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Software for techno-economic assessments of gas CHP

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Abstract

Sustainable energy future is one of the key goals to achieve for the European Union. Reducing dependency on fossil fuels, eliminating hazardous emissions and increasing the share of renewable sources of energy are crucial steps in the process of energy transition. One of the ways to accomplish these goals is the development of combined heat and power systems. In order to support the decision making and investment processes, a dedicated software has been written that performs preliminary technical, environmental and economic assessment of gas CHP systems, concentrating on the Polish market. The program's focus is on development of CHP for district heating grid which corresponds to Poland's current energy policy and has a potential of minimizing the air pollution which is an issue for Poland during the winter season. The software allows to analyse gas and biogas fuelled CHP units in terms of modernization project of coal heating plants to gas cogeneration plants as well as separate, new investment project. The investment is assessed based on annual technical performance, emissions, elements of financial statement and economic investment indicators such as Net Present Value, Internal Rate of Return and Discounted Payback Period.

O futuro sustentável é um dos principais objetivos a atingir pela União Europeia. Reduzir a dependência de combustíveis fósseis, eliminar emissões perigosas e aumentar a participação de fontes renováveis de energia são etapas cruciais no processo de transição energética. Uma das maneiras de atingir esses objetivos é o desenvolvimento de sistemas combinados de calor e energia. A fim de apoiar os processos de tomada de decisão e investimento, foi desenvolvido um software dedicado que realiza uma avaliação técnica, ambiental e económica preliminar de sistemas de cogeração de gás, concentrando-se no mercado polaco. O foco do programa está no desenvolvimento de CHP para a rede de aquecimento urbano, que corresponde à política energética atual da Polônia e tem um potencial de minimizar a poluição do ar, que é um problema para a Polônia durante o inverno. O software permite analisar unidades de cogeração a gás e biogás em termos de projeto de modernização de centrais de aquecimento a carvão para centrais de cogeração a gás, bem como novos projetos de investimento separados. O investimento é avaliado com base no desempenho técnico anual, emissões, elementos das demonstrações financeiras e indicadores de investimento econômico, como Valor Presente Líquido, Taxa Interna de Retorno e Período de Retorno Descontado.

Keywords

Combined heat and power (CHP), renewables, techno-economic assessment, software

Calor e energia combinados (CHP), energias renováveis, avaliação técnico-econômica, programa de computador

Abbreviations

Variables used in the equations with respective typical units are presented below.

1. Technical assessment

Ash – ash content in coal, %.

E_{el} – electrical energy, kWh.

F_{gb} – amount of gas for peak-reserve boiler, Nm^3.

F_{gtotal} – total value of natural gas used, Nm^3.

F_{CS} – amount of coal which is saved due to CHP installation, t.

F_{Ctotal} – total amount of coal used, t.

i – respective hour of the year, h.

L – introduced load of CHP unit, %.

G_{fg} – exhaust gas flow, kg/s.

G_{fgl} – reduced exhaust gas flow, kg/s.

LHV – lower heating value of given fuel, kJ/kg or kJ/Nm^3.

LHV_{coal} – lower heating value of coal, kJ/kg.

LHV_{gas} – LHV of natural gas, kJ/Nm^3.

N_{cap} – electrical energy for captive power consumption, kWh.

N_{CHP} – electrical power produced by CHP, kWh.

N_{chpl} – reduced value of gross electrical power, kW.

N_{compr} – electrical energy consumed by compressor, kWh.

N_{el} – electrical power, kW.

N_{ELS} – electrical energy sold to the grid, kWh.

N_{ELA} – electrical energy produced from active power, kWh.

N_G – electrical power delivered to CHP unit from the grid, kWh.

N_{rep} – purchase of electricity replaced by own production (avoided cost), kWh.

N_{rest} – rest of own electricity consumption, kWh.

$\dot{P}$ – stream of fuel, kg/s.

P – amount of fuel consumed, kg.

$\dot{Q}$ – heat power, kW.

Q – produced heat energy, GJ.

$\dot{Q}_{chp}$ – heat power produced by CHP, GJ.

$\dot{Q}_D$ – heat power produced by CHP to district heating grid, GJ.

$\dot{Q}_{fuel}$ – chemical energy from delivered fuel as stream of energy (same meaning as power)., kW.

Q_{gb} – energy from gas peak-reserve boiler (from integration), GJ.

$\dot{Q}_S$ – heat power produced by CHP dissipated to the atmosphere, GJ.

SWR – solid waste reduction, kg.

t_i – time during the year ($t_i = i$), h.

T_{fg} – exhaust gas temperature, °C.

T_{fgl} – reduced exhaust gas temperature, °C.

T_{out} – outdoor temperature in °C.

T_r – reduced outdoor temperature (temperature of air), °C.

η_{el} – nominal efficiency of electricity production, %.

η_{ell} – reduced value of efficiency of electricity production, %,

η_{gb} – efficiency of gas boiler, %.

η_l – reduced total efficiency, %.

η – nominal total efficiency, %.

σ – electrical power (or energy) to heat ratio, -.

σ_l – reduced electrical power to heat power ratio, -.

2. Environmental assessment

$E_{X,Y}$ – emission of a given compound (y) from considered fuel (x), t.

F_X – amount of used fuel, t.

LHV_{CB} – LHV of coal used for benchmark, MJ/kg.

LHV_{GB} – LHV of gas used for benchmark, kJ/Nm^3.

WC_{CO2} – CO_2 emission factor from coal, kg/Mg.

WG_{CO2} – CO_2 emission factor from gas, kg/10^6 m^3.

W_{CB} – CO_2 coal benchmark, kg/GJ.

W_{GB} – gas benchmark, kg/GJ.

W_Y – emission factor of given compound, kg/Mg.

η_Y – value of emission reduction (capture), %.

3. Economic assessment

$a_{t,i}$ – discounting factor for given year i, -.

a_{wmc} – annual write-offs for maintenance (coal part), %.

a_{wmg} – annual write-offs for maintenance (gas part), %.

AQ – cost of acquisition, PLN.

AWR – cost of annual write-offs for major and ongoing repairs, PLN.

$C_{coal,i}$ – cost of coal for given year i, PLN.

CA – current assets, PLN.

CA_0 – value of current assets for the year of modernization, PLN.

$CASH$ – cash, PLN.

CCB_i – cumulated cash balance for given year i, PLN.

CF – net cash flow, PLN.

CMS – cost for current maintenance and service, PLN.

$CNPV_i$ – cumulated value of NPV for given year i, PLN.

$credit1$ – part of the investment covered by first credit. -.

$credit2$ – part of the investment covered by second credit, -.

CVI_i – cumulated value of investment for given year i, PLN.

D_c – cost for depreciation, PLN.

$D_{coal,i}$ – days of coverage of coal in given year (30 days) i, -.

Dca – depreciation of current assets, PLN.

Dna – depreciation of new assets, PLN.

DCB_i – discounted cash balance for given year i, PLN.

$equity$ – part of the investment covered by equity, -.

ER – employment rate, -.

ETE – excise tax on electricity, PLN.

F_{gmax} – maximum gas for CHP system, Nm^3.

FE – factory expenses, PLN.

FI_i – financial income for given year i, PLN.

FIE – financial expenses, PLN.

GB – estimated cost of peak-reserve gas boiler, PLN.

GC – estimated cost of gas compressor, PLN.

$GFCR$ – general factory cost ratio, %.

GT – estimated value of cogeneration unit with piston engines, PLN.

HS – heat sale, PLN.

i – analyzed year, -.

i_1 – first year of operation, -.

inf – inflation rate, %.

$inctax_i$ – value of income tax, PLN.

inv – investment expenditure index, -.

I_{STL} – interest of short-term loans, PLN.

$INSTALLATION$ – estimated cost for transport and installation of equipment, PLN.

$INCC$ – income from capacity market, PLN.

IRR – internal rate of return, -.

$land$ – cost of purchasing of the land, PLN.

L_{ch} – total value of charged interest payment, PLN.

L_{ins} – total value of installments for loans, PLN.

n – number of years for the analysis, -.

$netsub$ – part of the acquisition expenditure for modernization project covered by net subsidies, -.

$netsubm$ – part of the investment expenditure for modernization project which is covered by net subsidies, -.

NPV – net present value, PLN.

NS – total value of net subsidies, PLN.

ocs_c – other costs of service (coal part), PLN/GJ.

os – operation service for cogeneration modules cost, PLN/kWh.

OSE – other sale, PLN.

OVC – other variable costs, PLN.

P_{cm} – price of MWh for capacity market, PLN/MWh.

