# Influence of oil and gas fuels on the exploitation of boilers

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*Abstract*— **Nowadays, most of the world's industries still depend on fossil fuels. Governments and non-governmental organizations are tackling the problem of emission 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 photovoltaic panels 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. Many entrepreneurs and factory owners in Poland to come across European Union requirements are implementing another solution, which is a change of the type of fossil fuel with a modernization of the exploiting unit. The first part of the thesis will be presented the current European energy situation and European Union restrictions, with the focus on the Polish industry sector. The second part will contain a description of the current technologies and the fuel types used in the oil and gas sector. The experimental part will cover the real case study of the boilers' performance, environmental and economic analyses, that are installed in the powdered milk factory in Suwalki, Poland. The Thesis is presented in a form of case study, supported by the model creation 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***

## 1. 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).

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. Particularly in Poland, the energy structure 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 would be 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).


Figure 1. The structure of the final energy consumption by sector in Poland in 2007 and 2017 [2]

Actually, the main goals to diminish the greenhouse gases production are set for 2030, which is the next step after those to be reached by 2020, 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. The most important regulations, directives and programmes are set by the European Union and those are:

- *2020 climate & energy package* [3] – as a set of legislations, 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
- *2030 climate & energy framework* [4] 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* [5] - *is a step further from the 2030 climate & energy 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.
- All *Strategies* are basically based on the Energy Efficiency Directive 2012/27/EU [6], which is regularly amended to the requirements that are set as a next step in reaching carbon neutrality, and from this Directive the next ones are developed per particular sectors (e.g., Energy Performance of Buildings Directive 2010/31/EU)
- The European Union emissions trading system (EU ETS) [7] 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. Covers circa. 45% of total emissions produced in EU.
- The Effort Sharing [8], the legislation concerns the remaining ~ 55%, produced from transport, agriculture, and buildings sectors with a waste segment. Legislation sets requirements to be reached by the companies by the certain amount of time towards decreasing in the pollutants production in the aspect of Kyoto Protocol: carbon dioxide $CO_2$, methane $CH_4$, nitrous oxide $N_2O$, hydrofluorocarbons HFCs, perfluorocarbons PFCs, sulphur hexafluoride $SF_6$ and nitrogen trifluoride $NF_3$

## 2. CHANGE TOWARDS RENEWABLE ENERGY SOURCES

Poland is a country where it is relatively hard to replenish a significant amount of renewable energy sources, as current overwhelming majority in its total energy consumption or production structure belongs to the fossil fuels. One of the aspects working versus renewables is a 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 is 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. 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. Despite those pros, the share of biofuels in total energy mix is diminishing, caused by the total energy consumption increase and covering the created gap by other new investments, especially with the wind energy technologies.

Poland has relatively flat surface and it is 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 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 [9].

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.

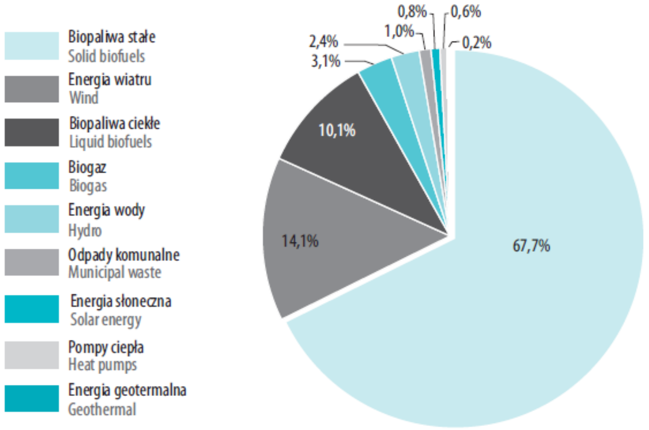



Figure 2. Structure of primary energy production from renewable energy sources in 2017 in Poland [10]

### A. *Technology used in Polish industry*

Most of the Polish industry (all branches) is currently powered using fossil fuels, combusted in the range of boilers in the mean of steam and electricity generation.

