carriers used in the facility (heavy oil and gas) from the Polish producers – ORLEN Południe – heavy oil and Polskie Górnictwo Naftowe i Gazownicze SA (PGNiG) – natural gas.

6.5.1 ORLEN – Heavy Oil 1E

The fuel is produced in the ORLEN's refinery in Trzebinia, Southern Poland, and according to the producer it is high quality oil fraction produced from the heavy distillates in the process of the crude oil's atmospheric refining. It characterizes with: low sulphur contamination; high calorific value; lack of non-burnable elements affecting, effecting with low ash amount; decreasing possibility of corrosion, due to small sulphur content and lack of water; very low coke content decreases the coking tendency across the installation. It finds the usage in the heavy industries, energy sector, road buildings or agriculture, and it is distributed using the means of road and rail transport across Poland and other countries. The analysis is performed basing on the data presented below, which is provided by the supplier.

Table 10. Normative requirements and properties of heavy oil of type 1E [55]

Property	Requirement due to the norm	Marked value based on the sample
Density in 15°C [g/cm^3]	Min. 0,8901	0,8934
Ignition Temperature [°C]	Min. 62	106
Distillation under lowered pressure, up to 350°C distils [%(v/v)]	Max. 29	3,5
Flow temperature [°C]	Max. 40	36
Kinetic viscosity in 100°C [cSt]	Max. 25	10,78
Calorific value [MJ/kg]	Min. 40	42,334
Water content [%(v/v)]	Max. 0,20	0,05
Ash [%(m/m)]	Max. 0,20	0,03
Sulphur content [%(m/m)]	Min. 0,51 – max 1,00	0,8
pH	neutral	neutral
Solid contamination content, extraction method [%(m/m)]	Max. 0,30	0,04
Vanadium content [mg/kg]	Max. 150	≤ 1
Carbon content [%(m/m)]	-	81
Hydrogen content [%(m/m)]	-	13,1
Nitrogen content [%(m/m)]	-	1,05
Oxygen content [%(m/m)]	-	3,05

6.5.2 ORLEN – Heavy Oil C1

The producent is dedicating his heavy oil type C1, as a carrier for the central heating boilers, flame and smoke tube boilers, steam generators, steam boilers, industrial furnaces and for technological processes.

Heavy oil C1 is produced as a product of mixing light and heavy compounds, created as a result of technological processes of original distillation and crude oil reforming by PKN Orlen. The composition of the product is determined by quality benchmarks - regulated by Polish and European Union norms – in correlation to the heavy oil; the biggest focus is given to the value of kinetic viscosity and sulphur contamination. Contamination by sulphur in this heavy oil type is limited to 1% (m/m). Producer is giving an attest that his type of heavy oil fulfils the requirements stated in Polish Norm PN-C-96024 “Petroleum products. Fuel oils.” in the aspects of heavy oil, and the Decision of Minister of Energy from 1 December 2016, in the matter of quality requirements of the amount of sulphur for oils and installation types, and the conditions in which the heavy oil are going to be used (Journal of Laws from 14th December 2016, position 2008).

Due to the lack of exact specification marked by the measurements in the laboratory environment but having only requirements dictated by Polish Norms it was chosen to use a value in a middle per each element. It is to use Heavy Oil type C1, as a benchmark of the worst of the three types of fuel used in the analysis. As usually within the oil&gas industry, the better quality of the fuel, the higher the price. In presented situation Heavy Oil C1 is the cheapest from the fuels available to use in the factory, to leverage low quality and high number of emissions that are produced from burning the fuel.

Table 11. Normative requirements and properties of heavy oil of type 1C [77]

Property	Requirement due to the Polish Norm	Specification taken as a benchmark in the analysis
Density in 15°C [g/cm^3]	0,890 – 1,00	0,955
Ignition Temperature [°C]	Min. 62	
Distillation under lowered pressure, up to 350°C distils [%(v/v)]	Max. 29	20
Flow temperature [°C]	Max. 40	36
Kinematic viscosity in 100°C [mm^2/s]	Max. 55	40
Kinematic viscosity in 50°C [mm^2/s]	Max. 800	700
Calorific value [MJ/kg]	Min. 39,7	40,5
Hydrogen sulphite content [mg/kg]	Max. 2,00	1
Water content [%(v/v)]	Max. 1,00	0,5
Ash [%(m/m)]	Max. 0,20	0,1
Sulphur content [%(m/m)]	Max 1,00	0,8
pH	N/A	N/A
Solid contamination content, extraction method [%(m/m)]	Max. 1,00	0,8
Vanadium content [mg/kg]	Max. 1,00	0,8
Carbon content [%(m/m)]	-	81,4
Hydrogen content [%(m/m)]	-	13,1
Nitrogen content [%(m/m)]	-	1,05
Oxygen content [%(m/m)]	-	2,01

6.5.3 PGNiG – Natural Gas

The Liquefied Natural Gas used in the Laktopol facility is produced from the natural gas by PGNiG in the nitrogen removal plants in Odolanów and Grodzisk Mazowiecki, Poland. In both facilities the primary method is to convert highly-nitrogenized natural gas into methane-rich natural gas. It takes approximately 600 times less volume than natural gas after regasification in the matter of energy storage and transportation – lack of direct gas pipelines connection with the facility and even the area of North-East Poland. The analysis is performed basing on the data presented below, which is provided by the supplier. Using this kind of fuel cause the need of installing the evaporation station to convert the fuel from liquid state, into gaseous one, that is able to be used as an energy carrier for the boilers, that are already installed at the Laktopol production site. The investment also requires purchasing the additional LNG storage tanks.

Table 12. PGNiG's Liquified Natural Gas properties [78]

Property	Requirement due to the norm
Molecular weight	16,4
Colour	Colourless
Odour	Odourless
Boiling temperature (1013 hPa) [°C]	- 169,5
Density in liquid state (- 169,5 °C) [kg/m3]	450,36
Gross calorific value [MJ/m^3]	39,26
Calorific value [MJ/m^3]	35,40
Calculated density in 25°C and p = 1 bar [79] [kg/m^3]	0,846
Specific heat capacity in 300 K [80] [kJ/(kg*K)]	2,226

Table 13. Chemical composition of PGNiG's LNG [78]

Compound	Chemical formula	Normative range [mol %]	Calculated molar composition [mol %]
Nitrogen	N_2	≤ 4	3
∑ combustible compounds	-	≥ 96	97
Methane	CH_4	≥ 93,83	95,193
Ethane	C_2H_6	≤ 1,72	1,53
Propane	C_3H_8	≤ 0,4	0,26
i - butane	i – C_4H_{10}	≤0,03	0,01
n - butane	n – C_4H_{10}	≤ 0,015	0,005
Pentane$^+$	C_5^+	≤ 0,005	0,002
Carbon dioxide	CO_2	≤ 0,005	-
Water	H_2O	≤ 0,0002	-
Sulphur compounds	-	≤ 0,0006	-
Lead	Hg	≤ 0,001 [mg/Nm^3]	-
Carbon content [%(m/m)]	C	-	72,72
Hydrogen content [%(m/m)]	H_2	-	24,28
Nitrogen content [%(m/m)]	N_2	-	3
Oxygen content [%(m/m)]	O_2	-	0

7. Analysis of the boiler's performance, when used heavy oil and gaseous types of fuels

The unified scheme of the process was designed using IPSEpro software. Process Simulation Environment allows to introduce different fuel types, boiler types and working conditions that are desired for the simulation's purposes, without changing the entire scheme. Further analysis was conducted as a set-up of each heating source present in a respective case, with each of the introduced fuel types, also with a check of different working conditions, with focus on the air-fuel ratio present in the boiler's chamber, for each set-up.

Table 14. Efficiencies of the mechanical devices present in the installation, introduced into the model

Device	Type	Efficiency
Boiler	Overall efficiency of the boiler, that includes loss efficiency at the outlet and others	0,94
Turbine	Isentropic efficiency	0,99
	Mechanical efficiency	0,99
Pumps	Pump efficiency	0,88
	Mechanical efficiency	0,9
Generator	Electrical efficiency	0,99
	Mechanical efficiency	0,99

Table 15. Variables introduced into the model in IPSEpro

Device	Parameter	Value
Clayton boiler steam outlet	Temperature [°C]	250
	Pressure [bar]	25
	Mass flow [kg/s]	2,9931
Babcock boiler steam outlet	Temperature [°C]	250
	Pressure [bar]	15
	Mass flow [kg/s]	2,9931
LOOS Boiler steam outlet	Temperature [°C]	250
	Pressure [bar]	20
	Mass flow [kg/s]	2,9931
Exhaust fumes – all boilers	Temperature [°C]	120
	Pressure [bar]	1,1

7.1 Excess air coefficient and fuel-air ratio

In the excess air coefficient, the real amount of air (mass) in which the fuel is combusted, to the amount of air needed to the complete combustion of the fuel, calculated stoichiometrically. When using solid fuel as a carrier, usually the ratio is relatively high (more air needed than calculated). This is used to common inequalities between the current state of the machine or device and the ones that are presented in the manual. The industry's heat and power supply infrastructure are relatively old, which comes with the efficiency loses at various steps of the combustion process, the examples are the corrosion inside the chamber, irregular distribution of either fuel or air at the intake or small pipelines leakages. When liquid or gas fuel is used, usually the ratio is slightly above 1. When the coefficient λ is lower than 1, fuel mixture is called lean, and when above 1, we are respective rich mixture [81].

$$\lambda = \frac{L_r}{L_t}, \quad (1)$$

where:

λ – excess air coefficient

L_r – real amount of air in which the fuel is combusted

L_t – theoretical amount of air in which the fuel is combusted

The ratio is important coefficient regulating the amount of pollution that come as the exhaust from the combusted fuel. It is related to the fuel quality, and its chemical composition, the method and environment of the combustion, and the way that fuel and air are distributed into the combustion chamber. The industry is putting an effort to keep the excess air coefficient closer to 1, as the lower λ causes heat losses and non-complete burning, providing to higher pollution, and higher λ causes exhaust of the heat with exhaust fumes (heat losses), and breaking up CO2 into CO and unformed coal – soot [81].

On a similar manner works the air-fuel ratio, where to calculate the amount of air for the complete combustion of the fuel, the mass of air is divided by the mass of fuel, used to upkeep the process of powering the production with heat and electricity as a biproduct.

$$AFR = \frac{m_a}{m_f}, \quad (2)$$

where:

AFR – air-fuel ratio

ma – mass of air

m_f – mass of fuel

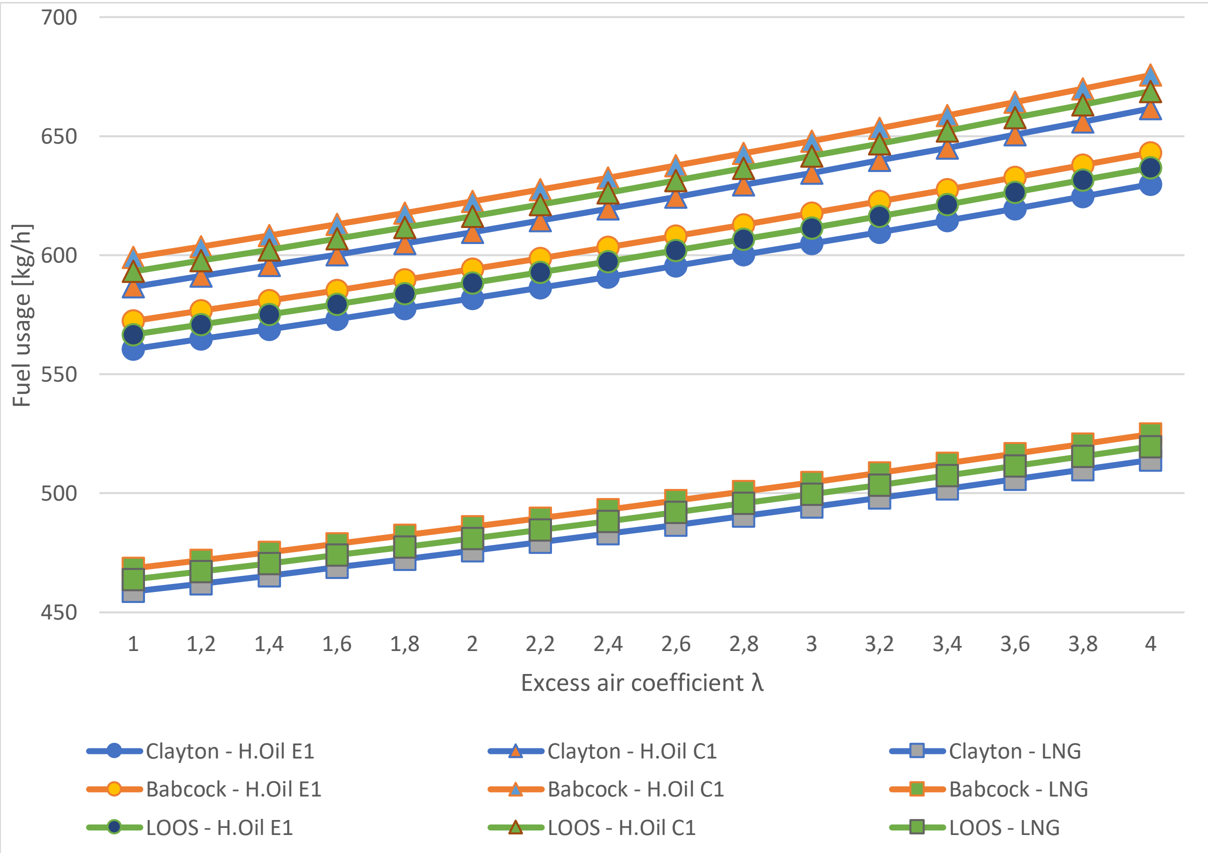
The simulation on the changing coefficient λ was conducted in the IPSEpro environment to analyse how the combinations of each boiler, with each type of fuel behave, to find the most optimal amount of the fuel necessary to be sourced at the Laktopol facility, to keep highest process efficiency possible, prevent surplus of the emission production and excessing cost on the fuel itself, by prevention of heat losses and uncomplete combustion. The air excess coefficient is relying not only on the process efficiency, but also on the environmental and economic aspects of the whole installation.