P_{coal} – cost of purchasing coal, PLN.

P_{rng} – raw price for the natural gas, PLN/ Nm^3.

P_{dng} – distribution price for natural gas, PLN/ Nm^3.

PC_i – production capacity for i year, -.

PCC – personnel cost, PLN.

PCR – personnel cost ratio, PLN.

Q_{coal} – heat produced by coal unit, GJ.

$r_{at,i}$ – discount rate for given year, -.

r_{c1} – interest rate of credit 1, %.

r_{c2} – interest rate of credit 2, %.

r_{coal} – cost increase rate of price of coal, %.

r_{dca} – depreciation rate of fixed current assets, %.

r_{dna} – depreciation rate of fixed new assets, %.

r_d – discount rate, -.

r_e – assumed return on equity, %.

r_{mat} – cost increase rate for materials and maintenance, %.

r_{rem} – cost increase rate of remuneration, %.

r_{rc} – interest rate for retained capital for given year, %.

r_{stl} – interest rate for short-term financing, %.

R_{gmax} – rate for maximum gas delivery, PLN/(m^3/h).

RB – estimated cost of recovery boiler, PLN.

RE – accounts receivable, PLN.

$S_{coal,i}$ – cost of supply of coal for given year i, PLN.

S – monthly subscription for gas delivery, PLN.

SE – sale to external distributor, PLN.

SP – site preparation, PLN.

ST – stock inventory, PLN.

STF – value of short-term financing, PLN.

T_{fixed} – expenditure for fixed assets, PLN.

T_{oc} – total operation costs, PLN.

T_{pex} – pre-production expenditure, PLN.

T – total investment expenditure, PLN.

TE – total expenditure.

TI – total income.

TR – total revenue, PLN.

$TSPC$ – total sold production cost, PLN.

$To_{coal,i}$ – period of turnover of coal in given year, -.

To_{rec} – period of turnover of receivables, -.

USD – exchange rate between PLN and USD, PLN.

WC_i – working capital for given year i, PLN.

1. Introduction

1.1. Scope of the study

Thesis' aim has been to develop and demonstrate a dedicated software performing preliminary technical, environmental and economic assessment of CHP units and describe the reasons which justify the need for such software.

Introduction of the thesis discusses reasons behind the need for this program, emphasizing the aspect of the environment as well as Polish background, and gives some more specific technical information about cogeneration technology. Further, it discusses available software review which presents commercial programs which are capable of performing such calculations and provides literature review which discusses some papers and sources that provide valuable information related to issues described in introduction. Finally, problem statement presents the decision making problem of distributed energy systems and indicates the possibilities of the program in solving the issue. Following chapter, designed software and model, defines the structure of written program and presents the details about implemented methodology. Chapter results of simulation shows the outcomes from sample calculation and comments further information that can be drawn based on those values. Final chapter, conclusions, recapitulates the possibilities of the software in terms its advantages and limitations as well as it indicates the direction for further development. Appendix contains additional figures that help to illustrate the subjects covered in the introduction.

1.2. Fossil fuels

Development of the world sturdily depends on energy. Industrial revolution of the turn of 18th and 19th centuries introduced machines with equipment creating technologies that changed the way society used to function forever. As a result, increase of energy demand appeared, since all of those infrastructure required fuelling. Resources, which seemed to be the most suitable for this purpose, due to their availability as well as thermodynamic properties, were hard coal, lignite, natural gas and crude oil which are all non-renewable energy sources and are known as fossil fuels. Energy is released from them through combustion. Progressive development in the 20th and 21st century causes the energy consumption to grow to this day. It is used for residential and commercial purposes, transportation and industry. For instance, in 2015 in the USA, these sectors accounted for 40%, 28% and 32% of energy consumed, respectively [1].

Global Energy and CO_2 Status Report 2019 presents the current data about worldwide energy demand and the extent to which respective resources cover it. We see that fossil fuels dominates as 80% of total primary energy demand is covered from coal, oil and gas what is presented in the table 1 (appendix).

Table 1. Distribution of resources covering worldwide energy primary demand [2].

Energy Demand (Mtoe)		**Growth rate** (%)	**Shares** (%)	
	2018	**2017-2018**	**2000**	**2018**
Total Primary Energy Demand	**14 301**	**2,3%**	**100%**	**100%**
Coal	**3 778**	**0,7%**	**23%**	**26%**

Oil	**4 488**	**1,2%**	**37%**	**31%**
Gas	**3 253**	**4,6%**	**21%**	**23%**
Nuclear	710	3,3%	7%	5%
Hydro	364	3,1%	2%	3%
Biomass and waste	1 418	2,5%	10%	10%
Other renewables	289	14,0%	1%	2%

Ongoing exploitation of these resources revealed however several problems. First of all, reserves of fossil resources are not infinite and might be depleted. According to Octopus Energy (electricity and gas supplier in the United Kingdom), overall estimation is that fossil fuels will finish around 2060 with the exception of oil, which demand is driven mostly by transport sector, as oil reserves will run out by 2052 assuming no new and easy to use reserves will be discovered [3].

Second issue is a clear relationship between products of combustion of these fuels and the environment as the emission of hazardous compounds occur. Firstly, there is an issue of global warming which is caused by the emission of carbon dioxide CO_2 and methane CH_4 and which rises global temperature of the Earth. Some of the consequences of this occurrence are: shrinking of ice sheets, glacial retreat, decrease of snow cover, sea level increase, extreme events and oceans acidification. According to NASA's Gravity Recovery and Climate Experiment, between 1993 and 2016 Greenland lost an average of 286 billion tons of ice per year, whereas in the same time Antarctica lost about 127 million tons. We also notice a decrease of snow layer the Northern Hemisphere and retreat of glacials for instance in Alaska, Alps, Himalayas. Those cause the sea level to grow which is a serious concern as it increases the risk of flooding for coastal regions and islands forcing migration of people, losing agricultural land and damaging existing infrastructure as well as habitat of animals and plants. Other issue is the frequency of extreme events such as record high temperatures and intense rainfalls, both of which have been registered by NASA to grow in the U.S. since 1950. Yet another problem, ocean acidification, disrupts marine ecosystem as about 2 billion tons per year of carbon dioxide is absorbed in upper layer of oceans [4].

Huge emission of carbon dioxide is an issue in terms of global warming, however it is not a pollutant understood by a compound which is directly harmful to humans. This is not the case for other compounds that are being released when burning fossil fuels. Sulfur dioxide (SO_2) emissions contribute to respiratory illnesses such as asthma, nasal congestion, and pulmonary inflammation. Nitrogen oxides (NO_x) support smog (ground-level ozone) responsible for e.g. asthma and bronchitis. Emission of carbon monoxide (CO) leads to emission of poisonous gas, particulate matters which are the particles present in the air (we distinguish PM10 and PM2.5 where PM10 are the particles with the diameter less than 10 μm) and which contain heavy metals like arsenic, cadmium, nickel, lead and hydrocarbons like benzo(a)pyrene) that make people susceptible to damage of circulatory and reproductive system, allergy, asthma and in worst cause could lead to a tumor. Those compounds affect also the environment as SO_2 and NO_x are also responsible for acid precipitation that damages aquatic and forest ecosystems, agriculture areas and architecture. CO emission promotes global warming as it is also a greenhouse gas [5, 6].

Negative impact on the environment in terms of intense exploitation of fossil fuels is however not only achieved in the stage of combustion of these fuels. Extraction of fossil fuels leaves an impact, especially on water resources. Underground coal mining is associated with movement of ground layers which could impact infrastructure built above, but there is also a risk of water that could reach such mine and become rich in heavy metals and get acidic. Surface coal mining often forces changes to local environment destroying e.g. forest ecosystems but also affecting water flows which could lead to devastation of drinking water. Oil and gas drilling brings to surface underground water rich in solids, heavy metals, hydrocarbons and radioactive elements which would not have been brought to surface if not for the extraction. Hydraulic fracturing which is a supporting technology process in the excavation phase serving to fracture the bedrock, requires between 3 to 6 million gallons of water per well (11.4 – 22.7 million liters) with addition of 15 to 16 thousand gallons of chemicals, what also naturally contaminates water resources [5]. Beside of water usage, there are also direct emissions. In the process of oil drilling additional methane emissions occur. Although it can be captured, it is very often vented or flared (as a way of reducing environmental impact so that carbon dioxide is emitted instead of methane) according to The World Bank estimation around 5.3 trillion cubic feet of natural gas is flared annually worldwide, generating 400 million tons of CO_2 [5]. Facilities required to access oil resources also lead to land degradation as extensive infrastructure is built. Another stage where the impact from fossil fuels on the environment can be noticed is the transportation. First thing is the energy required to fuel the transportation sector itself (rail, transport cars, ships) creating additional demand for those fuels. During transportation of coal, dust is released to the air worsening quality of this air within areas close to transport roads. Losses and leaks from pipelines are responsible for emission of methane when transporting natural gas due to long distances and not necessarily renovated infrastructure as e.g. 3356 leaks within city streets in Boston were founded [5]. Oil leaks from drills located on the ocean as well as spills from onshore pipelines are also a considerable threat devastating ecosystems. For instance, 2010 Enbridge spill in the US is estimated to have released 20,100 barrels into Michigan’s Kalamazoo River.