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.

The most abundant boilers in Polish industry are flame and smoke tube boiler and steam generators, especially for the relatively smaller scale usage, like in the food&drinks industry:

- *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 is taking 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 [11]. Usually, the construction of the device consists of a flue tube and two exhaust ducts, creating a three-pass boiler. 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.
- *Steam generators* - 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. 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.

## 3. FACTORY AND CASE STUDY 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 in the name 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.

The aim of the case is to develop strategies for the Laktopol company and give recommendations, which to follow. The final choice is divided into 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 (evaporators), 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.

Figure 3. Polindus-Laktopol's factory in Suwalki, PL [12]

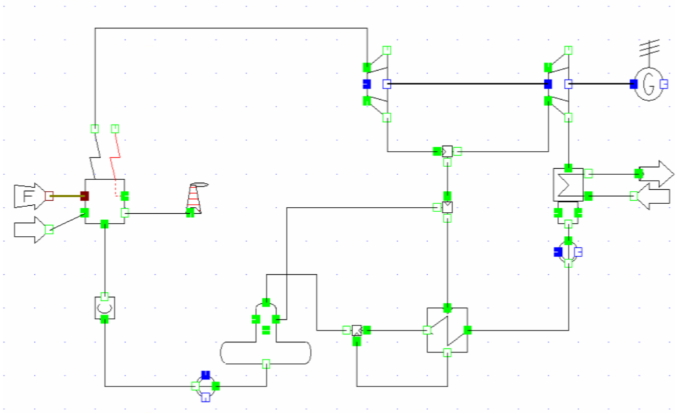
Due to the European Union's directives, projects, and Emission Trading System more restrictive every year, the company is considering change in the currently used carrier – heavy oil. Laktopol asked for consultation in the matter of switching the fuel to natural gas to lower its impact on the environment, 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.

*A. 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. 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) [13]. 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.

*B. 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 and additional production




devices is estimated at the level of 1,8 MW.

Figure 4. Scheme of heat and power generation installation at Laktopol production facility, designed in IPSEPro

The main elements in the installation:

Boiler: Clayton E-604, Babcock Omnical – OMNIMAT 33 HD 7.0 – 18 or LOOS; Back-pressure reduction micro-turbine, 2-step by GESTRA; DNA coat and tube heat exchanger by Secespol; Deaerator; Condenser; Generator

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.

### C. Main devices and their specification

- *Clayton E-604* - Steam generation, 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.

TABLE I. TECHNICAL SPECIFICATION OF CLAYTON'S STEAM GENERATOR TYPE E-604 [14]

| 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 |

- *Babcock Omnical – OMNIMAT 33 HD 7.0 - 18* - 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 II. TECHNICAL SPECIFICATION OF BABCOCK OMNICAL FLAME AND SMOKE TUBE BOILER – OMNIMAT 33 HDA 7.0 [15]

| 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 |

- *LOOS* - 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.

TABLE III. TECHNICAL SPECIFICATION OF LOOS FLAME AND SMOKE TUBE BOILER [16]

| 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 |

- 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.

TABLE IV. PROPERTIES OF BACK-PRESSURE REDUCTION MICRO-TURBINE, 2-STEP, OPERATIONAL RANGES GIVEN BY PRODUCER – GESTRA POLONIA [17]

| 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 |

- Additional properties introduced to the simulation environment

TABLE V. 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 VI. 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 |

### *D. Fuel properties*

When conducting the analysis the most important parameters for all types of fuels were their chemical compositions and calorific values, as the rest of their physical and chemical properties were not influenced the final result of the case study.