7.2 Simulation and analysis

The heat and power production simulation in IPSEpro software was conducted for all the combinations of fuel type with each boiler in relation to excess air coefficient ranging from 1,0 to 4,0. The program operates on the variables introduced into each element of the model, and calculates on the principle of heat and mass balances. Software environment does not allow for the introduction of coefficient λ with a value below 1. The data was gathered in the MS Excel software and proceeded with necessary calculation. Results are presented on Graph 1.

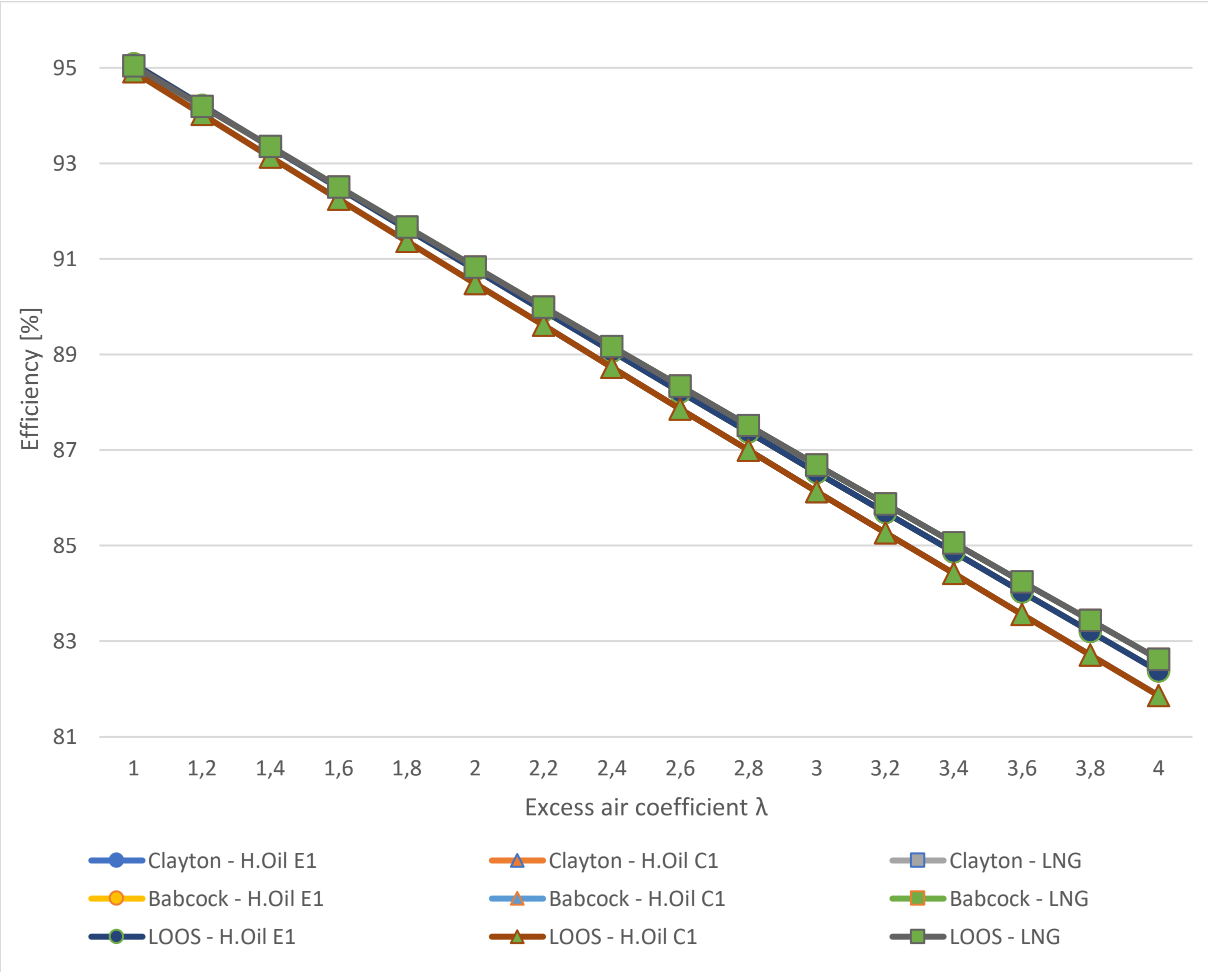
The amount of fuel to be used per hour in the Laktopol's facility to generate 2 MW of heat and 1,8 MW of electricity increases with the excess air coefficient in every combination, due to higher amount of sourced air. The reason is the amount of Oxygen and Nitrogen contained in the air, increasing the fuel's usage. As presented on the Graph 1, the amount of the fuel increases almost linearly, with an addition of around 20 kg/h of the carrier per increase of 1 in the coefficient λ.

When analysing dependencies based on the investigating fuel types, the most preferable one is LNG with the range of 460 – 515 kg/h to be sourced (depending on the boiler's type), then Heavy Oil type E1, with around 100 kg/h more carrier to be sourced, followed by Heavy Oil type C1 as the worst with ranges 580 - 675 kg/h (depending on the installed boiler). The best performance, when it comes to the fuel usage, belongs to the Clayton's boiler, then for the LOOS and Babcock respectively, and for fuels LNG, Heavy Oil E1, Heavy Oil C1 respectively. Basing on the conducted analysis and its outcome presented on the Graph 1, the lowest amount of fuel to be sourced is for the combination Clayton boiler – Natural Gas, which is the most preferable to be used in the future by the company. The worst performance belongs to the combination Babcock – Heavy Oil type C1.



Graph 1. Fuel usage per hour in Laktopol's facility depending on the excess air coefficient, for the different boiler-fuel combinations

In line with the increasement in the fuel's usage in all nine example comes the downfall of efficiency, as the more fuel needs to be combusted to produce the same amount of heat and electricity, due to higher excess air ratio. The difference in efficiency performance is noticeable when respecting the type of fuel, not which boiler was exploited as it is shown in the Graph 2, and it is connected with chemical composition and calorific value of the fuel. The efficiency's curves show linear diminishing tendency from around 95%, when λ =1 to 82-83% when λ = 4. The best available option to be used, when respecting the aspect of energy efficiency is the LNG, followed by little worse outcome for the Heavy Oil type E1, and with Heavy Oil type C1 as the worst option, which is not recommended to use.



Graph 2. Boiler's efficiency at the Laktopol's facility depending on the excess air coefficient for different boiler-fuel combinations

8. Environmental and economic comparison according to the used type of fuel and boiler's type

During decision process, which strategy should be picked to follow by Laktopol, after analysing the efficiency of the process and the amount of the fuel needed to power the facility, are two next indicators linked with the performance analysis. The first one is the environmental impact of the emissions produced during burning certain type of fuel, followed by economic analysis. The second part is strongly connected with the amount of pollution emitted, as it has a significant added value to the fuel prices and investment costs if needed. Greenhouse gases emissions does not only affect the environment, but also the profitability of the certain strategy, due to taxation and European Union Emission Trading System.

The simulation was conducted in IPSEpro software for all the combinations of fuel types with each boiler in relation to excess air coefficient ranging from 1,0 to 4,0. Software's environment does not allow for the introduction of coefficient λ with a value below 1. The data was later gathered in the MS Excel software and proceeded with necessary calculation. Results are presented in the subsections 7.1 – 7.2 depending on the different indicator, which was investigated.

8.1 Environmental analysis

To evaluate the best available option, that is the most environmentally friendly, the calculations were conducted, using Microsoft Office – Excel software. Basing on the coefficient assigned to every pollutant the sum of the emissions, was converted into CO_2 equivalent benchmark, and was the most important indicator when evaluating, which combination of type of boiler, and type of fuel should be used for further exploitation at the powdered milk production facility.

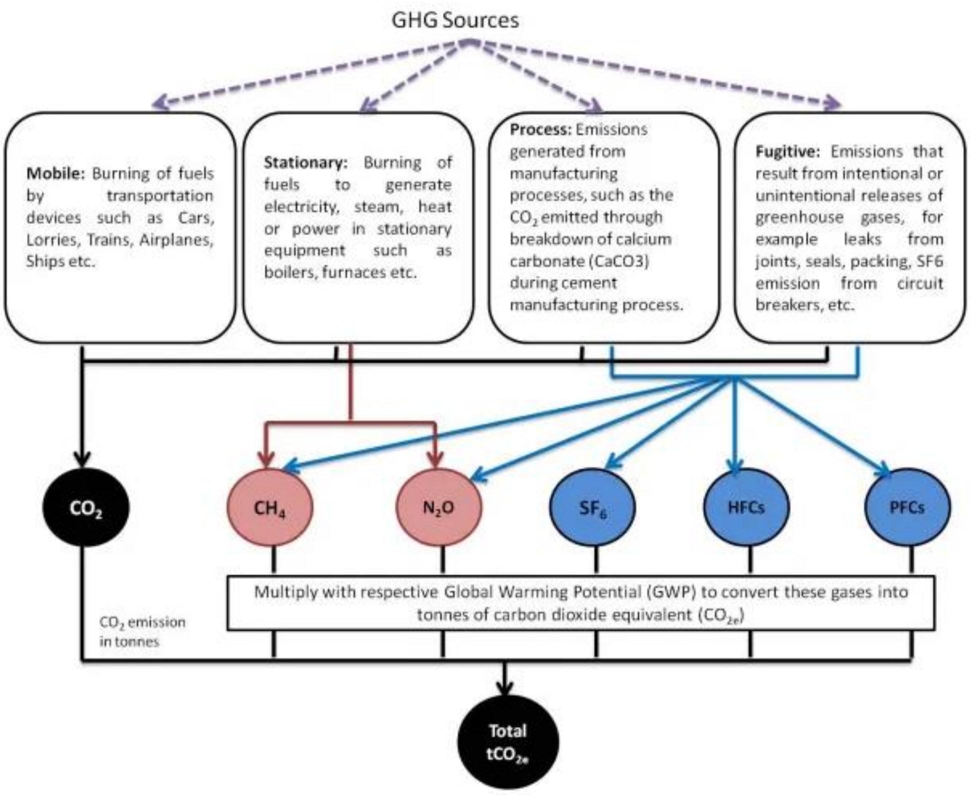


Figure 22. Simplified graphical explanation of the methodology of the emission amount calculation [82]

The calculation is based on the multiplication of the amount of certain greenhouse gas or another pollutant produced when burning respective type of carrier, by the Global Warming Potential values relative to CO_2 in 100-year time horizon developed by The Intergovernmental Panel on Climate Change (IPCC). The amendments to the values are introduced with Assessment Reports (AR), that are released on a few-year basis. The new one AR6 is currently under development, with the postpones due to COVID-19 pandemic, to be published in 2022.