Fossil fuels problems include also the issue of waste. Before coal can be used as a fuel it has to be purified from sulfur but also from heavy metals such as arsenic, mercury, chromium. Combustion of coal is the reason for generating fly and bottom ash both of which contains hazardous metals. Both pre-combustion and post-combustion waste are captured and stored in reservoirs so that they could be managed and, if possibly, somehow used. Wastewater from oil and gas extraction also requires storing and managing, so that it does not pollute the environment. In order to notice the whole picture from fossil fuel exploitation, life cycle assessments are needed, given examples indicate some of the most pressing concerns.

All of those reasons force worldwide energy industry to change direction towards high efficient and renewable sources of energy. The objective is to use fuels as efficiently as possible and avoid harming the environment as well as human’s lives.

1.3. Cogeneration technology

1.3.1. Background

One of the key concepts that helps to achieve considerable energy savings is cogeneration. Cogeneration is a well-known technology which could be defined as thermodynamic conversion of chemical energy from primary fuels simultaneously into the form of several useful carriers such as heat, cold and electrical energy. The definition of cogeneration provides that two energy carriers are produced (e.g. heat and electrical energy), and one of them results from utilization of by-product (waste heat) from a power generation device. Such device can be thermal engine (e.g. gas turbine, reciprocating engine) or fuel cell. Cogeneration is also known as Combined Heat and Power, CHP. If three products are generated simultaneously (e.g. power, heat and cold), the process is called trigeneration. In the case of more than three products (for example mechanical energy, fuel of other product can be added to the portfolio), there is used the term of poligeneration.

The most important advantage of CHP is its higher overall energy conversion (ratio of total useful energy to energy delivered) when compared to separate electricity and heat production. As a consequence, less fuel is required to obtain the same amount of useful energy, comparing to separate individual production process and therefore exploitation costs and environmental impact (emissions) are lower. Considering heating plant (delivering heat solely) with efficiency of 90% [7] and conventional power plant with electrical efficiency 45% (typical range is 38% - 47% [8]) input of fuel 100 kWh to each of these plants delivers 90 kWh of heat and 45 kWh of electrical energy. Meanwhile, CHP plants with efficiency of 75% [9] (with electrical energy to heat ratio 0.5), in order to produce the same amount of energy carriers requires 180 kWh input of fuel, which is 20 kWh less.

In case that heat from conventional heat power plant is not treated as a waste but as useful energy carrier, cogeneration takes place, however this technology has several limitations. If e.g. back pressure type turbine is used, a strong correlation between temporary electrical and heat demand needs to exist. If condensing turbine with bleeds is used, it allows to neutralize the correlation between heat and electrical energy, to certain limitation, however it lowers the overall energy efficiency. Thermal plants that use cogeneration are usually huge power plants (several dozen of megawatts) as their efficiency is higher, when working at high loads, but such facilities need to be built at certain distance from final heat consumers, what increases the losses along the way and rises the demand to cover those losses. Apart from the size of power plant, a type of fuel which is used, influences the performance of a plant. If coal is used, which is the case for Poland, as in 2018 coal accounted for 47.3% of electrical energy production and lignite for 29.1% [10], there are problems related to pretreatment, (transportation, storing, preparation – grinding, milling), harmful emissions, low flexibility (limitation of minimum system power) and managing amounts of solid waste.

Due to these limitations concerning using conventional thermal power plants for cogeneration purposes, a small and medium scale cogeneration (CHP) modules, fueled by natural gas, have been developed, as they allow to minimize issues with conventional units. Main advantages of those units are [7]:

- Electrical energy and heat can be produced more independently with high energy efficiency.
- The units are flexible and can be adjusted to match the demand more precisely.

- Exploitation costs are lower (reduced number of staff).
- Emissions and waste issues are reduced due to coal to gas switch.
- Building and installation procedures are simpler (less time for construction needed).

Small and medium scale cogeneration units are used for:

- Small scale power plants which deliver district heating – heat and electrical energy are sold to number of households (e.g. residential) connected to district heating grid, located nearby CHP plant.
- Supplying heat and electrical energy to facilities such as: airports, hospitals, universities, hotels, office buildings, sport centers etc.

Currently, CHP units of higher power outputs are also available. For instance, taking a look at an offer from the company TEDOM a.s. a module of output power of 10 MW_e is possible to purchase (piston engine). Wärtsilä offers gas engine based units up to 19 MW_e. In the case of higher power required gas turbines of modular solution can be applied. This development allows to modernize coal based heating plants to gas cogeneration systems, which is a great advantage. Such modernization as well as new type of investment are implemented into the designed software.

1.3.2.Technology

There are two types of engines used for CHP, piston engine or turbine engine. A typical cogeneration system consists of:

- Thermal engine (piston or turbine).
- Generator.
- System of heat exchangers.
- Filters and exhaust gas discharge.
- Control system.

If the CHP unit is built in order to provide the heat for district heating grid, a peak-reserve gas boiler could be attached. A simplified schemes of such systems are shown in figures 1 and 2 (based on [7]). Figure 1 shows cogeneration unit with piston engine, figure 2 presents cogeneration unit with turbine engine (appendix). Figures do not present all the equipment, as it is required that before the chimney there is a flue gas cleaning installation. Also, the schemes present the examples with one engine unit, whereas in reality a few of them might be linked in series (however it is rarely more than three). Some of the piston engine systems might also have additional fan cooler installed (on the water side), in case it is not possible to provide heat for end users, yet allowing the engine to work at full load. In case the CHP is destined for small scale application, peak-reserve boiler might not be included.

1.3.3. Performance indicators

In order to assess the performance of cogeneration system, energy indicators are used. The most important performance indicators are [7]:

1.3.3.1. Efficiency of electricity production

a. Instantaneous electrical efficiency:

$$\eta_{el} = \frac{N_{el}}{\dot{P} * LHV} \tag{1}$$

where: N_{el} – electrical power, $\dot{P}$ – stream of fuel, LHV – lower heating value of fuel.

b. Average electrical efficiency:

$$\overline{\eta_{el}} = \frac{E_{el}}{P * LHV} \tag{2}$$

where: E_{el} – produced electrical power (over a period, energy+), P – amount of fuel consumed.

1.3.3.2. Total efficiency of chemical energy from fuel conversion, also known as Energy Utilization Factor (EUF)

a. Instantaneous total efficiency:

$$\eta_C = \frac{N_{el} + \dot{Q}}{\dot{P} * LHV} \tag{3}$$

where: $\dot{Q}$ – heat power.

b. Average total efficiency:

$$\overline{\eta_C} = \frac{E_{el} + Q}{P * LHV} \tag{4}$$

where: Q – produced heat power.

1.3.3.3. Association indicator defined as electrical power (or energy) to heat ratio

a. Instantaneous value:

$$\sigma = \frac{N_{el}}{\dot{Q}} \tag{5}$$

b. Average value:

$$\bar{\sigma} = \frac{E_{el}}{Q} \tag{6}$$

Indicators give insight into basic assessment of energy effects of cogeneration unit, under given technical specifications, and are a basis for technical (thermodynamic) and economical assessments.

A range values which one usually can expect are the following [7]:

- Electrical efficiency takes values between 0.25 – 0.48 for piston engines and 0.14 – 0.44 for gas turbines.
- Total efficiency takes values between 0.78 – 0.90.

Range of values for association indicator varies depending on power output and efficiencies. Typical values of small scale CHP units are presented in table 2 (appendix) [7].

These performance indicators are known as local indicators. Global indicators are also defined for cogeneration, which include: fuel chemical energy savings, primary energy savings and avoided emissions in the energy system.