- ORLEN – Heavy Oil type 1E

TABLE VII. NORMATIVE REQUIREMENTS AND PROPERTIES OF HEAVY OIL OF TYPE 1E [18]

| Property | Requirement due to the norm | Marked value based on the sample |
|---|---|---|
| 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 |
| Solid contamination content, extraction method [%(m/m)] | Max. 0,30 | 0,04 |
| Carbon content [%(m/m)] | - | 81 |
| Hydrogen content [%(m/m)] | - | 13,1 |
| Nitrogen content [%(m/m)] | - | 1,05 |
| Oxygen content [%(m/m)] | - | 3,05 |

- ORLEN – Heavy Oil type 1C

TABLE VIII. NORMATIVE REQUIREMENTS AND PROPERTIES OF HEAVY OIL OF TYPE 1C [19]

| Property | Requirement due to the Polish Norm | Specification taken as a benchmark |
|---|---|---|
| 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 |
| 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 |

- PGNiG – Natural Gas

Gross calorific value of Natural Gas produced by PGNiG (Poland) is 39,26 MJ/$m^3$, and it is delivered in form of Liquified 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

TABLE IX. CHEMICAL COMPOSITION OF PGNIG'S LNG [20]

| Compound | Chemical formula | Normative range [mol %] | Calculated molar composition [mol %] |
|---|---|---|---|
| Nitrogen | $N_2$ | $\leq 4$ | 3 |
| ∑ combustible compounds | - | $\geq 96$ | 97 |
| Methane | $CH_4$ | $\geq 93{,}83$ | 95,193 |
| Ethane | $C_2H_6$ | $\leq 1{,}72$ | 1,53 |
| Propane | $C_3H_8$ | $\leq 0{,}4$ | 0,26 |
| i - butane | $i-C_4H_{10}$ | $\leq 0{,}03$ | 0,01 |
| n - butane | $n-C_4H_{10}$ | $\leq 0{,}015$ | 0,005 |
| Pentane$^+$ | $C_5^+$ | $\leq 0{,}005$ | 0,002 |
| Carbon dioxide | $CO_2$ | $\leq 0{,}005$ | - |
| Water | $H_2O$ | $\leq 0{,}0002$ | - |
| Sulphur compounds | - | $\leq 0{,}0006$ | - |
| Lead | Hg | $\leq 0{,}001$ [mg/$Nm^3$] | - |

TABLE X. ELEMENTARY COMPOSITION OF PGNIG'S LNG [20]

| Element | Symbol | Mass fraction [% m/m] |
|---|---|---|
| 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 |
| Sulphur content [%(m/m)] | S | 0,8 |

## 4. SIMULATION AND ANALYSIS

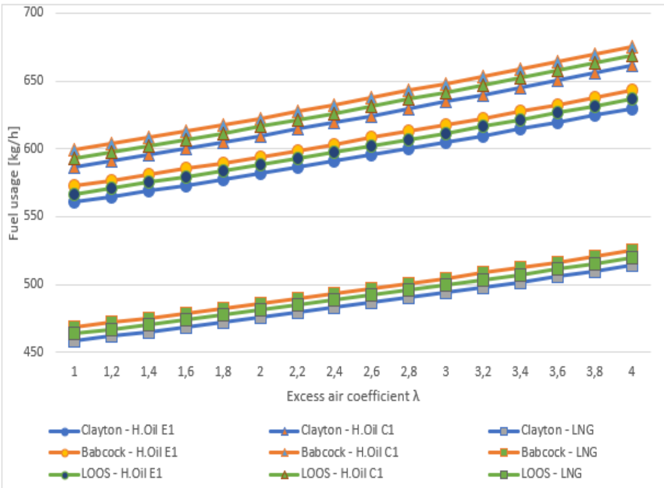
The simulation in IPSEpro software was conducted for all combinations of fuel type with each boiler in relation to excess air coefficient ranging from 1,0 to 4,0. Software environment does not allow for the introduction of coefficient λ with a value below 1. The data was gathered in the MS Excel software and proceeded with necessary calculation. Results are presented in the subsections below.