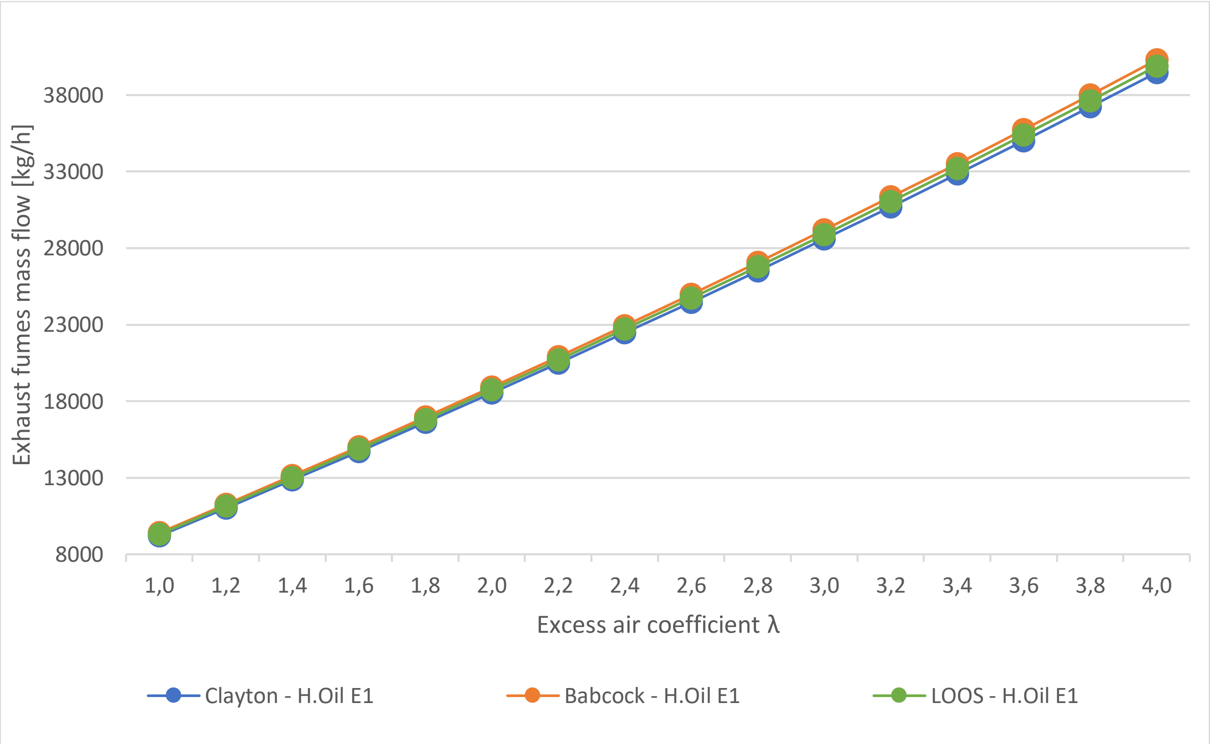
The calculations were run in line with the data introduced with the Fifth Assessment Report (AR5) by IPCC from 2014, presented in a table below.

Table 16. Global Warming Potential (GWP) values relative to CO_2 [83]

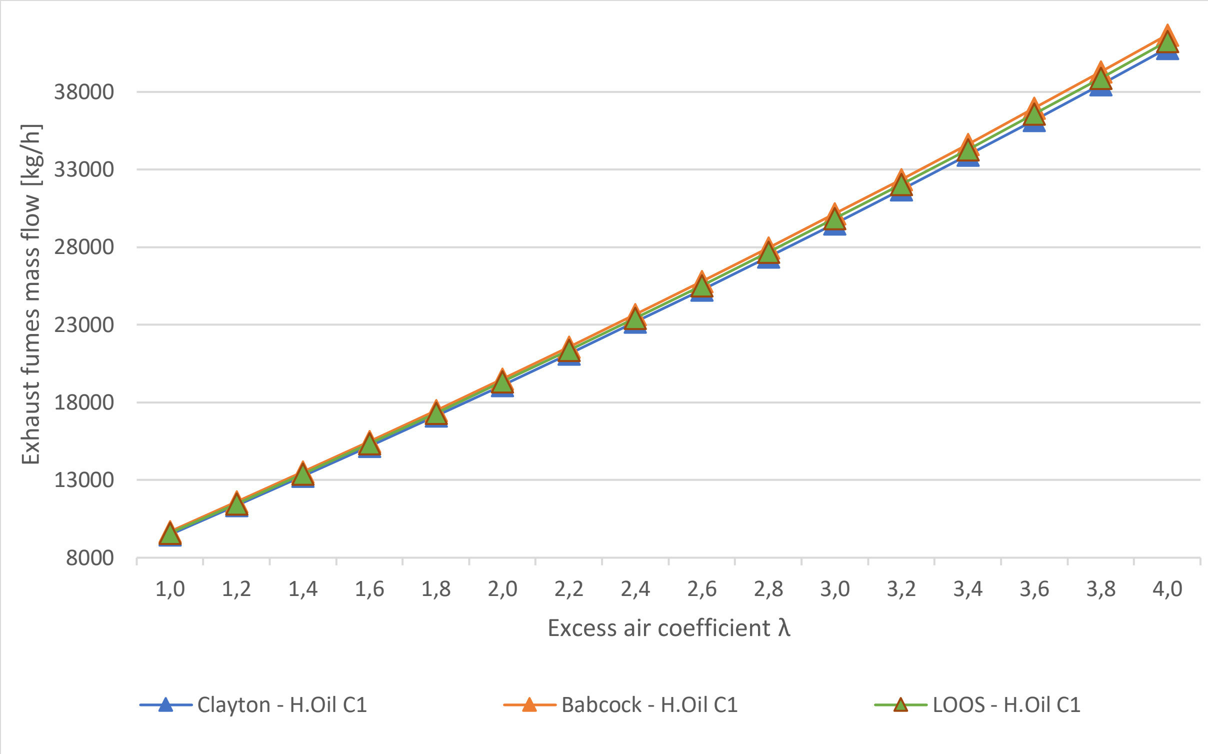
Common name	Chemical formula	GWP values for 100-year time horizon	
		Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)
Carbon dioxide	CO_2	1	1
Methane	CH_4	25	28
Nitrous oxide	N_2O	298	265
Sulphur hexafluoride	SF_6	22800	23500
Nitrogen trifluoride	NF_3	17200	16100

8.1.1 Exhaust fumes

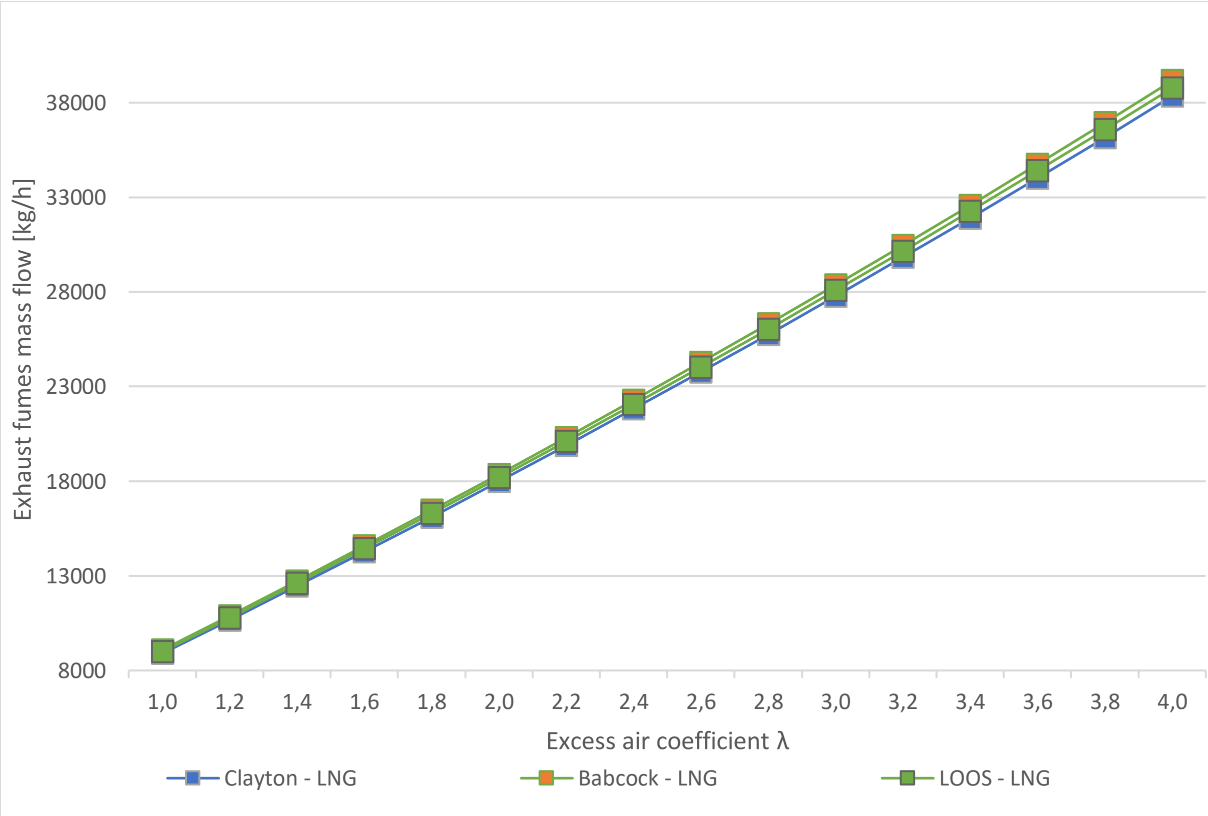
The amount of the exhaust fumes produced is strongly related with the excess air coefficient, as presented in the Graphs 3 - 5, with a rapid increase in kg/h related with higher value λ. Such vast expansion is mainly connected with the Oxygen and Nitrogen that is provided as an excess to the combustion chamber. The increasing part in these exhaust fumes, for all investigating combinations, are O_2, N_2 and H_2O formed when burning the fuel, with the greenhouse gases and pollutants level relatively stable, not such dependable on the coefficient λ.



Graph 3. Exhaust fumes mass flow in Laktopol's facility depending on the excess air coefficient for Heavy Oil E1 with different boiler combinations



Graph 4. Exhaust fumes mass flow in Laktopol's facility depending on the excess air coefficient for Heavy Oil C1 with different boiler combinations



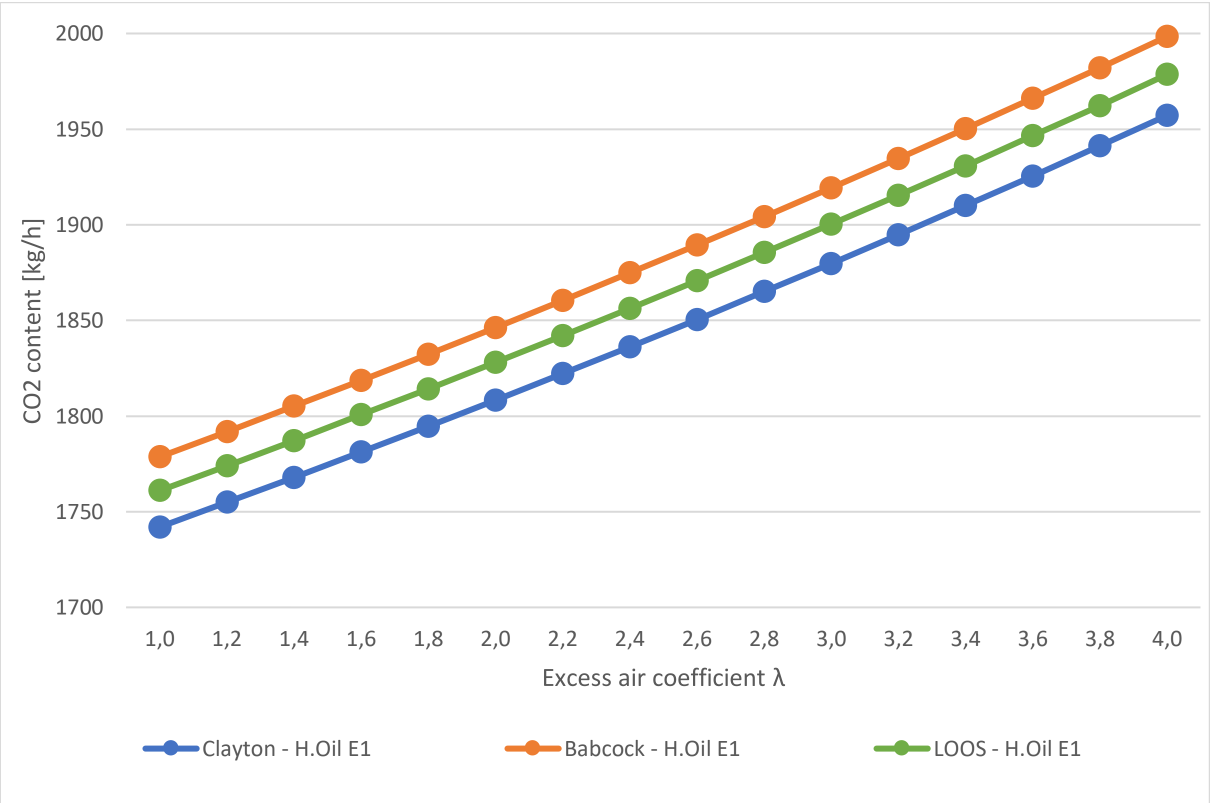
Graph 5. Exhaust fumes mass flow in Laktopol's facility depending on the excess air coefficient for Natural Gas with different boiler combinations

Similarly to the Performance Analysis presented in Chapter 6, the lowest level of production of exhaust gases is signed to the Clayton's boiler and for LNG fuel. Regarding all analysing examples, the amount of the exhaust fumes rises linearly, from the level of around 9 000 – 9 700 kg/h of fumes produced with λ = 1,0, to the 38 000 – 41 500 kg/h with λ = 4,0, depending on the certain fuel – boiler combination.