1.4. Background for Poland

1.4.1. Legislation

Efficient energy future is one of the key goals for the European Union. This is reflected through the Energy Efficiency Directive (2012/27/EU) and a corresponding CODE2 project which provides support for Member States in terms of legislation and business case in the process of implementation of cogeneration on broader scale. Cogeneration Observatory and Dissemination Europe, as part of CODE2 project, has prepared summary reports for member countries including Poland. Report (2014) generates "Strategy for development of cogeneration till the year 2030" containing three main goals [11]:

- "Electricity generation in the high efficiency cogeneration should double till the year 2030 compared to 2006 to 48TWh.
- High efficiency cogeneration on the RES should reach at least 20% of the total cogeneration capacity installed in the year 2030.
- Enforcing the sustainable local energy planning to enable sustainable solutions for heat supply with a special emphasis on the further development of the district heating and cooling (DHC) with cogeneration, use of RES and waste heat utilization."

Crucial aims Poland to achieve in terms of overall energy strategy are to: "improve the energy efficiency, increase utilization of renewable energy sources and decrease the emissions of CO2, SO2, NOX and dust in the next years".

These recommendations are naturally comprehensive to latest general EU strategy. Quoting from European Parliament website, five main policy goals to accomplish are [12]:

- "Ensure the functioning of the internal energy market and the interconnection of energy networks.
- Ensure security of energy supply in the EU.
- Promote energy efficiency and energy saving.
- Decarbonise the economy and move towards a low-carbon economy in line with the Paris Agreement.
- Promote the development of new and renewable forms of energy to better align and integrate climate change goals into the new market design.
- Promote research, innovation and competitiveness."

As a response to these directives, Polish government have prepared a PEP2040. It is a prevailing act describing energy strategy and its goals for Poland until 2040. The act contains major directions crucial to achievement of policy compliance between Poland and the European Union. Direction 7 regards development of heating systems and cogeneration. It emphasizes expanding district heating networks and modernization aimed at improvement of efficiency of existing units, which is compliant to the recommendation given in report from CODE2. For the purpose of expanding those networks, 7th Strategic Plan PEP (org. in pol. “7. Projekt Strategiczny PEP”) has been launched. Direction 7 provides following statements [13]:

1. Support for electrical energy generated in highly efficient cogeneration. Until 2018 a system of certificates was serving for this purpose. Companies that run cogeneration plants received financial instruments known as certificates of origin which they could sell through dedicated stock exchange system. Electricity distribution and transmission companies were obliged to purchase those certificates as they had to submit certain number of certificates in accordance with requirements from Energy Regulatory Office. Through such system, electricity generating company received an additional income from the sale of certificates what stimulated investments in cogeneration plants. Certificates were also granted for companies that generated electricity e.g. through renewable sources of energy and companies that used Carbon Capture Storage technologies. However, since 2019, for highly efficient cogeneration, there is a new system of support from the government. Guaranteed tariffs for generating electricity or capacity market, where energy producers might be remunerated for readiness to supply power to system with parallel obligation to supply it in case of power shortages (risk periods), are available. That does not refer to the UE emissions trading system as emission allowances for greenhouse gases (CO_2) through a “cap and trade” system is still valid.
2. Increase of renewable sources of energy. Rise in exploitation of biomass, biogas, solar collectors for the purpose of heating.
3. Development of waste-to-energy systems. CHP units equipped to process solid fuels with highly efficient exhaust gas cleaning systems could be used to utilize waste. It is an activity complementary to circular economy concept. In a long term thermal waste treatment should not be possible without energy recovery.
4. Development of district heating systems for power plants which treat heat as waste and release it to the environment. Number of households that consume fossil fuels for heating purposes on their own should decrease. These households should be attached to the heating grids.
5. Modernization of existing district heating systems in terms of thermal insulation that reduces losses.
6. Simplifying investment procedures to encourage investors.
7. Integration of cogeneration with trigeneration, using heat for cooling purposes through adsorption and absorption technologies. Generating cool in this way contributes to reducing the demand for electrical energy.
8. Promoting energy storage technologies helping to minimize heat losses and balancing demand in energy clusters.
9. Promoting intelligent networks contributing to optimal operation of power plants.

Some of the mentioned quantitative targets are [13]:

1. Until 2030 connect 70% of households, located in urban areas, to district heating systems.

2. Until 2030 at least 85% of heating and/or cooling systems for which the power exceeds 5 MW should meet the requirements of efficient heating system. The criteria which such a system needs to meet, in order to be considered efficient, in the process of heat/cool production are to use at least:
   - 75% of generated heat from CHP (combined heat and power) unit, or;
   - 50% of generated heat from waste energy (e.g. heat as by-product from industrial process), or;
   - 50% of generated heat from RES, or;
   - 50% of generated heat from a combination of sources mentioned above.
3. Annual increase in the use of renewable sources of energy for heating purposes should reach 1.1 %.

The act stresses also the fact that if there is no possibility of attaching a household to the district heating system, it should use a source of energy with lowest emissivity. RES that are noncombustible (heat pumps. solar collectors etc.), electrical heating systems (conjugated to solar panels), gas systems and “eco-design” boilers (boilers that meet the standards in terms of emission levels) will be supported, in various forms, from public funds (subsidies, loans). This activity is performed due to the fact that one of the most serious environmental issues in Poland is the occurrence of so called “superficial emission”. The emission coming from households which consume solid fuels for heating purposes is understood by this term. The problem arises because a lot of these households use old and inefficient boilers which are a main source of particulate matters emissions and no flue gas cleaning installations exist there. It is estimated that there are still about 3 million households using such equipment across the country (data for 2019) [14].

1.4.2. Air quality

In order to notice the “superficial emission” effects an investigation towards air quality in Poland is necessary. There are two types of criteria assessing concentrations of PM10 across Poland. These are presented in table 3 (appendix) [15].

Distributions of PM10 concentrations across Poland as 24-hours concentrations, expressed as 36th maximum daily concentration, and yearly values are presented in figure 3.

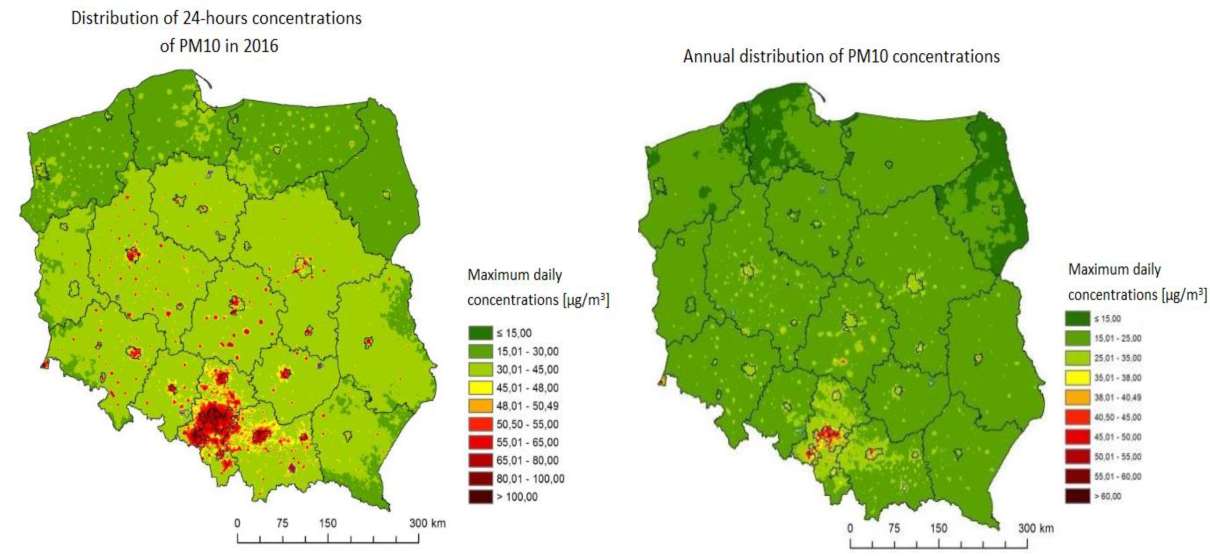


Figure 3. Maximum 24-hours PM10 concentrations and annual PM10 concentration in Poland, 2016 [15].

Regions, where higher concentrations of PM10 were registered, overlap on agglomerations and denser populated areas where there is a higher demand for heating purposes as most of particulate matters are emitted due to this need. Other than from "superficial emission" occurrence, particulate matters and hazardous emissions are from energy sector (coal plants), agriculture, transportation and industry. Data from KOBiZE (pol. "Krajowy Ośrodek Bilansowania i Zarządzania Emisjami", eng. "National Center for Management and Emission Balancing", own translation) show the source of emission of PM10 in total and emitted hazardous benzo(a)pyrene with it. These are presented in tables 4 and 5 (appendix) [14].