### A. *Performance analysis*

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 X, the amount of the fuel increases almost linearly, with 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

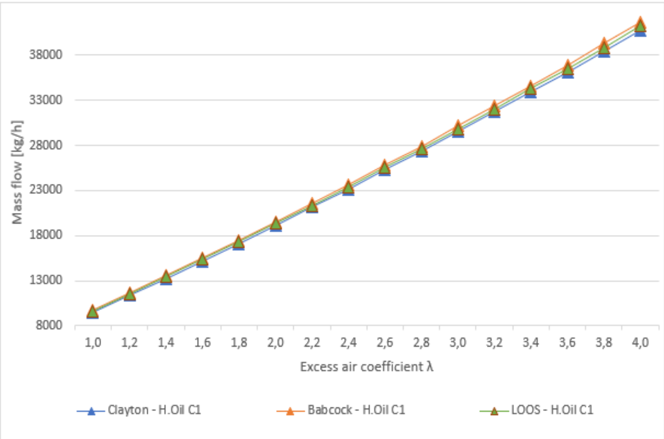
The efficiency per each example is behaving in line with the outcome showed in the Graph 1. When the higher amount of the fuel needs to be sourced to the combustion chamber, the efficiency falls linearly, with increase of the excess air ratio coefficient. This linear diminishing tendency falls from around 95% (all combinations), 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.

### B. *Environmental analysis*

The second part of the analysis is directly connected with the amount of pollution emitted, and the impact on the global warming effect. Moreover, 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, which may be the decisive factor, whether or not to invest in technologies that are more environmentally friendly.

- Exhaust fumes

The amount of the exhaust fumes produced is strongly related with the excess air coefficient, as presented in the Graph 2, 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 O2, N2 and H2O formed when burning the fuel, with the greenhouse gases and pollutants level relatively stable, not such dependable on the coefficient λ. The data on the Graph 2 represent all boilers combinations with Heavy Oil C1, and it mirrors the behaviour of the rest of the combination. 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.



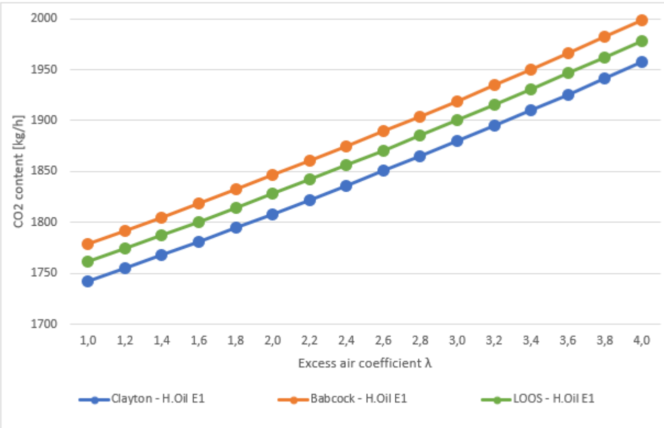

Graph 2. Exhaust fumes mass flow in Laktopol's facility depending on the excess air coefficient for Heavy Oil C1 with different boiler combinations

- $CO_2$ and $SO_2$ 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 Graph 3 and increases linearly in each investigated example. The showed data is for the boiler options for Heavy Oil E1, but mirrors also the other ones. 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).

Sulphur dioxide can be measured only when respecting heavy oil options, as Natural Gas from PGNiG is not contaminated with sulphur element. The $SO_2$ production rises with the excess air coefficient, as simply more fuel is required to be sourced, and with it more sulphur dioxide is emitted to the atmosphere. For Heavy Oil E1, the sulphur dioxide production varies from around 6 to 7 kg/h, and for the C1 type the production is around 3,5 kg/h higher per each example. It is connected with lower sulphur contamination of E1 type (by 0,3%)

Per each respective example the number of carbon dioxide and sulphur dioxide produced rise 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 3. CO2 content in exhaust fumes in Laktopol's facility depending on the excess air coefficient for Heavy Oil type E1 in different boilers combination