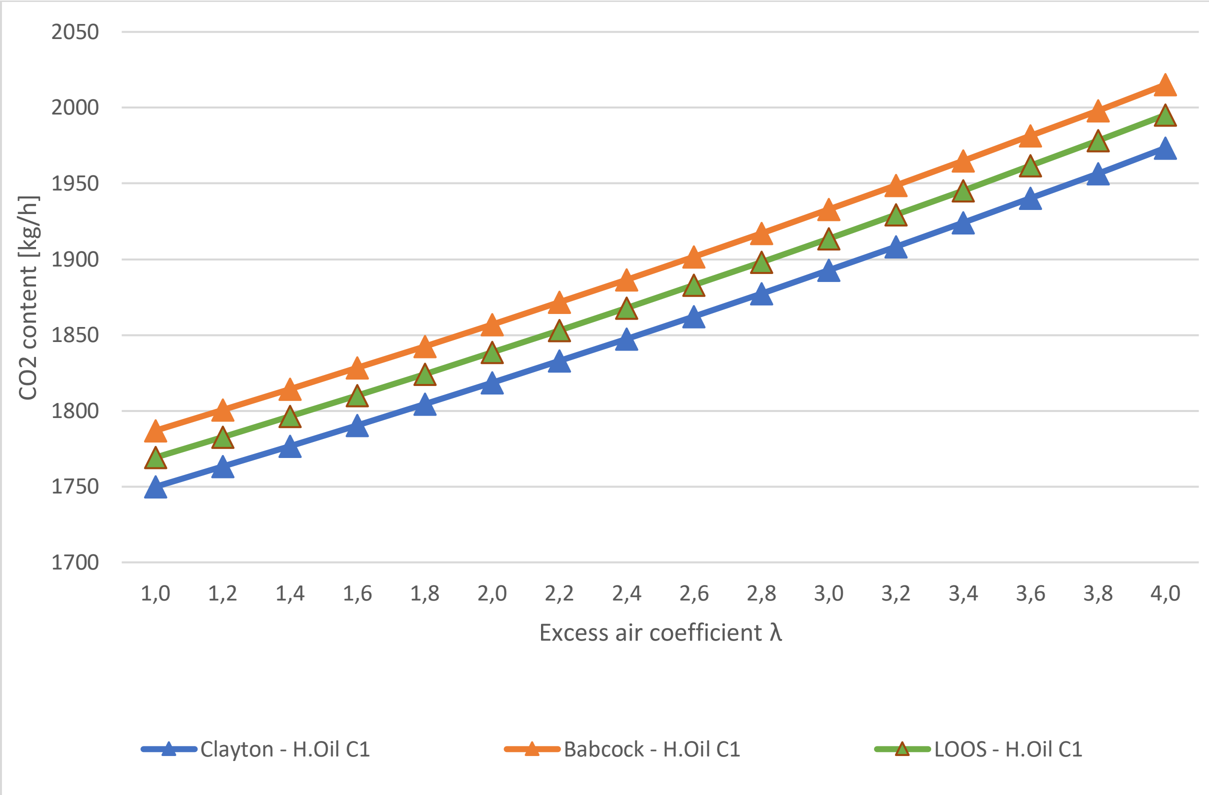
8.1.2 CO_{2e} production

The most important benchmark, when it comes to the environmental analysis is the amount of the carbon dioxide produced when combusting fossil fuels. The amount of this compound emitted into atmosphere, does not only affect the environment and global warming effect, but also the economy and profitability of the factory. The production of CO_2 is presented in the graphs 6 - 8 below and increases linearly in each investigated example. The increase in CO_2 production level, in line with rising excess air coefficient is related to the larger amount of fuel, needed to source the production (also in line with coefficient λ), that is presented in Chapter 6.

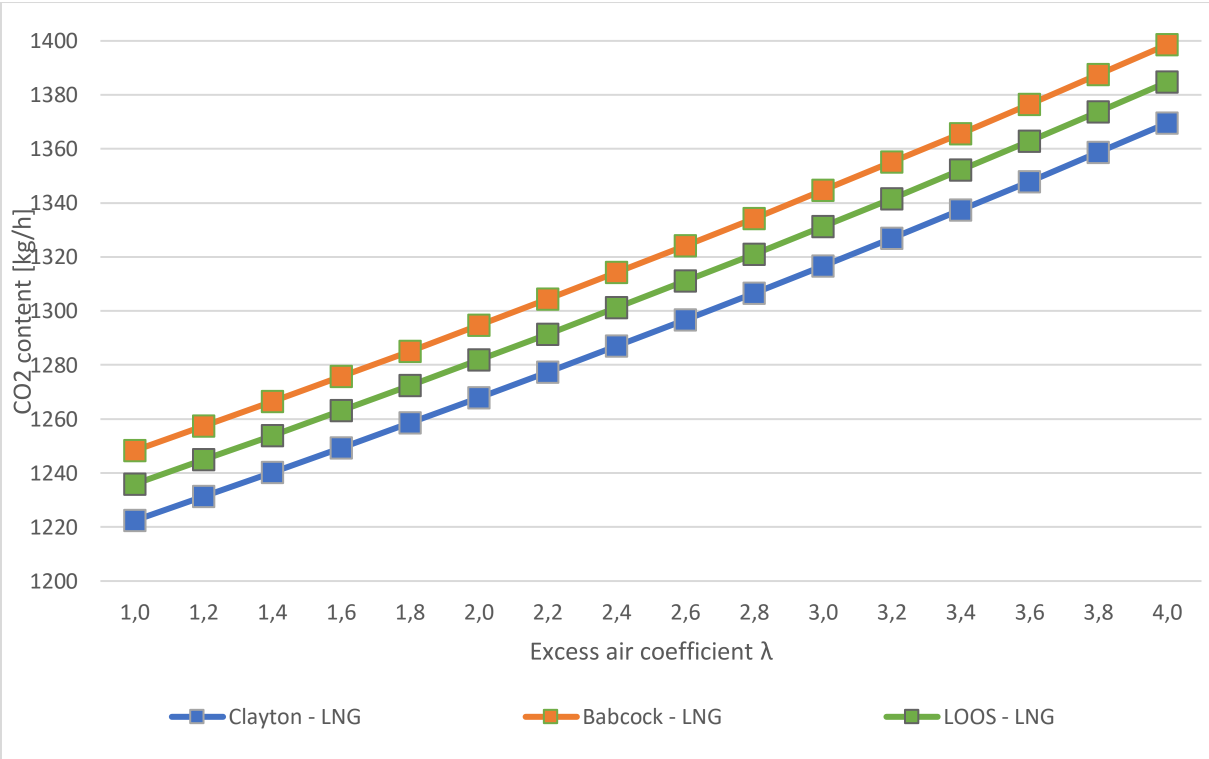
Per each respective example the number of carbon dioxide produced rises linearly in line with higher excess air coefficient, as the more fuel is sourced, and with that carbon share in the fuel-air mixture. Similarly to the analyses presented before, the most environmentally friendly solution is to use Clayton boiler, and the worst one – Babcock, desirably sourced with LNG (followed by Heavy Oil E1, and then Heavy Oil C1).



Graph 6. CO_2 content in exhaust fumes in Laktopol's facility depending on the excess air coefficient for Heavy Oil type E1 in different boilers combination



Graph 7. CO_2 content in exhaust fumes in Laktopol's facility depending on the excess air coefficient for Heavy Oil type C1 in different boilers combination

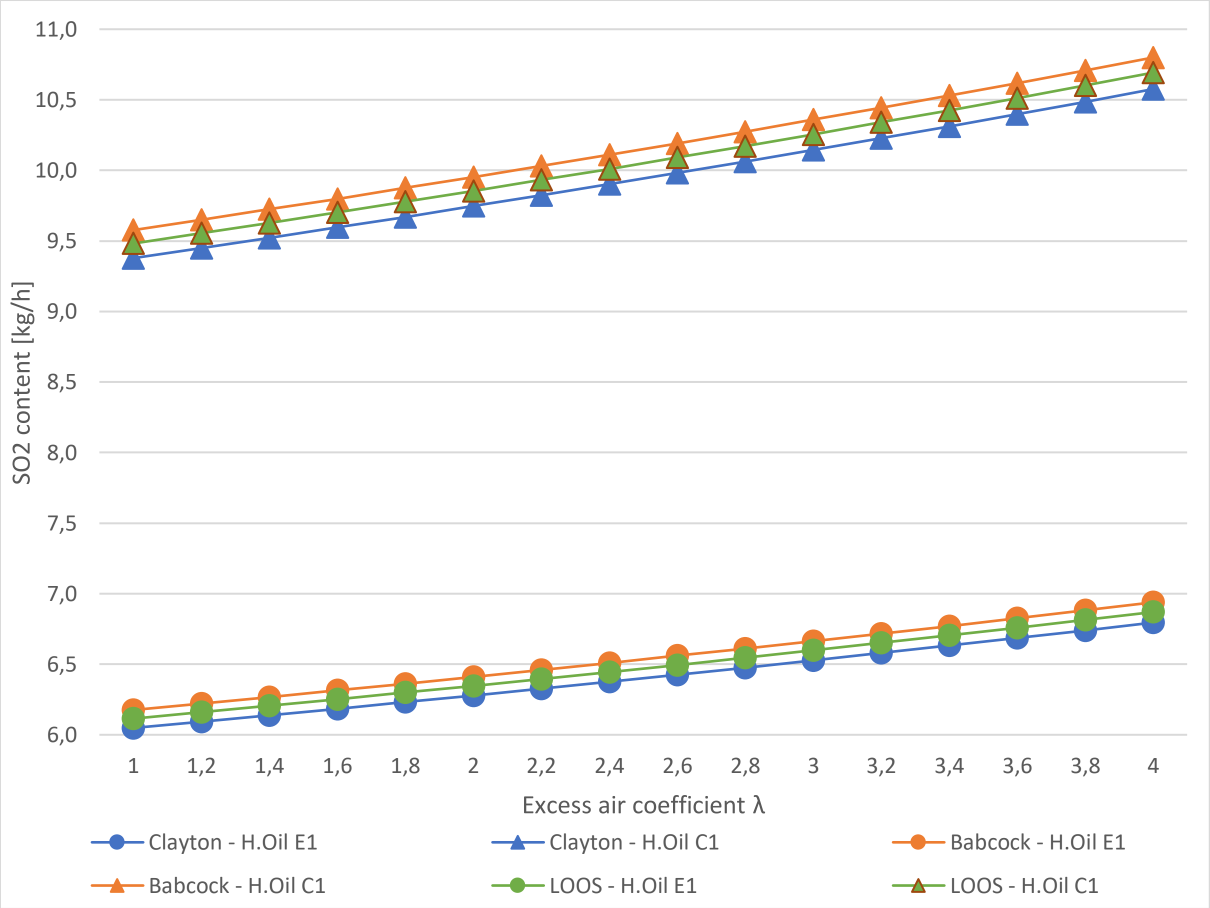


Graph 8. CO_2 content in exhaust fumes in Laktopol's facility depending on the excess air coefficient for LNG fuel in different boilers combination

8.1.3 SO_2 production

The production of Sulphur Dioxide, as presented in the Graph 9, is relatively stable, when introducing higher amount of air to the combustion chamber. The slight increasement is observed per each boiler-fuel combination, due to higher amount of the fuel needed to be sourced, when increasing coefficient λ (Chapter 6). Even with highly rising amount of the exhaust fumes, the level of sulphur dioxide remains relatively stable, due to the fact that the high portion of air is introduced, which does not contain any share of sulphur element, and in fuel itself it is below 1%.

The data presented on the Graph 9, excludes LNG fuel, as liquified natural gas produced by PGNiG, does not contain this element in its chemical structure.



Graph 9. SO_2 content in exhaust fumes in Laktopol's facility depending on the excess air coefficient for different boiler-fuel combinations

Similarly, to the previously presented outcomes, the lowest level in sulphur dioxide production is represented by the Clayton's boiler, but in respected situation, with Heavy Oil type E1. The noticeable is that Heavy Oil type E1 in all combinations with 3 boilers, has significantly lower lever of SO_2 production, than when using Heavy Oil type C1 as a carrier. It is related to the lower sulphur contamination present in the first fuel (difference of 0,3%). For Heavy Oil E1, the sulphur dioxide production varies from around 6 to 7 kg/h, and for the Heavy Oil C1 the production is around 3,5 kg/h higher per each example.