Benzo(a)pyrene emission is of special importance if we investigate the situation of Poland in a broader perspective. Figure 4 shows levels of emissions of B(a)P across Europe (appendix) [16]. Threshold concentration of B(a)P in the air, according to the European Union, is 1 ng/m^3. The value recommended from World Health Organization is 0.12 ng/ m^3. Concentration of this compounds in the air in Poland exceeds the second value over a dozen times. Peak and record value appeared in city of Pszczyna (South Poland, Silesian region), where in 2017 in January the concentration of B(a)P reached a value of 90 ng/ m^3, which is 750 times higher than the WHO recommendation [17]. Benzo(a)pyrene is responsible for damage to the liver and adrenal glands, feeling tired, headache, loss of appetite, depression, shortness of breath, skin irritations, weakening of the immune and blood systems, fertility problems and cancer. International Agency for Research on Cancer recognized this compounds to be the most carcinogenic factor. It is the reason why neutralizing the "superficial emission" occurrence is one of the key goals to achieve as soon as possible.

Other emissions which are also monitored are: PM2.5, SO_2, NO_x, CO, tropospheric ozone (O_3) and heavy metals such as: lead (Pb), cadium (Cd), nickel (Ni) and arsenic (As) [15]. Monitored areas are divided into zones which are considered to be the most susceptible to hazardous emissions, shown in figure 5 (appendix) [15].

Comparison of results for all zones gives us information about which compounds the focus should be put the most. Figure 6 (appendix) [15] shows summary data in respect to all zones using the division between A as good reference and C as bad reference. If a zone is classified to C category, it means that within this zone there are regions requiring action towards cleaner air, not that the whole zone is polluted. Most of the zones suffer from PM10 pollution and, as a consequence, from benzo(a)pyrene, what makes them the most pressing concerns. In case of other emissions the situation varies, but generally it is less serious.

1.4.3.Current CHP situation

Recapitulating these information, there is no doubt that cogeneration systems serving to deliver district heating are going to play w vital role for Poland in order to achieve desirable environmental standards and emission levels. Heat production in 2014 was denoted to be 393.2 thousands of TJ, whereas 64% of this production was performed by cogeneration units. In the figure 7 (appendix) [18], we can see such heat production in respect to voivodships (administrative regions). Cogeneration units distribution varied among the country. In some regions more than 70% of heat generation came from cogeneration units, like for example in Dolnośląskie and Lubuskie, however in the others, it was a significantly less value. In the region of Podlasie it did not exceed 20%.

Coal is the main source of supplying those units as about 88% of electricity production from cogeneration is based on coal technologies with steam turbines. Share of combined cycle with gas turbines (CCGT units) and internal combustion engines does not exceed 12% (data for 2012) [18]. In 2018 cogeneration plants accounted for 7.7% of total electrical power installed. 18.5% of total electrical power installed was from renewable sources of energy (mostly wind but also biomass, biogas, and solar sources) [10].

1.5. Coal to gas switch

In order to achieve policy goals investments are necessary. Preliminary feasibility studies need to be performed as a way to conduct initial assessments of the projects and support the investors in decision making process. For the purpose of this thesis, a dedicated program has been written which aim is to perform a preliminary technical, environmental and economical assessment of cogeneration units. Software allows to analyze a modernization project of switch from coal to gas cogeneration unit as well as an analysis of new investment of gas cogeneration unit. The strategy is to gradually reduce the share of coal and for this purpose a switch from coal to gas has been modelled. Such switch brings several benefits. Typically natural gas power plants allow to decrease emissions of CO_2 than coal units due to their higher efficiency but emissions of CH_4 appearing in the stage of extraction and transportation of natural gas might neutralize this benefit. Nevertheless, natural could be considered to be a “cleaner” fuel than coal, as it emits less SO_2, NO_x and particulate matters PM2.5 and PM10 [19]. That can be clearly seen on the example of the U.S. where from 2010 gas technologies have started to expand stronger than before and solely this switch from coal to gas has decreased the emission levels more than any other factor. Each added gas unit caused emissions to decline by an average of 0.6 tCO2e/MWh [20]. Figure 8 (appendix) [20] compares the emissions from power sector for the U.S.

Decreasing price of natural gas is also an additional incentive for investors [19]. If we take a look at a natural gas price at commodity market, we see that despite the fluctuation its medium value has been decreasing over last 10 years. Average change over this period is at -3.50 USD/mln btu [21]. This is shown in figure 9 (appendix) [21]. Other benefit is that gas power plants can be launched or stopped faster than structural switches that require time to accumulate (such as coal thermal plants). It is a benefit in terms of operation as it can help to balance the grid more appropriately and minimize heat losses [20].

Switching from coal to gas can be treated a phase in the process of energy transition. It has a potential of improving the air quality in Poland but it does not fulfill the concept of sustainability and decarbonisation since natural gas is a fossil fuel and is a source of certain of problems. Therefore, increasing the share of renewable sources of energy is of utmost importance. An idea is to subside some part of natural gas that is delivered to CHP unit with biogas. Additionally, if the project is about the modernization of existing plant and the coal unit is not going to be switched off, a coal could be co-fired with biomass. Software allows to include the shares of biomass in used coal and biogas in used natural gas.

1.6. Increase in share of renewables

Introducing biomass and biogas has several advantages. First thing is the infrastructure for firing coal can be used for co-firing coal with biomass and require little additional investments (e.g. some additional pretreatment installations might be necessary) [22]. Secondly, biomass, in general, could contribute to lowering undesirable emissions. Ash, sulfur and nitrogen contents in biomass fuels are typically lower than in the case of coal. Comparison between hard coal and different types of biomass is shown in table presented in figure 10 (appendix) [23].

Using biomass as fuel contributes also to reducing amount of waste. Since by biomass we understand agricultural residues, animal waste, forestry residues, wood waste, industrial (food industry) waste and municipal solid wastes and sewage utilization of these waste through combustion we can use energy contained in them. If such wastes are not treated appropriately, the process of decomposition of organic components is a source for methane, nitrogen and odors emission [22], [24]. Although combustion of biogas emits CO_2, the release of methane to the atmosphere, would be worse as CH_4 is stronger than CO_2 in terms of global warming effect. The Global Warming Potential (GWP) for methane is about 28-36 over 100 years (CO_2 is 1 as it is a reference gas). Additional benefit is this way we reduce the amount of waste on landfills. Biogas, similar to biomass, does not require additional engines to be used, and it can be co-fired with natural gas. Anaerobic digestion or fermentation are attractive ways of biomass utilization, since the fuel we obtain is cleaner and can be used also for other purposes such as household cooking or lighting requirements. Biomass can be also changed into biogas through gasification process. Syngas, despite direct heating application or fuel for internal combustion engines, is used to produce methanol – attractive chemical feedstock in industry [22].

The main idea however for implementing biomass and biogas is due to CO_2 emissions. Avoided emissions is what we achieve by collecting organic waste and using them as biomass fuel but there are also renewable sites of certain plants that are used for energy purposes. These are considered to be renewable sources of energy as during the lifetime of biomass it absorbs carbon dioxide. As an effect, once it is combusted and CO_2 is released to the atmosphere, new biomass is replanted and it captures the carbon emitted during combustion. Theoretically, no new carbon is added to the atmosphere and the total balance is considered to be zero. That is the reason why companies that own and operate power plants have introduced co-firing coal with biomass as through such system they can lower carbon dioxide emissions, as they exploit less fossil fuels, and decrease costs for those emissions. The flaw is in the detail of assumption that biomass has always zero net carbon dioxide emission as it is not always necessarily true. The U.S. Environmental Protection Agency in 2014 gave statement: “Whether or not biomass is truly carbon neutral depends on the time frame being studied, what type of biomass is used, the combustion technology, which fossil fuel is being replaced (since the combustion of both fossil fuels and biomass produces carbon dioxide), and what forest management techniques are employed in the areas where the biomass is harvested”. Adequate choice of type crops to be cultivated is crucial and regrowth of plants must offset carbon released during combustion. Choosing a site for plant growth is also important as deforestation for the purpose of planting energy crops might increase net CO_2 emission, as if the forest remained untouched. Trees that would be capturing carbon dioxide are removed and sequestering of this added carbon might take decades [25].