### C. *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.

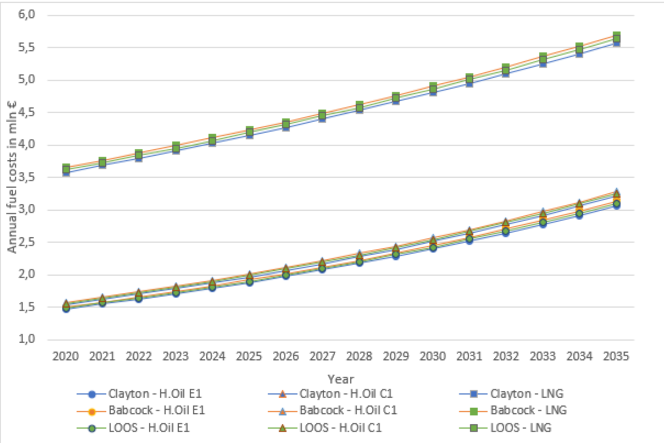
Basing on the previous analyses, the fuel demand per year was chosen and then calculated for each boiler-fuel combination for the excess air coefficient λ = 1,2. The production is stable over a day, working 24h/7 days week, all year, with no plans to increase production capacity, and with that energy demand for the facility. The fuel prices are 1342 PLN/ton [21] for both types of Heavy Oil and 2,72 PLN/$m^3$ of Natural gas [22], with omitting the logistic cost, as they are relatively the same for all the options.

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.

- 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 [21], 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 fuel prices are 1342 PLN/ton [22] for both types of Heavy Oil and 2,72 PLN/$m^3$ of Natural gas [23], with omitting the logistic cost, as they are relatively the same for all the options.




Graph 4. Average annual cost for the fuel for each boiler-fuel combination

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 oscillating around the level of 2 million €/annually is creating the barrier that is almost impossible to break, even with the smaller increasement rate in gas price, than in oil prices.

- 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. 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. 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 [24] and even 100 €/$t_{CO2e}$ by 2050 [25] (including inflation), which doubles the current price oscillating around 25 €/$t_{CO2e}$ [26] through 2020.

It is assumed that 50% of the emission produced will be covered by the free allowanced distributed by the government and the conducted analysis shows that following LNG option will allow to decrease costs of EU ETS by ~60 000 € in 2020, and around 120 000 € in 2030.

- Total annual costs

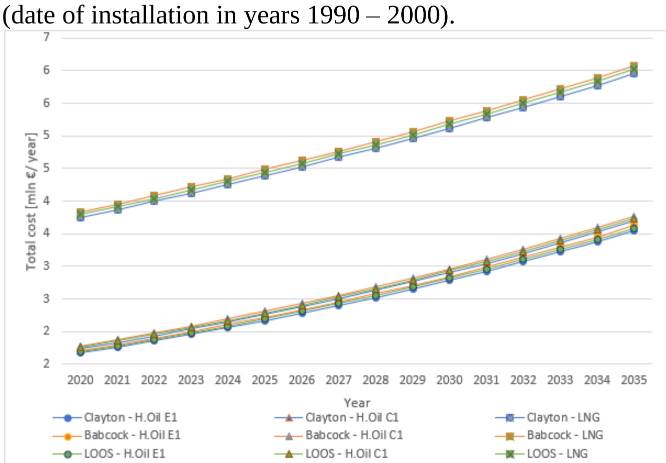
In the final analysis the costs of heat and electricity production was conducted in the form of sum of the variable and fixed costs, for each of the 9 investigation options, operating on data and conclusions developed in the analyses showed before. The Graph 5 shows the rising annual costs for each year for 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 (3 million PLN [27]) and indispensable infrastructure, the total investment cost divided for per 16 years equally – assumed life cycle of the investment. 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 5. Total cost per year for the heat and energy production in years 2020 – 2035 for each boiler-fuel combination

## 5. Conclusions

As shown in the Graph 5 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.