8.1.4 Environmental analysis - summary

For further analysis – economic - the values for the excess air coefficient λ = 1,2 were chosen, due to the satisfactory outcomes from the performance and environmental analyses. It is highly desirable to keep the excess air coefficient at the level of 1,2, due to significantly rising fuel demand and exhaust fumes amount with it. In addition, the high values of excess air coefficient are providing problems connected with unstable burner's flame. Furthermore, λ = 1 was excluded as the ratio of the oxygen to be used to the provided is exactly 1, and there is realistic possibility of incomplete burning of the fuel, relating to the efficiency and heat losses, and higher contamination of exhaust fumes, as the simulation usually does not fully mirror the reality lowering the ratio between fuel and air needed to operate most sufficiently (when λ = 1).

Similarly to the outcome from the Performance Analysis, the best results are performed by the combination Clayton - LNG, and the worst one by the Babcock-Heavy Oil type C1.

8.2 Economic analysis

The annual cost estimation and investment profitability were calculated using MS Excel software, by introduction of the average fuel prices, emission trading costs and the cost of investment when switching the fuel source to the gaseous one, as the most important benchmarks, decisioning on the final recommendation of the strategy. In the analysis the operation and maintenance cost are omitted as they are almost the same, when respecting each from the options, and does not influence the final recommendation on the short-term strategy to be followed.

Basing on the previous analyses, the fuel demand per year was chosen and then calculated for each boiler-fuel combination for the excess air coefficient λ = 1,2. The production is stable over a day, working 24h/7 days week, all year, with no plans to increase production capacity, and with that energy demand for the facility.

The analysis conducted below is for years 2020 – 2035, as it is assumed that it is the maximum year, where current technologies will reach their limits and it will be more profitable to switch for the one different technology from the options presented in Chapter 8.2 – "Long-term strategies".

Table 17. Annual demand for the fossil fuel at the Laktopol's factory, depending on the boiler-fuel combination calculated in Chapter 7

Number	Boiler - fuel combination	Unit	Value
1	Clayton - H. Oil E1	ton/year	4947,05
2	Clayton - H. Oil C1	ton/year	5178,53
3	Clayton - LNG	ton/year	4047,96
4	Babcock - H. Oil E1	ton/year	5051,12
5	Babcock - H. Oil C1	ton/year	5287,96
6	Babcock - LNG	ton/year	4133,74
7	LOOS - H. Oil E1	ton/year	5000,98
8	LOOS - H. Oil C1	ton/year	5235,61
9	LOOS - LNG	ton/year	4092,74

The analysis is based generally on the Operational Expenses due to the significant differences in the fuels costs that are used on daily basis in Laktopol's facility, as well with the additional costs that comes with the fossil fuel-based production exploitation, mainly European Union Emission Trading System. The rest of Operational Expenses and Capital Expenses are almost equal when comparing each boiler-fuel is relatively the same and does not influence the decision-making process as well the analysis itself, as for example logistics are almost the same for the deliveries of Heavy Oils E1 and C1 and LNG are operating on the same purpose and for similar distances. The only CAPEX expense is the investment into the regasification infrastructure for the LNG operation purpose and is included into the analysis split over the years of exploitation.

8.2.1 Fuel prices

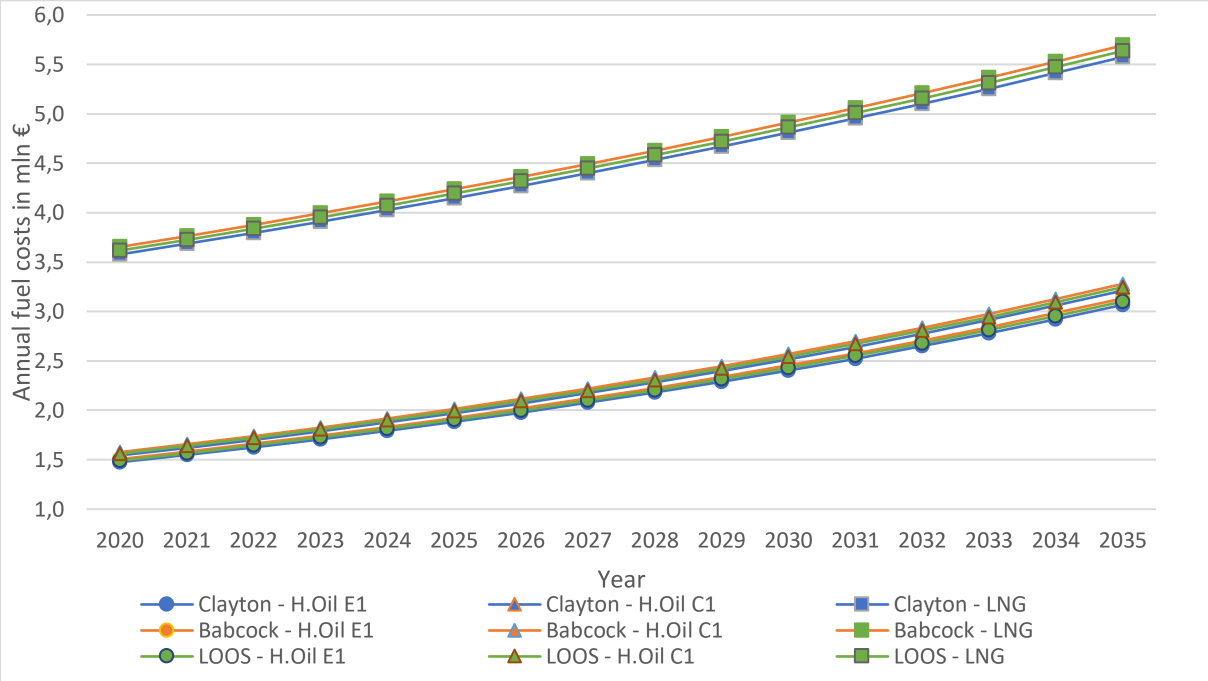
Despite facing the significant fluctuations in the oil and gas market in 2020 due to the COVID-19 pandemic, the prices are predicted to be back to their original pre-pandemic level by the end of the year 2020 and bring back growth tendency likewise at the beginning of the year 2020. The costs of buying a barrel of oil in late August 2020, were reaching around 75% of the price cap from January [84], earlier that year, and the demand came back to 90%, comparing pre-pandemic times. These indicators are reflecting in the multiple forecasts stating the relatively quick come back to the original fuel prices from the beginning of the year 2020 and increasing demand in line with prices.

For the analysis purposes, the 5% per annum increasement rate was taken in order with the forecasts for next few years for the oil market, and 3% for the gas market. The different rate of increasement is taken due to the fact that to the price itself is assigned approximate added value in form of inflation and additional taxation or payments for pollution produced in other form (utilization, maintenance, penalties), which are not covered by EU ETS, e.g. sulphur dioxide. It is difficult to estimate how the fossil fuels prices will behave over the next decades due to new technologies introduction, and significant fluctuations present in the oil&gas market (the most recent ones are price drops due to virus pandemic of SARS-CoV-2). The assumed increase rate covers also new additional costs of possible new laws and restrictions, with the variable costs that would come in line with them. Every new legislation in the whole fuel production, logistic chain to the combustion with final pollution emission. The 2% difference in price increasement rate indicates from the governments preferences toward cleaner solutions for the industry and energy sectors and secondly that the less pollution emitted lines with the significantly smaller costs of its utilisation or allowances and penalties.

Table 18. Oil and gas fuel prices for day 29/11/2020

Operator	Fuel type	Price
ORLEN	Heavy Oil type 1E	1342 PLN/ton [85]
ORLEN	Heavy Oil type 1C	1342 PLN/ton [85]
PGNiG	Natural gas	2,72 PLN/m^3 [86]

The costs of logistics are omitted due to very close range of all of them and due to the fact that fuel delivery for every kind of respected fuel needs to be conducted by road. Cost of supply slightly vary depending on location of refinery on the Polish roadmap (South and Middle Poland), nevertheless the difference is neglected and even thou it does not influence the final strategy recommendation. All deliveries are conducted using roads network and the Laktopol's facility is connected to the main Polish road network.



Graph 10. Average annual cost for the fuel for each boiler-fuel combination

Basing on the previously analysed data, combined with the data provided above, the annual variable cost on the fuel was calculated, including expected 5% oil price and 3% gas price increases each year. The exchange rate used in the analysis is 4,50 PLN to 1 EUR. The calculations were conducted in MS Excel software, with the outcome presented on the Graph 10.

Despite the outcome from the Performance and Environmental Analyses was always in favour of the LNG usage in combination with Clayton's boiler, the annual costs for the fuel are making the operation on this fossil fuel unprofitable in the matter of economics. The annual spending on the fuel that oscillates around the level of 2 million € gap per year is creating the barrier that is almost impossible to break, even with the smaller increasement rate in gas price, than in oil prices.

8.2.2 EU Emission Trading System

The price for the emissions produced is the second most important benchmark, when it comes to the strategy development, and working on the facility's profitability, when it comes to the heat and electricity production. Every year companies in Europe are being granted with a number of free allocation allowances to prevent monopolies' creation in multinational markets, but with ensuring that the companies are moving towards decreasing emissions production and technology progress. Continuous operation based on fossil fuels, without any improvement installation, is going to emit the same amount of emission as currently, with the rapidly rising costs for purchasing the allowances to produce them. With the constant, year-to-year increasement for the CO_2 price it is estimated that within decades the amount of money for the emission, will be close to the cost of the fuel itself, from which pollutants are produced, almost doubling its price. According to Thomson Reuters Agency's prepared scenarios, within 10 years emission, allowance for 1 ton of CO_2 equivalent produced price is going to increase to more than 50 €/t_{CO2e} by 2030 [87] (including inflation), which doubles the current price oscillating around 25 €/t_{CO2e} [88] through 2020. The McKinsey company developed intensive report regarding reaching decarbonization in Poland, with the forecasts claiming that at the wake of 2050, the CO_2 allowances are going to reach the price of 100 €/t_{CO2e} [91].

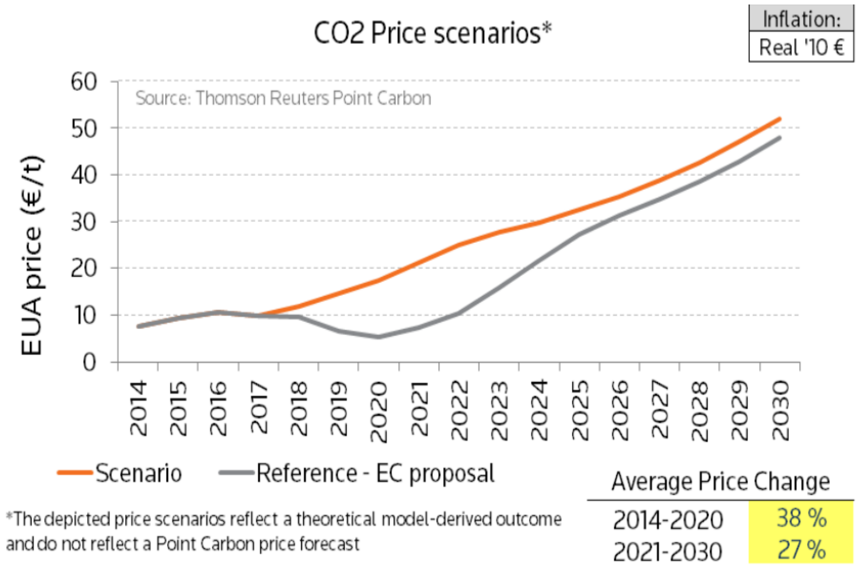
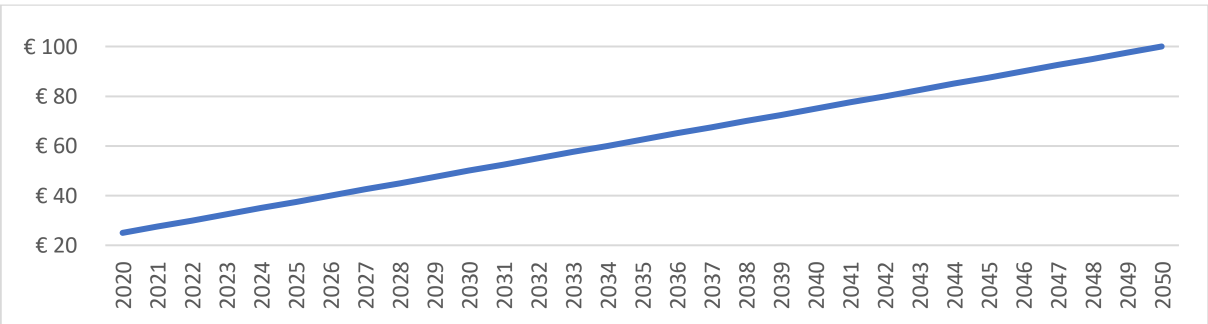