The limitation of biomass in terms of emissions comes with its lower calorific value than comparing to coal, as in order to obtain the same amount of energy, more of the fuel is needed. As a consequence, if the biomass used is, for instance, sorghum, which nitrogen content is at 0.9%, the total nitrogen oxides emissions would not necessarily be lowered comparing to if no biomass would be used. In the same time, it is noticeable however that it would improve sulfur dioxide emissions, as sorghum has sulfur content at 0%. Depending on specific example of power plant and exhaust gas cleaning system installed (or planned to be installed), appropriate type of biomass should be chosen.

Biomass and biogas are vital for Poland to achieve policy goals. The most accessible source of biomass from crop production in Poland is straw. Main use of straw in agriculture is as fodder and bedding for animals and as a substrate in the process of reproduction of organic matter in soil but recent changes in agricultural production (reduction of animal population) contributed to obtaining straw surpluses. In 2015 such surplus was capable of delivering of 219 934 TJ assuming that 1 ton of straw with a moisture content of 15% has a calorific value of 13.1 GJ [26]. If calorific value for coal is assumed to be 24 MJ/kg^{-1}, such amount of biomass could replace around 9.16 million tons of coal. The most capacious regions of straw in Poland are: Wielkopolskie – 30 415.3 TJ/ year, Dolnośląskie – 27 791.0 TJ/year and Lubelskie – 23 191.2 TJ/year, located on western side of Poland [24]. A map with straw potential is presented in figure 11 (appendix) [26].

Similar situation is with the second biomass resource with high potential for Poland and which is hay. The expected hay harvest allows for the production of 41,249 TJ of thermal energy and can replace

1,719,000. tons of coal with an average calorific value considering that 1 ton of hay with a moisture content of 15% has a calorific value of 13.4 GJ [26].

Another investigated idea is a possibility develop plants for perennial energy crops. Cumulated energy potential for such crops is estimated to be at 44.6 thousands of TJ. Most promising regions are: Mazowieckie – 5 225.7 TJ/year, Zachodniopomorskie – 4 486.6 TJ/year, Podlaskie – 4 224.4 TJ/year [24]. Potential of energy crops is shown in figure 12 (appendix) [26].

Rise in exploitation of biomass and biogas for energy purposes is in accordance to PEP2040 directive. Parallel investments in biogas chambers (supported through financing from government) as well as in CHP units for district heating create a need for tools that would help potential investors to assess the situation. A created program for the purpose of such analysis could support energy transition in Poland towards sustainable and environmental neutral future.

1.7. Available software review

Process of transition from conventional fossil fuels technologies towards highly efficient and renewable generation creates an issue of uncertainty when planning new investments or modernizations. Appropriate defining of energy systems has gained a lot of interest as it helps to understand considered variant in a better way and contribute to making adequate decision considering optimal resource allocation and desired goals. Feasibility of CHP and renewable energy systems can be analysed through various models. Division of models can be made according to approach in mathematical modelling as we can distinguish parametric (equations derived experimentally) or analytical models (theoretical basis). Analytical models can be further divided into models that perform analysis in steady-state of dynamic models (considering change in time). Development of computer modelling contributes to dynamic modelling as advanced calculations can be performed through dedicated software. However, choosing the best software, for the purpose of one’s investigation, is not a trivial task as tools differ in respect to their structure, operation, application and uncertainty of results (accuracy of the model).

In order to distinguish and categorize the tools serving to assess performance of energy system a following definitions have been developed [27].

- Simulation tool – simulation of energy system is performed in respond to input energy demand. Usually hourly time step over one year period is implemented.
- Scenario tool – a tool which combines data for one-year period into a series of years obtaining long-term scenario. Typical timeframe of scenario programmes is 20-25 years.
- Equilibrium tool – a program that identifies supply, demand and prices from the perspective of market situation and aims to indicate optimal way of operation.
- Top-down tool – software which use macroeconomic data in order to predict energy prices and demands and based on this information proposes a solution. These are usually also the tools which allow to find equilibrium point.
- Bottom-up tool – a tool which analyses specific energy technologies and then investigate investment assessment.

- Operation optimisation tool – software which allows to find optimised solution. It is usually also a simulation tool that optimise the operation of given system.
- Investment optimisation tool – a type of program which finds a solution focused on the highest financial profitability. Typically it is also a scenario tool.

Classification of available programmes is presented in figure 13 (appendix) [27].

It is clearly seen that majority of software are simulation and scenario tools that use bottom-up approach. More advanced ones allow also to optimize the solution in terms of operation and/or investment outlays. Some of the tools which allow to analyse CHP systems are Balmoral, BCHP Screening Tool, Compose, EnergyPLAN, eneryPRO and RETScreen.

Balmorel is a partial equilibrium bottom-up tool which is capable of simulating electricity sector and district heating grid with integration of heat storage and hydro, wind or solar power (also electrical storage through pumped hydroelectric). It can deliver an analysis of a scenario of maximum 50 years and provide optimisations points (both operation and investment as seen in figure 13). It uses time-step of 1 hour, but in case of larger projects different subdivision can be made e.g. 250 time segments per year over 20 years, and the analysis is not linked to certain geographical area. *Balmorel* is an open source project, meaning that any user can adjust it to his own needs and it is a free of charge software, written through GAMS modelling language. Optimization capabilities of the program are about optimal investment in electrical and CHP technologies in respect to restrictions such as maximum annual investment or maximum fuel availability [27, 28, 29].

The *BCHP Screening Tool* is a dedicated tool developed specifically for the purpose of investigation of CHP feasibility in commercial buildings considering HVAC equipment, electricity generation, thermal storage with energy carriers demand and weather data. It allows to simulate a single year with the time-step of 1 hour (no scenario generation) using bottom-up approach and indicate optimal point of operation. It has been developed by Oak Ridge National Laboratory in the USA and it is available to use free of charge. It does not support investment optimisation option [27, 30].

Compose (Compare Options for Sustainable Energy) software proposes bottom-up approach in order to find optimal points in terms of operation and investment options for energy projects. The focus of the program is the investigation between intermittency and distribution of costs and benefits. It can process thermal, renewable and storage technologies with emphasize on integration of CHP with heat pump or electric boiler. Program uses 1 hour time-step and it is not limited by upper limit timeframe. Software supports also a social platform containing case studies regarding energy supply, demand and market interactions. It has been shared by Aalborg University (Denmark) and it is available to download for free [27, 29, 31].

EnergyPlan is another option of software to choose in order to perform an assessment of energy systems. The program is focused on energy planning strategies (regional or national level), therefore it allows for complex analyses of electrical, thermal, storage and renewable technologies. It enables to simulate 100% of renewable energy generation (also within smart energy systems) and it uses hourly time-step for a period of 1 year. The implemented algorithm is based on bottom-up approach allowing to optimise operation and investment. The software is free of charge and it has been developed by Aalborg University in Denmark [27, 29, 32].

Program *energyPRO* is a software designed for analysis of technical, economical and optimization assessment for thermal and CHP units with integration of renewable sources of energy (including bio-fueled cogeneration units) and storage. Valuable feature of the program is its capability of analysis of CHP units which participate in the spot market. It simulates the working of energy system with a one minute time-step and the maximum timeframe which can be used is 40 years. The program has been developed by EMDInternational A/S in Denmar and can be valued for its wide possibilities, but it requires purchasing as it is commercialized and not available for free (price according to [32] in 2010 was in a range between 2700 – 5600 € depending on installed modules) [27, 29, 33].

Authors [27] mention the software *SIVAEL* (SImulating heating ("VArme") and ELectricity) which was a software developed by Danish transmission system operator (TSO), Energinet.dk, dedicated for analyses of CHP, condensing plants, wind power and battery energy storage. It was especially useful for wind power generation assessment as the tool used dedicated algorithms for weather forecasting purpose. Program delivers information about optimal way of operation of given plant including variable costs, however fixed costs (investment and operation and maintenance costs) were not included. Simulation was based on 1 hour time-step, scenario timeframe was 1 year and it had a free for download version available. Currently, SIVAEL has been replaced with SIFRE (Simulation of Flexible and Renewable Energy) which focuses on simulation of the spot market and analyses of integration of various energy systems. The simulation is flexible and allows to account for different energy carriers [29].

RETScreen (Clean Energy Management Software) is also a bottom-up approach software which offers the a vast range of analyses for various technologies including highly efficient and renewable units. It works on the basis of comparison between of actual technology and a new one, proposed in its place, focusing on difference between costs rather than total costs involved which should be kept in mind when analyzing results. Program produces economic indices serving for assessment of an investment i.e. net present value (NPV) and internal rate of return (IRR) are being calculated. Time-step used for calculation is 1 month, maximum timeframe of scenario is 50 years. Program has been developed by Natural Resources Canada (contributions from government and industry) and it used to be free charge. Currently, an updated version, *RETScreen Expert*, is in use, which uses the same approach and allows the user to perform even more complex analyses, although it is free of charge only in its viewer mode (saving and exporting of files is not available). Generally, software is a very advanced tool which allows the user to perform technical, environmental, economic and risk analyses [27, 34].