The long-term strategies that are to be developed for years 2030+, should be based on the currently developed technologies, with the keen eye on the technologies that are currently under development or implementation with a promising view on the future energy system. For those solutions, the followings are included:

- Full production process electrification
- Installation of renewable energy sources like solar photovoltaics, solar-thermal and wind power
- Operation on clean combustible sources like biofuels and hydrogen
- Implementation of Carbon Capture, Utilization and Storage technologies

## References


[1] U.S. Energy Information Administration, *International Energy Outlook 2019 with projections to 2050*, 24 Sept 2019, p. 7-12

[2] Statistics Poland, *Energy efficiency in Poland in years 2007–2017*, 2019, Warsaw

[3] European Commission, https://ec.europa.eu/clima/policies/strategies/2020_en#tab-0-0, page visited 25/12/2020

[4] European Council, *EUCO 169/14 CO EUR 13 CONCL 5, European Council (23 and 24 October 2014) – Conclusions*, Brussels, 24 October 2014

[5] European Commission, https://ec.europa.eu/clima/policies/strategies/2050_en, page visited: 25/12/2020

[6] The European Parliament and The Council, *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings*, Brussels, 19 May 2010

[7] European Commission, *EU ETS Handbook*, European Union, 2015

[8] European Commission, https://ec.europa.eu/clima/policies/effort_en, webpage visited: 25/12/2020

[9] Statistics Poland, Energy from renewable sources in 2018, 2019, Warsaw

[10] Statistics Poland, Energy 2019, 2019 Warsaw

[11] Mizielinska K., Olszak J., *Parowe Źródła Ciepła,* Wydawnictwo Naukowo-Techniczne, Warszawa, 2008

[12] Polindus – Laktopol, http://www.polindus.com.pl/galeria, webpage visited 01/07/2020

[13] SimTech Simulation Technology, *IPSEpro Process Simulator – Process Simulation Environment,* Manual version 7.0.002, 2017

[14] Clayton, *Manual E – 604C-E.-K*, 2018

[15] Babcock, *Manual for the automatized steam boilers Babcock Omnical type OMNIMAT 33 HD 7.0 – 18, high-pressured steam*, 1997

[16] LOOS International, *Manual C003*, 2018

[17] FLOWSERVE GESTRA, Marketing information. Micro-turbine – "rotational pressure reduction"

[18] ORLEN Południe, https://www.orlenpoludnie.pl/PL/NaszaOferta/StrefaBIOpaliw/OlejeOpalowe/Strony/Olej-opalowy-ciezki1E.aspx, 2018, webpage visited 29/12/2020

[19] Orlen, *Heavy oil type C-1* *https://www.orlen.pl/PL/DlaBiznesu/Paliwa/OlejeOpalowe/Strony/OlejOpalowyCiezkiC1.aspx*, webpage visited 29/12/2020

[20] Polskie Górnictwo Naftowe i Gazownictwo, *Karta charakterystyki Gaz ziemny skroplony – LNG,* 25.10.2017, http://pgnig.pl/documents/10184/2346596/LNG-wersja_1_10a.pdf/aaf9f4a6-2309-426c-b204-e6d833c73026, webpage visited 29/12/2020

[21] https://oilprice.com/oil-price-charts/, webpage visited 29/11/2020

[22] https://www.orlen.pl/PL/DlaBiznesu/OlejOpalowyCiezki/Strony/default.aspx, webpage visited 29/11/2020

[23] http://pgnig.pl/cng/cennik-cng, webpage visited 29/11/2020

[24] Schjolset Stig, *EU ETS in 2030: A long-term price forecast,* Thomson Reuters Point Carbon, 2014

[25] https://ember-climate.org/data/carbon-price-viewer/, webpage visited 29/12/2020

[26] Hauke Engel, Marcin Purta, Eveline Speelman, Gustaw Szarek, Pol van der Pluijm, *Naturalna emisyjnie Polska 2050, jak wyzwanie zmienić w szansę,* McKinsey Energy Insights, Warsaw, 2020

[27] https://www.psgaz.pl/-/psg-oddala-do-uzytku-stacje-regazyfikacji-lng-w-zatorze#, webpage visited 06/12/2020