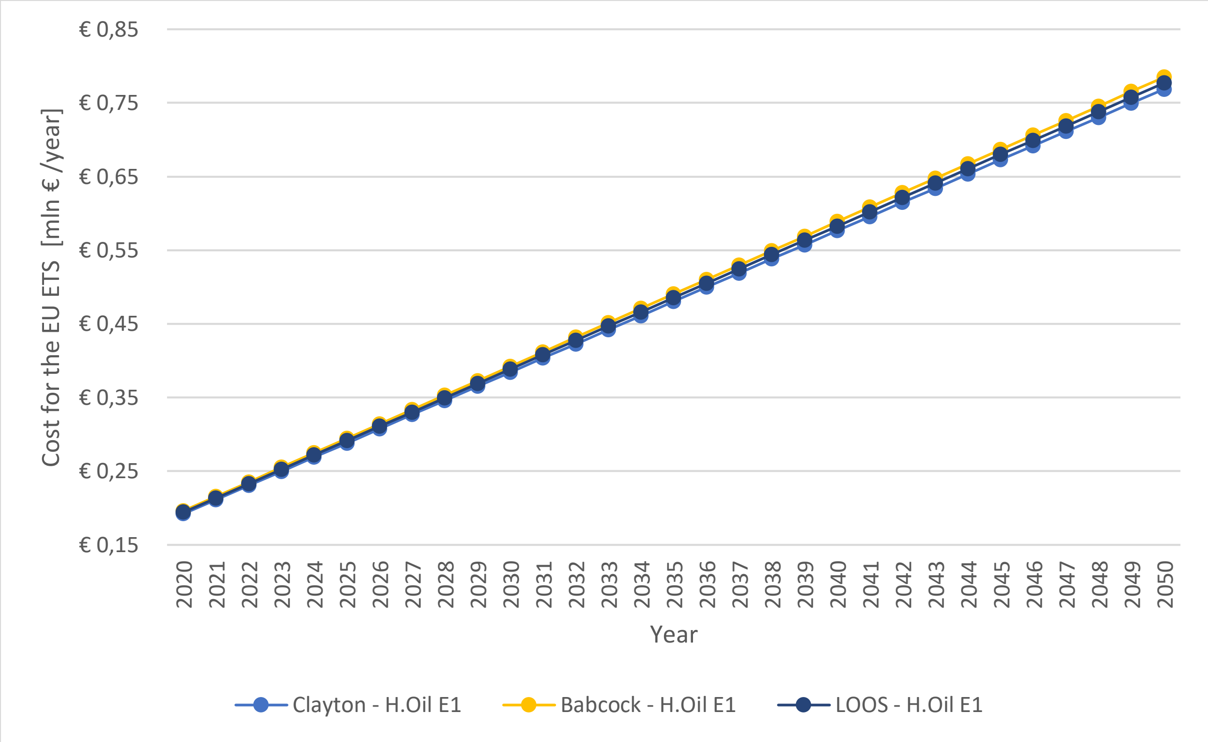
Fig 23. Carbon price forecast prepared by Thomson Reuters Agency [87]

The worst-case scenario is assumed that Laktopol is going to be granted with free allocation every year that covers only 50% of the emissions produced. The rest needs to be covered by the buy-out of the CO_2 emission allowance on the market. This assumption is based on the facts that Laktopol operates on the technology that is relatively old, and the continuity on operating using them, will go on at least for 10 years, and up to 15. Other indicators are that the primary carrier is heavy oil or natural gas and lack of improvements into the process cycle, on the machinery installed in late XX century, which is not so efficient nowadays. Due to these matters, it is utmost probable that free allowances limit is going to be significantly lowered by the government.

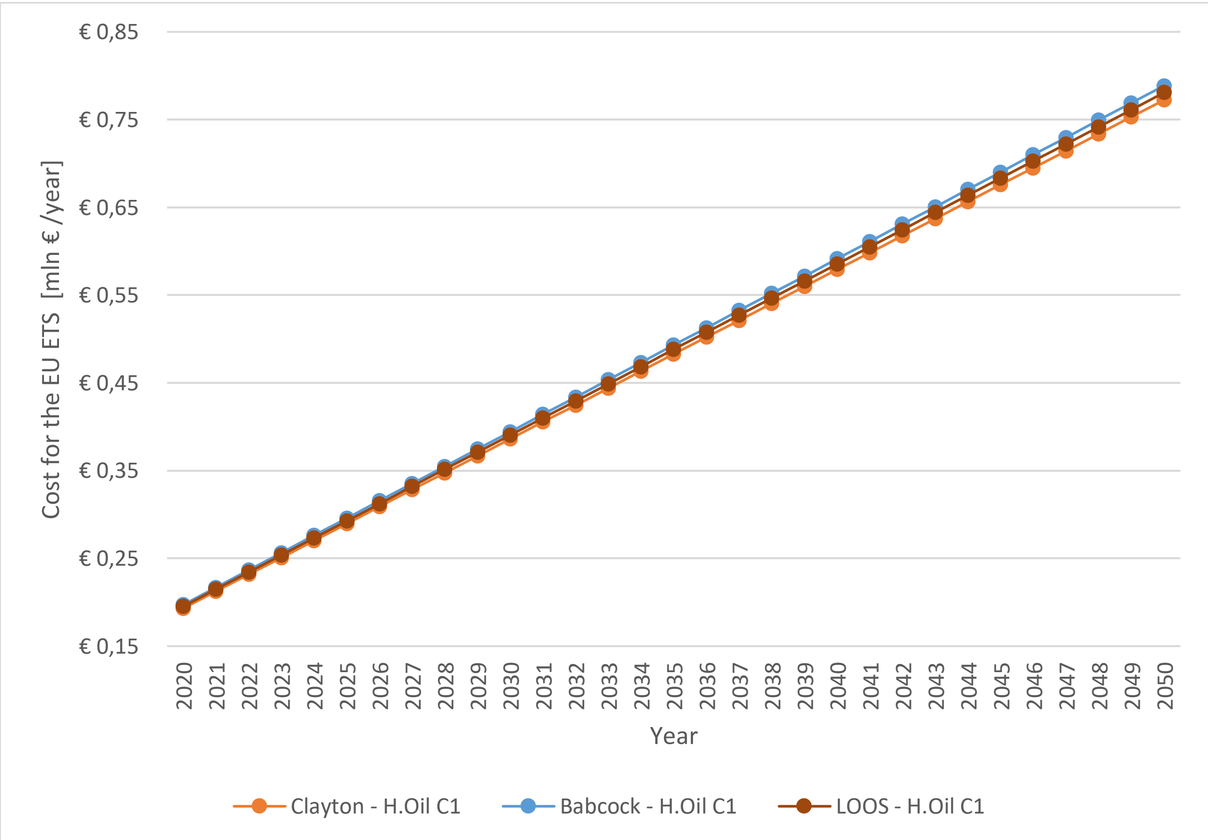
For the calculations purposes the linear growth in the carbon price is taken from 25 €/t_{CO2e} in 2020, up to 50 €/t_{CO2e}, followed by 100 €/t_{CO2e} in 2050, as presented on Graph 11. The Emission Trading System covers the sum of emission converted into CO_2 equivalent from carbon dioxide itself, nitrous oxides and perfluorocarbons (from aluminium production).



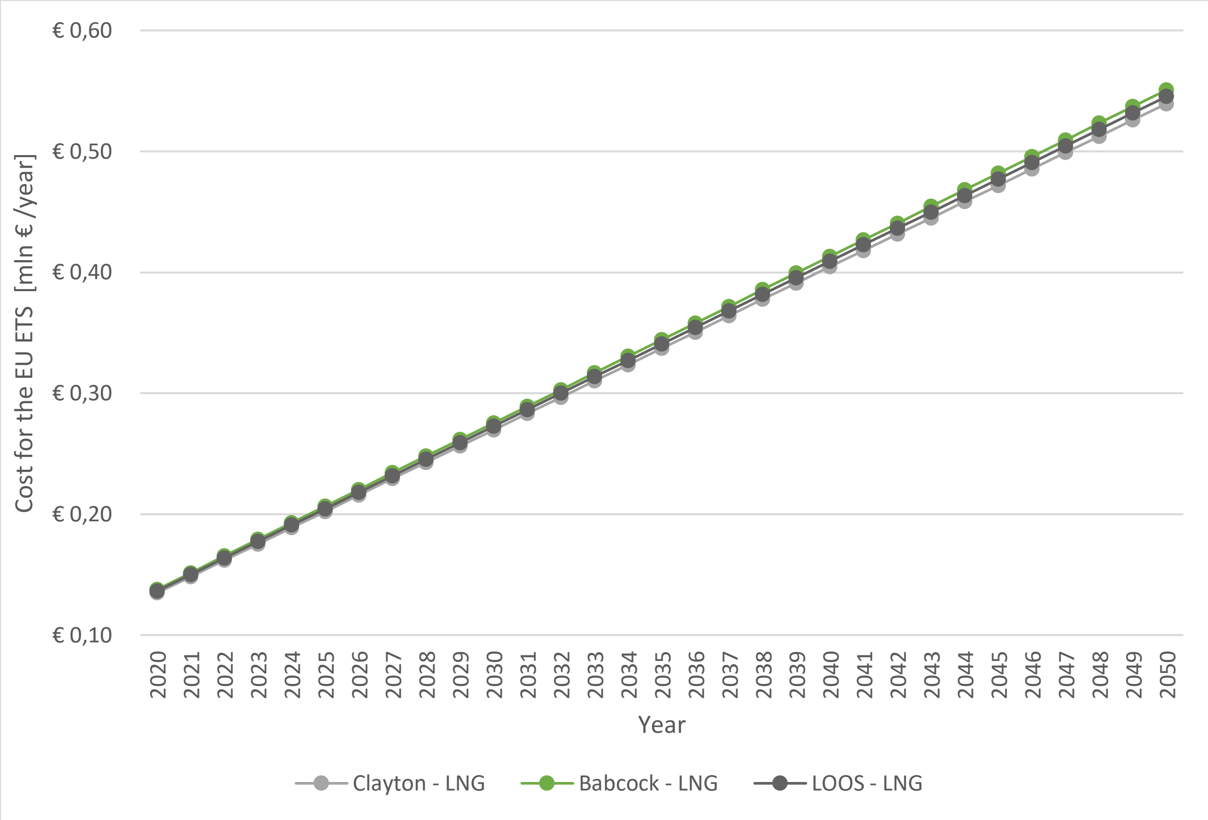
Graph 11. Estimated EU Emission Trading System prices for the $CO_{2\ equivalent}$ allowance, introduced to the model in Excel



Graph 12 The annual variable cost for the EU ETS for the emissions produced from Heavy Oil type E1 in different combinations with available boilers



Graph 13 The annual variable cost for the EU ETS for the emissions produced from Heavy Oil type C1 in different combinations with available boilers



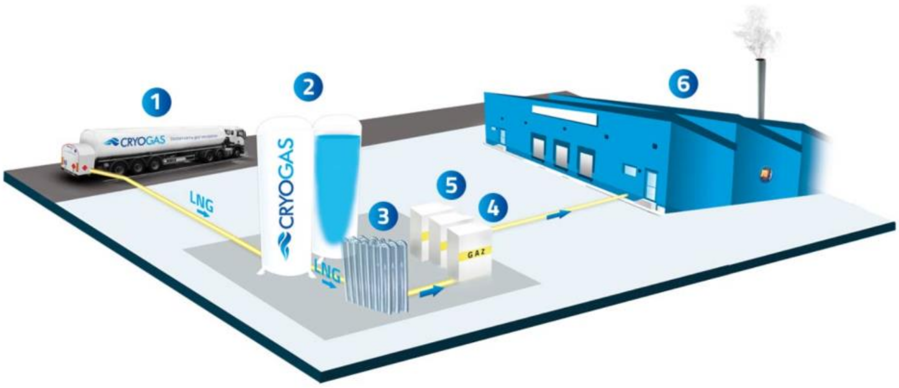
Graph 14 The annual variable cost for the EU ETS for the emissions produced from LNG in different combinations with available boilers

The data presented on the graphs 12 - 14, shows the annual variable cost for the buy-out of necessary emission allowances, having second half covered by the free allowances distributed by the Polish government. Despite of the significant difference between options sourced by LNG, and heavy oils, at the level of around 60 000 € in favour of LNG option for 2020 and around 120 000 € for year 2030, it is not enough to cover the gap in fuel price of ~2 million €, that is presented in the Chapter 7.2.1.