An interesting software which is not included in [27] and which could help to assess CHP units is DER-CAM (Distributed Energy Resources – Customer Adoption Model), a software designed for cost optimization. Program uses two main modules: investment and planning and operations. Investment and planning allows to allocate resources in optimal way considering energy generation and storage based on loads, tariffs and weather conditions within representative days throughout the year. Once the capacity is determined, optimization of operation of technology is performed so that annual energy cost or CO_2 emissions are minimized (or both through multi-objective function) in reference to a base case scenario. Implemented model requires respective loads and demands and it can serve to model PV, solar thermal collectors, wind generation, CHP, fuel cells, combustion engines. Outputs from the simulation include optimal scheduling strategy (in terms of operation) and detailed economic report [29].

According to [27], among the described programs, *RETScreen* and *BCHP Screening Tool* have the highest number of downloads and users. Final choice of software depends however always on one's specific requirements.

1.8. Literature review

Literature in the field of design and optimisation of cogeneration systems is vast, since energy and environmental situation changes rapidly, lots of the most actual information can be found through online articles from verified sources. This literature review refers to sources that support statements given in this paper, however there are also many others that can contribute to deeper understanding of those subjects.

The issue of fossil fuels and their impact on the environment has been discussed in this work based on information delivered by articles from The National Academies of Science, Engineering, Medicine, Octopus Energy, The National Aeronautics and Space Administration, The Union of Concerned Scientists, Scottish Environment Protection Agency and report from International Energy Agency regarding CO_2 emission [1, 3, 4, 5, 6]. As for the literature, authors Gaete Morales, Carlos & Gallego Schmid, Alejandro & Stamford, Laurence & Azapagic, Adisa. (2019) [35] present an interesting paper regarding life cycle environmental impact of fossil fuels used for electricity production for the case of Chile over ten-year period, between 2004 and 2014. The authors compare the impact from individual technologies (natural gas, coal and oil) obtaining results which classify coal to be the most hazardous fuel and indicating policies that should be applied in order to improve the current state. One of the conclusions the authors make is the proposal of gas to be a replacement for coal and oil plants, which is the same concept as proposed in this work. An informative paper regarding coal to gas switch, proposed in mentioned work [35] as a way to improve environmental standards, has been modelled for the case of China by Chen, Hao & Geng, Hao-Peng & Ling, Hui-Ting & Peng, Song & Li, Nan & Yu, Shiwei & Wei, Yi-Ming (2019) [36]. Authors examine three models focusing on physical, economic and environmental possibilities of fuel switch and comment on feasibility of such switch in respect to spatial conditions. Environmental effect of switch from coal to gas electricity generation for the case of USA has been described by Lueken, Roger & Klima, Kelly & Griffin, W. Michael & Apt, Jay (2016) [19]. They confirm the change of fuel to be positive due to the reduction of SO_2, NO_x and particulate matters. Valuable information about benefits from the switch can be also found from online source administrated by The Powering Past Coal Alliance (PPCA) [20]. Article discussing pollution situation (CO_2, NO_2, benzene, PM_4) in the air in Poland (Upper Silesia region) has been presented by authors Kozielska, Barbara & Mainka, Anna & Zak, Magdalena & Kaleta, Dorota & Mucha, Walter (2020) [37]. They examined the air inside and outside residential buildings studying respective rooms (kitchen, living room, bedroom) and verifying if the occupants are exposed to pollution, dangerous for human's health, which they found to be true (occupants are exposed to particulate matters).

Since introducing renewable sources of energy is a parallel goal for Polish energy policy, a concept of implementing biomass and biogas to CHP unit for the purpose of environmental and economic assessment is implemented in the software. Advantages of introducing biomass has been analyzed by Loha, Chanchal & Karmakar, Malay & Chattopadhyay, Himadri & Majumdar, Gautam. (2019) [22]. Authors deliver information about treatment of biomass in the process of conversion of biomass into useful energy form, explain which properties of the feedstock affect the treatment process and then comment on biomass in terms of positive impact on the environment as compared to fossil fuels. Further discussion about biomass properties has been made by Lalak-Kańczugowska, Justyna & Martyniak, Danuta & Kasprzycka, Agnieszka & Żurek, Grzegorz & Moroń, Wojciech & Chmielewska, Mariola & Wiącek, Dariusz & Tys, Jerzy (2016) [23] focusing on potential use for combustion purposes. Jarosz, Zuzanna. (2017) [26] comments on several types of biomass in terms of their potential in Poland. Similar discussion has been made by Korys, Katarzyna & Latawiec, Agnieszka & Grotkiewicz, Katarzyna & Kubon, Maciej (2019) [38] where authors provide the review of biomass potential in Poland, focusing on agriculture and food industry which generate considerable amounts of waste. Worth mentioning online source which provide some useful information about biomass is a webpage of State of the Planet from Earth Institute, Columbia University [25].

Cogeneration technology has been described based on book from Skorek J., Kalina J. "Gas cogeneration systems" (2004) [7]. Despite the fact that book does not belong to recent literature, it provides information necessary to understand the concepts, as the core of the technology has not changed over the years. Beside technical information, the book focuses on criteria serving to assess CHP unit in terms of profitability and shows some specific examples of techno-economic analyses. Recent publication from Breeze Paul "Combined Heat and Power" (2018) gives technical background of CHP technology and discusses some recent use of it in terms of integration of CHP with fuel cells as well as renewable and nuclear energy [8]. A valuable paper discussing integration of biogas and natural gas in gas turbine CHP system has been prepared by Kang, Jun & Kang, Do & Kim, Tong & Hur, Kwang (2014) [39]. The authors examine gases mixing ratio and heat sales ratio on the costs of electrical energy and heat produced concluding that higher proportion of natural gas makes CHP plant more susceptible to economic factors. An interesting paper has been also delivered by Sun R, Liu T, Chen X, Yao L [40] regarding co-firing of biomass with coal. Authors discuss optimization model seeking optimal biomass-coal co-firing method under constrains from multiple decision makers in respect to environmental-economic equilibrium. They analyze an example of Heilongjiang Province proving that power plants which utilize more biomass are less sensitive to CO_2 constrains. United States Environmental Protection Agency and Office of Energy Efficiency & Renewable Energy of the Energy Department (USA) provide informative online materials about CHP technology [31]. Development of CHP units in Poland has been delivered by Matuszewska, Dominika & Kuta, Marta & Gorski, Jan (2017) [18].

Introduction of new energy project brings the issues of uncertainty. Feasibility of CHP systems can be assessed using models. Authors Angrisani, Giovanni & Rosato, Antonio & Roselli, Carlo & Sasso, M. & Sibilio, Sergio (2012) [41] discuss tests on experimental plant (piston engine realizing micro-cogeneration and micro-trigeneration as coupled with thermo-chemical absorption) which is the basis for parametric model. Paper given by Wang, J. J., Jing, Y. Y., Zhang, C. F., & Zhai, Z. J. (2011) [42] discusses energy flows of CHP system through primary energy savings, exergy efficiency and CO_2 emission reduction analysis for a commercial building in Beijing, China, which is an example of analytical analysis conducted in steady-state. Authors Li, C. & Shi, Y. & Huang, X. (2008) [43] examine the impact of average, uncertainty and peaks on optimal operation and cost reduction based on dynamic analytical model (using max-integer nonlinear programming). Development of computational modelling has allowed to automate the process of assessing the feasibility of energy systems through introduction of complex dynamic models implemented into software. An informative paper regarding that matter has been delivered by Connolly, D. & Lund, Henrik & Mathiesen, Brian & Leahy, Martin (2010) [27] who present a review of different software which are designed for analyses (technical, economic, optimization) of energy systems in terms of their integration with renewable sources of energy. The article provides information required in order to identify the tool which is the most suitable for one's purpose. Another paper describing software tools designed for identification of socio-economic optimal operation and expansion of energy systems has been given by Kolstad, Magne Lorentzen; Backe, Stian; Wolfgang, Ove; Satori, Igor (ZEN Report No. 6 – 2018) [29]. Yet another review of such tools with focus on residential energy management (tools for analysis of building energy systems, building electrical loads, integration of renewables into buildings in terms of operation, economic factors and opitimization) has been presented by Mahmud, Khizir & Amin, Urja & Hossain, M.J. & Ravishankar, J. (2018) [44]. Papier reviews over 100 software in terms of their applications, limitations and strengths concluding that real case problems require specific models and none of the discussed programs is capable of analyzing of all applications for residential energy systems and one should always look for adequate software for given problem. Some more detailed information and, in some cases, links to respective textbooks of the specific programs can be found on theirs distributors websites [30, 31, 32, 33, 34, 45]. An example of analysis obtained through using one of these software has been delivered by Yu Pan, Liuchen Liu, Tong Zhu, Tao Zhang, Junying Zhang (2017) [46]. Authors used *RETScreen* software to analyze four scenarios of energy supply forms with implementation of renewable sources of energy for the case of Chongming, China. They obtain that development of natural gas based CHP and biomass is a must in order to meet the energy demand and lower the amount of imported energy. Results show that expansion of CHP systems allows to lower greenhouse gases emission and, even in case of the worst policy scenario, CHP proved to be still economically profitable. Another interesting paper has been delivered by Karlsson, K. B., & Meibom, P. (2008) [47]. The work investigates economic profitability of Nordic energy system with the majority of renewable energy in generation sector and hydrogen in transport sector using optimization model Balmorel. Authors show that in 2050 that it is viable to have 95% in generation sector and 65% in transport sector covered by renewable sources.