8.2.3 LNG regasification station

When analysing the third option – natural gas fuel – there is a need to include the installation of the additional storage for the liquified natural gas, and the station to convert LNG from liquid to gaseous state. The simplified installation scheme is presented on the picture below, where:

1. Cryogenic tank truck
2. Cryogenic tank
3. Evaporators
4. Reduction and control station
5. Odorization station
6. Boiler room



Pic 24. Simplified scheme of the LNG regasification station to be installed at company's facility [89]

It is assumed that the whole installation will cost around 3 000 000 PLN [90] (~ 666700 €) with a storage tank with volumetric capacity of 37 m^3, basing on the similar investment happened in Poland. The capacity of the tank is ideal for the one road delivery, as usual tracks for LNG could transport the LNG volume between 30 to 42 m^3, or between 12 000 kg to 18 000 kg at usual. In addition, the South-East region of Poland (Podlasie Voivodeship) is the region with the highest amount of LNG regasification stations in Poland. Due to this fact the logistics is not a problem, and technology is available at ease to be installed relatively quickly (a few months; various companies offer solutions for the companies like Laktopol in this region), as the regasification station for LNG does not require advanced technology and operation & maintenance resources.

It is assumed that technology would be exploited for at least 16 years (2020 – 2035), before the company would implement one of the solutions presented in the Chapter 8.2 "Long -term strategies", and for the analysis purposes the investment is equally divided equally between those 16 years as the added value in the form of fixed cost for the analysis purposes. Additional fixed cost for all the three options with LNG as a carrier, was added to each year in sum of 41 666,67 €.

9. Summary to the actual boiler's performance with the improvement recommendations.

The Laktopol company has a privilege to be a part of European Union Emission Trading System, which for additional OPEX cost allows them to postpone the investment in clean technologies. Comparing additional variable costs difference of around 60 000 € in 2020 and 120 000 € in 2030 (Heavy oil to LNG comparison) when continuing boiler's exploitation based on heavy oil, with around 2 000 000 € more each year when switching to natural gas, the gap is too immense to not stick to the current, already established method of powering the production.

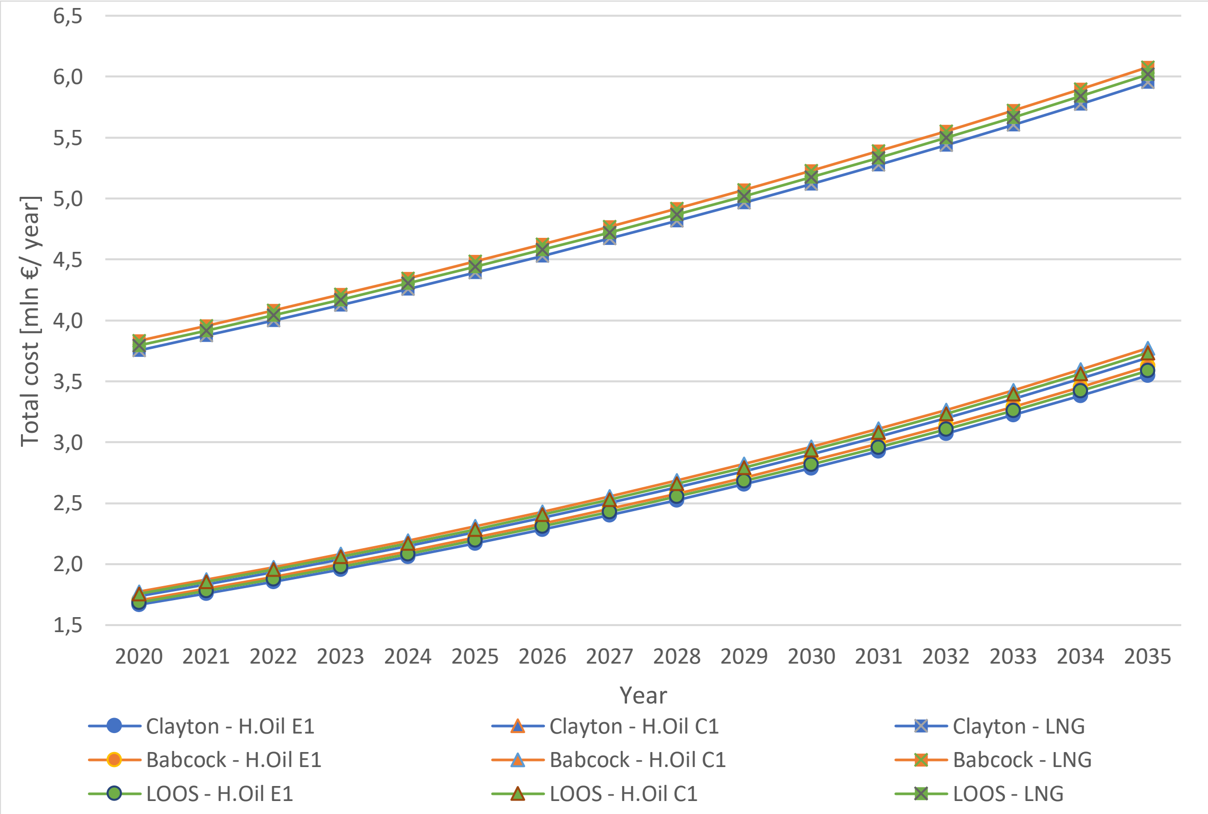
In the final analysis the costs of heat and electricity production was conducted in the form of sum of the variable and fixed costs, for each of the 9 investigation options, operating on data and conclusions developed in the Chapters 6 and 7. The Graph 15 shows the rising annual OPEX and CAPEX (LNG investment costs) costs for each year of the period 2020 – 2035. To evaluate the best available option, the calculations were conducted using Microsoft Office – Excel software.

$$Total\ cost = Variable\ costs + Fixed\ cost$$

Total cost – total annual spending on the heat and electricity production at Laktopol's facility site, annually

Variable cost – sum of the fuel cost per year and annual payment for the EU Emission Trading System

Fixed cost – applicable only for the option with LNG, the investment for the LNG regasification station and indispensable infrastructure, the total investment cost divided for per 16 years equally – assumed life cycle of the investment, and after this time, the need to invest into one of the Long-term Strategies (Chapter 8.2) will happen. The additional factor is the ending life cycle of the infrastructure that is currently installed at the production site (date of installation in years 1990 – 2000).



Graph 15. Total cost per year for the heat and energy production in years 2020 – 2035 for each boiler-fuel combination

When respecting the boiler types, similarly to the previously conducted analyses the Clayton's boiler shows the best efficiency and with it the lowest annual total cost. For all options the annual cost rises almost linearly due to the rising fossil fuel prices and also rising prices for carbon allowances, which are expected to upkeep continuous growth over the next decades, as one of the main factors to reach net zero-emission growth in 2050. Operation on heavy oil shows drastically lower total cost, than sourcing the facility with LNG, and the best from the analysed combinations is the Clayton – Heavy Oil E1 combo. The Heavy Oil type E1 is preferable over the Heavy Oil type C1, due to its higher Carbon content, and smaller share of elements that creates pollution, like Sulphur. This difference leads to the smaller costs for fuel (higher C content) and smaller costs for the EU ETS (less pollutants created) when comparing both heavy oils.

9.1 Short-term strategy

As shown in the Graph 15 the higher cost for EU ETS does not compensate the investment into a cleaner and more efficient option - LNG, as the fuel price difference between LNG and heavy oil (both types) creates the barrier that, from economical point of view, the company will not break. Through the whole period the Heavy Oil type E1, combined with the steam generator produced by Clayton is the most preferable option to continue operation over next years. Even the fact that the process is more efficient and more environmentally friendly when using LNG, the annual price gap is making it completely inefficient and unprofitable from economical point of view. Not in favour of the more environmentally option is also the fact that the installation at Laktopol's production site is relatively old, and even when choosing the path to follow with investment in LNG, at least the boiler will need to be replaced before 2035. Even choosing the steam generator that would be much more efficient, that the current one, the LNG pathways are considered as unprofitable.

The company is up to not consider using the Heavy Oil type C1 and also Babcock boiler in all its combinations, due to their worst performances in almost every analysis that was conducted (performance, environment, economy). It is recommended to utilize boiler or to keep it as a backup source of heat and power generation in case of emergency. In addition, the LOOS boiler signed with the second-best performance and should be keep installed at the facility, ready to work in case of any emergency. The unquestionable asset of flame and smoke tube boilers is their quick start-up time.

The company should keep operate on the current technology, with the fuel deliveries of the ORLEN's Heavy Oil type E1 over the next decade and start developing investments towards renewable energy sources or picking other strategy from the ones presented in the chapter 8.2 "Long-term strategies", to finally implement those in years 2030+ or even earlier. The installation is already fully maintained, with no improvements needed to be implemented. Even if the Clayton boiler's operational capabilities will end before its assumed life cycle, the back-up in form of LOOS boiler, or even Babcock can sufficiently power the facility for a few years, before the new investment (strategy) is implemented.

9.2 Long-term strategies

Solutions presented in the Chapters before, are only short-term solutions, that require relatively low investment costs. The Paris Agreement, European Green Deal and decarbonization plan by 2050 are forcing companies and industries to completely abandon power and heat generation from or to balance emissions produced with installations like Carbon Capture and Storage or implementation of renewable energy surplus. The threat of significantly higher prices for carbon emission allowance (even 100€/t $_{CO2e)}$ within next decade is real and almost sure, that after 2030 operating purely on combustible fuels will become unprofitable. Assuming that the World will rely on the current technologies, that are fully developed, there are a few possible strategies that Laktopol might pick and follow in a longer plan to continue profitable operation. Additionally, in favour of the variants presented below, speaks the fact, that current heat sourcing machineries that are present in Laktopol's factory, are relatively old, and it is assumed that within next few decades they will not be able to operate at all, or with satisfactory efficiency of the whole process. Those facts force the need to develop long term plans, that would assume the changes that the Polish energy market is and will be overcoming, by new policies, laws and technologies implementation.

- **Process electrification:**

Despite rising electricity prices, connected with continuing increase in the Levelized Cost of Energy Worldwide (energy production from renewables is more expensive, comparing with fossil fuels, due to its high investment costs) the one of the solutions is to convert the whole process to be fully powered by the energy provided by National Grid. It is assumed that in years 2030 – 40, the more and more investments are to take place in Poland, with focus on the off-shore and on-shore wind energies. It is estimated that in years 2030 -2050 the share of wind energy in Polish total energy production, will rise from around 2% in 2030 to 73% in 2050 (more than 50% in 2040) [91]. The industry is the sector that is going to be influenced by the electrification the most, comparing with others. Majority of the pollution currently produced by this sector is caused by heavy industry, nevertheless food&drinks branch is also responsible for the significant number of emissions that need to be decreased to the net-zero level by 2050. The electrification of the processes that can be substituted with electricity from fossil fuels, lies also in line with significant energy efficiency boost, and the need to invest in new technologies available or to be available on the market, to make the production as efficient and sustainable as possible. Following the path of electrification of the powdered milk production process is going to generate savings from lack of logistics and operation and maintenance costs and also creates opportunity in diminishing the possibility of failure or error, which are usually strongly connected when continuity of work on the old technologies occurs. In addition, devices based on new technologies, are less energy intense, which generates additional savings from variable costs.

- **Installation of renewable energy sources:**

With a rapidly decreasing prices for renewable energy sources, it would be assumed that picking up this solution is currently the best available. Regrettably, this strategy has major bottlenecks that are creating the need of reliability on the National Grid or other power source, with a threat of energy shortages. The main drawback that the investor should take under consideration are the lowest average temperatures and the highest number of snow days in Poland. The need of energy storage implementation is inevitable and the most accessible is in the form of batteries. The two most commercialized methods of producing clean energy are photovoltaics and wind energies, highly dependable on the weather conditions (sunny days, and windy days with a proper wind velocity). Despite of high costs of batteries itself with sufficient capacity, there is a need to dedicate additional storage area within the company's terrain - preferably indoors, as North-Eastern Poland is at risk of low temperatures and changing climate over the year. In addition, depending on the number of cycles that would be loaded upon the unit, there is a vision of decreasing efficiency of it, with increasing risk of failure within the years. The weather that occurs in region of Suwałki, also creates additional major drawbacks, that are causing the solar investment much less profitable. Due to the biggest number of rainy and snowy days across the year and lowest average temperature in Poland in the area of Laktopol's production site, photovoltaics is not an operative option. Often cloud cover and low temperatures are major issue, but additional issue occurs in form of thick snow cover during winter and often storms mixed with high forestation of the region. These make the photovoltaics installation more vulnerable on being damaged by the external factors connected with frequently changing weather conditions, than in the other parts of the country.

The method that even in a near future might be a solution for production sites like Laktopol is liquid air battery, where the surplus of energy produced by photovoltaics or wind may be stored in the form of compressed air. But the technology is still under development process and requires addition of the parcel with a significant area nearby Laktopol production site (additional fixed costs in the form of rent, or parcel's buyout), investment in the battery site's building and additional operation and maintenance costs.

- **Operation on clean combustible sources**

Hydrogen and biofuels are the one that are predicted to be used in a future, as their environmental impact is limited and balanced, when considering reaching net-zero emission target till 2050. Both carriers do not require additional infrastructure, except decompression station for hydrogen. Main advantage is that hydrogen and biofuel can be delivered by using existing roads, having in mind that North-East Poland is relatively worse connected than the rest of the country, when considering all means of transportation. It is possible that hydrogen production for the facility's purposes will be much more abundant and decentralized, that H_2 production by water electrolysis, will be domestic. The technology of water electrolysis is well known nowadays, but the energy input is highly higher than the energy output from the hydrogen produced, and electricity that the process requires usually comes from pollutive carriers, especially in Poland where ~80% of it, is produced from coal. One's solution is to combine the hydrogen production site with renewable energy sources to produce green hydrogen, but it is going to highly increase costs of the investment.

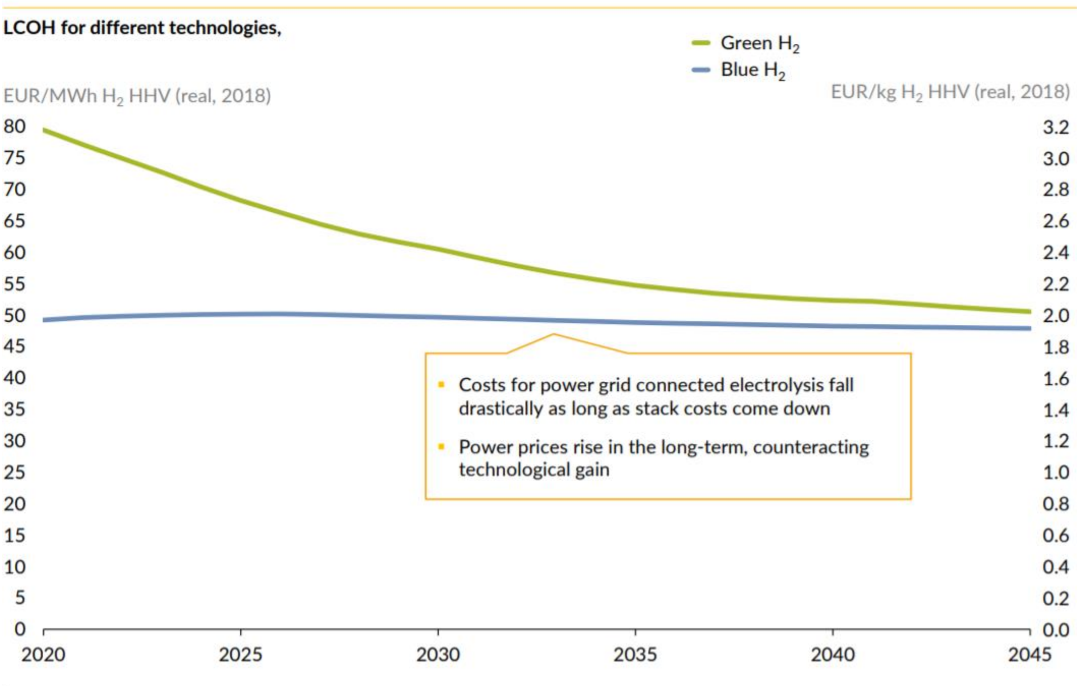


Fig 25. Levelized Cost of Hydrogen using different technologies – forecast by Aurora Energy Research [92]

According to the Aurora Energy Research, price for the green hydrogen is going to be close to intersect with the blue hydrogen price when considered production costs (H_2 produced from Steam Methane Reforming, with the control and utilization of CO_2 produced during the SMR process) in around 2040. Current price for the cheapest blue hydrogen is 49 EUR/MWh_{H2} and 80 EUR/MWh_{H2} for cheapest green hydrogen [92], as respecting Levelized Cost of Hydrogen production. The cost barrier prevents the investor from switching the carrier. Within next decades the break point will be cross-section between the gas prices plus carbon price, which is constantly rising, with the LCOH, which shows lowering tendency over the years.

Respecting the solution based on the liquid biofuels the company's main asset is that the current installation allows the investor relatively quick adaptation, when implementing this kind of solution. The blends with certain percentage of the bio-compounds (e.g., fuel type B 20 – FAME 20% + and diesel 80%) are granting the possibility to lowering the emission's production level step by step over the years, which is bound to the opportunity of lowering the cost of buying out the carbon allowances over the years, connected with the increasing abundancy of the biofuels. Over the next decades the supply of bio-sources might not face the demand, as the growth of energy crops takes time and their area of agricultural cultivation is limited the existing land, bearing in mind that cities are growing and expending their areas and forestry cultivation is also growing as the preventions for our ecosystem. As the Laktopol facility energy capacity for the production purposes is oscillating around 2 MW, which is not so significant comparing with the large industry. The small needs of the powdered milk production site are creating the convenience to use biofuels, as the supply shortage risk should be comparably limited, and even if the biofuel's deficit would occur, it can be easily substituted with conventional fossil fuels. Currently Poland is one of the top countries in Europe, respecting biofuels and biocomponents production, with the forecast that this trend will remain at least stable, which is an advantage for the company located in this country, as the fuel prices should be lower, when comparing with other European countries.

- **Implementation of Carbon Capture, Utilization and Storage technology**

Basing on the current market prices and also a scale of implementation of this technology nowadays it is strongly advised against following this strategy. At the middle of year 2020, only 2 production sites worldwide are gathered in one place together with carbon capture and storage facilities and decades will follow until it going to be developed on bigger scale, despite the need to capture and reuse the pollution produced, especially from heavy industry sector and from power and heat plants worldwide. Building the whole infrastructure for CCUS nearby Suwałki for the purposes of only one, and relatively small factory is completely not feasible and is estimated to still be over the next decades.

The alternative for this solution might be initiative in the kind of Northern Lights in Norway, where various companies are going to transport CO_2 they produced in ships for the underwater caverns at the coast of Bergen, where the whole facility is currently under construction as the cooperation of various companies like Shell, Total or Equinor. Emissions are going to be shipped from a number of countries in Europe, not being dedicated only for Norway. There is a chance that similar initiatives will be implemented on smaller scales and more decentralized, where number of investors will bound themselves to store the pollutions in one place, making the solution more commercialized, more abundant and cost effective. The last is the strongest barrier to overcome in the matter of Carbon Capture, Utilization and Storage. Even if the logistic cost of CO_2 transportation to the storage site will be high this is the opportunity window to bear in mind within next years, as this solution still might be much more profitable than paying for the allowances in the European Union Emission Trading System.

9.3 Final recommendations

The three final scenarios were developed and presented below, as the recommendation for the facility, showing the possible results of following them in the future.

- **Following the current operation method**

The life cycle of the machinery currently installed at the facility is estimated to last for next 10-16 years, as so it is profitable to stick to it. In addition the logistic supply chain of the Heavy Oil deliveries is already established in cooperation with ORLEN company, and this option shows the best economic output when it comes to the annual cost for the fuel only, and better results in favour of LNG option (less fuel needed, less greenhouse gases and pollutants produced, smaller cost for emission allowances EU ETS) do not compensate the immense price gap created by difference between LNG – Heavy Oil price, and investment costs for the LNG regasification station and infrastructure.

Following this pathway will create the increase in the EU ETS costs, as well in the fuel price, due to the vast changing market situation, as well because of the new law, directives and taxation procedures introducing day-by-day to tackle the problem of Global Warming, air pollution and quality and people's life quality. The same forecast is observed in each analysed option, as it the governmental restrictions cover the whole range of fossil fuels.

Laktopol's management should start investing and planning on the renewable energy sources implementation at the facility, with the recommendation to slow investment in solar and wind, that could support heat and electricity production year-by-year increasing its share, finally at the end of boiler's exploitation switch to full process electrification in years 2030 – 2035, as the easiest and most profitable strategy to be implemented. The most important indicator, deciding on the proposed strategy are the total costs when sticking to heavy oil option, and constantly diminishing prices for the solar and wind implementation, that are expected to continue. In a few years it is worth to look again into Hydrogen option, as the situation on the market is developing and rapidly changing. Unfortunately, nowadays the H_2 infrastructure (especially in the matter of Poland) is underdeveloped and price for the fuel are relatively high, with a number of different forecasts for the future. It is certain that Hydrogen-based solutions will play a significant role in the future's energy system, but it is yet not established how big the role will be, and for what costs.

- **LNG Investment**

Locating resources in the LNG option is the least favourable option, due to its high exploitation cost, and also the fact that certain devices in the installation (especially boilers) will need to be replaced in relatively close future. Liquified Natural Gas is still a fossil fuel, which share in global energy mix is set to be diminished over time, and it is almost certain that over next 10-20 years Laktopol will be obligated to change its energy strategy towards non-pollutive methods like renewables. Regardless having a more positive impact on the boiler's exploitation (best performance in Performance Analysis) and on the environment (Environmental Analysis), the political and economic aspects in the bigger spectrum, leading to the conclusion that this option is completely unprofitable and undesired – having in mind that this strategy is not influencing only next 10 years of Laktopol's operation, but more than 30 years.

- **Instant renewable scenario**

The instant investment in the one of the options presented in the Chapter 8.2 is not advisable due to its current relatively high investment costs and the situation that some technologies are currently under development and it is advisable to postpone such an investment on further plan. When implementing the change in a next few year (2021

– 2025) it is the most reasonable to invest into mixed solar and wind energies as the most abundant ones, supported with the biofuels, that are combusted in the currently installed heat and power generation infrastructure. Apart from the drawbacks in form of changing weather conditions renewable energy sources are the cheapest, most research developed and almost instant to be implement, when comparing to other technologies. The solar power plant to cover energy demand of 2 MW (heat only) will cost around $ 15 million, assuming current costs of cheap PV farm ($1,1 million for 1 MW from solar system [93], and system efficiency of around 14% [94]), with a life cycle of max. 25 years of effective work. The instant investment cost is considered as too high, especially when the solar prices are rapidly decreasing over the years and it is advisable to invest in PV to possess some share of renewable in the fossil fuel-based energy mix for the Laktopol's facility, increasing its share, step-by-step over the next years.

10. Conclusions

The change toward clean energy sources and decarbonisation of the World's economies is extremely difficult challenge to overcome, especially from the perspective of the overlook of the current technology that is available on the market and economic reasons. The change toward more sustainable future is leaded by the Organisation for Economic Co-operation and Development member countries, which are significantly more developed than non-OECD ones. On the contrary the non-OECD countries are still in development phase, and they are counted as almost 2/3 of the World's population. The change toward economic development causes increases in energy consumption, and it is forecasted that until 2050 the benchmark will rise over 50% when comparing with the current state, and this change is going to be led by mentioned emerging communities. The European Union put a requirement to develop the *2050 long-term strategy* to reach the net zero-emission target for the European Union Member States including Poland.

As it is presented in the performed analysis, the investments in cleaner energy production installation are not economically feasible, where only one company is generating 2 million € losses, located in additional costs when replacing highly pollutive energy carrier (Heavy Oil) with much cleaner fossil fuel, which is LNG. In addition, in investigated facility there was no need for the installation replacement, which highly limited investment costs as a plus. Without the significant support from the level of Polish government and European Union it creates the barrier for the entrepreneurs almost impossible to overcome, especially in the sector of Polish industry. Each branch of the industry in Poland is relying mostly on fossil fuels, as the infrastructure is relatively old and energy intensive, as a result of communist party rule over decades in XX century. Despite the vast change and new technologies implementation in each sector of Polish economy, the country still suffers from those time where the development was limited, which is shown as an example in energy mix, where still around 75% of electricity produced comes from plants operated on coal as a primary resource. Currently, for the companies like Laktopol, it is recommended to keep on operating on already installed machinery basing on fossil fuels if possible (except from Natural Gas option which is too expensive, when comparing with e.g. heavy oil). Those installation in most examples is relatively old and out-dated, and will require the replacement over next 5 – 15 years. It is recommended to invest into clean technologies just then to switch for fully renewable option, or undergo completely electrification of the production process powered by the National Grid, basing on the contracts with the local DSO. Despite of the fact that the change in significant part or complete change towards renewables for the Polish industry is not recommended and not economically feasible it is advisable to invest in clean energy sources in some part to possess partially established infrastructure, when the life time of current installations will end and to support the current production in some of its part.

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