1.9. Problem statement

Designing technological systems of distributed energy encounters optimization problem which could be formulated in a following way, at certain variability of the final energy demand the technological system should be configured in such way that the rated and operating parameters of the devices allow to achieve extreme (maximum or minimum) value of objective function under existing limitations and considered time horizon [48]. Modelling of energy systems contributes to solving the problem through analysis of specific solutions. Optimization programs are capable of indicating the most desirable solution, considering given criteria and assumptions. Designed program is not a direct optimisation tool as it does not indicate priority of one variant over the other. It should be rather perceived as a tool which deeply analyses CHP system and verify expected results. It is convenient from the perspective of investors, owners or operators of the power plants which already know e.g. which technologies will be supported on policy level and, based on the experience, will be most likely profitable. Gas fuelled cogeneration system is the example of such technology for Polish market.

In order to perform preliminary analysis of CHP system in the dedicated software, the user needs to decide about:

- Selection of technology (system configuration, piston or turbine engine can be chosen).
- Selection of rated parameters (power of the system).
- Selection of operating parameters (load of the system).

Depending on evaluation criteria which are the basis for objective function, different solution might be indicated as the most favourable. For private investors, typically criteria based on directly economic objectives are the most important. Most common decision criteria are [48]:

- Maximum net present value.
- Maximum internal rate of return.
- Minimum payback period of the investment.
- Minimum value of total expenditure for investment.

From this criteria, usually NPV and IRR are most often used. If the investment is financed from public funds, socio-economic effects and implementation of energy policy might be primary. Main objectives for the EU membership countries nowadays are to decrease the exploitation of fossil fuels with increase of renewable generation and decrease of emissions. Objective function in such cases could aim to determine [48]:

- Minimum hazardous emissions (PM10 and PM2.5).
- Minimum GHG emissions.
- Maximum value of energy efficiency of the system.
- Maximum fuel chemical energy savings.

Energy and ecological goals are in such case basis criteria in optimization of distributed power generation systems. Analysis of local profitability of the project should be perceived as auxiliary assessment aimed at verification of convergence between investment and public interest and the utility of financial support mechanisms for investment projects.

Main limitations of the investment which are the constraints of the objective function are determined by [48]:

- Load profiles (heat load in case of designed software, electrical energy or specific parameters of given energy carrier in general case).
- Requirements for parameters of final energy carriers.
- Availability of fuels and materials.
- Technical characteristics of machines and devices.
- Fuel parameters.
- Investment outlays.

Approach proposed in the software requires from the user to declare prices of fuels, materials and energy carriers which allow to determine annual costs and revenues and therefore perform investment assessment over considered lifetime. The assumptions of constant prices and the fact that only one technology is analyzed at a time are the simplifications which make it impossible to clearly identify optimal solution. Another barrier is that worldwide energy market is susceptible to changes and local market strongly depends on current legislation (subsidies, capacity market, but also change in policy, additional taxes, penalties etc.) and trade agreements (e.g. supply of gas from other country in form of contract for few years), what can significantly influence incomes and outcomes for the company. Although cost increase rates are implemented in the program (the user declares annual increase of given price), fluctuations of the prices might be too strong and greatly affect the profitability of the investment. In order to address this issue, a sensitivity analysis is implemented in the software, which allows the user to obtain the results of investment analysis, with a change of given price in reference to a base price introduced before. In this way, a set of scenarios accounting for different prices can be determined and the user can notice how the potential change in price of given parameter affects the final solution. Ultimately, a comparison of different technologies at different powers can also be performed, however it needs to be performed manually as the program does not support an option of finding the optimal solution on its own. Designed software is however dedicated for companies that run power plants delivering district heating (and other entities interested in analysis of CHP system) which already have the knowledge about technology and its specific performance, namely what kind of powers and loads they can expect. In such case, two scenarios, one considering piston engine and the other considering turbine engine, can be compared and more favourable one could be chosen.

2. Designed software and model

The designed program is a basic desktop application, programmed as Graphical User Interface, divided into series of tabs. The software has been written in Python 3 through tkinter module using notebook and frame widgets. Notebook serves as upper layer which uses subsequent frames for the tabs. General way of using the software is presented in figure 14.

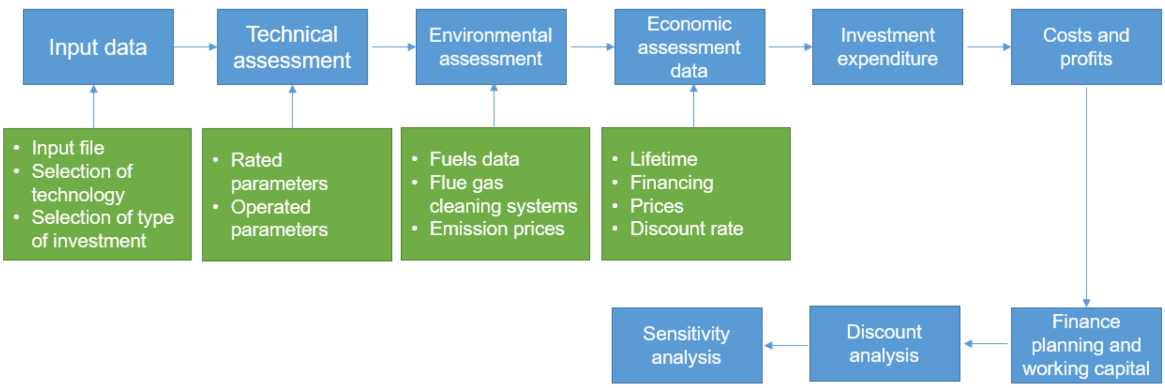


Figure 14. General structure of the software.

Green boxes present the information that the user needs to input, blue ones correspond to particular tabs. Each tab is a separate frame for which the calculations are performed. The results from one tab are required in order to perform calculations in the next tab. The user should introduce the data in given tab, perform calculations, make changes to data if necessary, perform calculations again, and then proceed further.

In order for the user to input data, entry widget is used. The results, as well as all the descriptions are made using label widget.

A detailed discussion of subsequent tabs is presented in the following subchapters.

Methodology and specific equations implemented in the program are based on dedicated spreadsheet package created in Microsoft Excel:

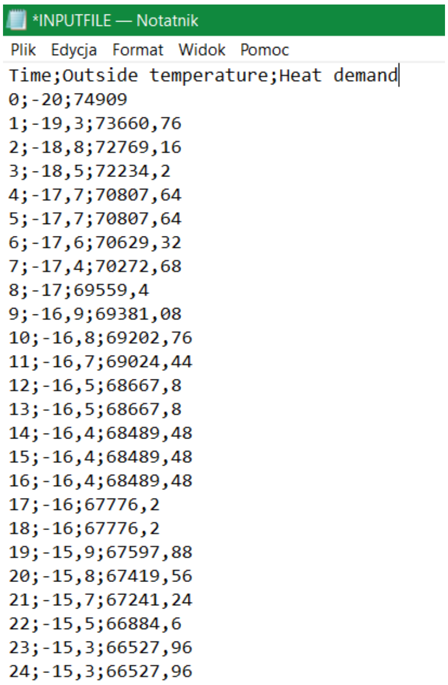
- Slengine.xls - workbook for the analysis of systems with a gas piston engine.
- Gtsimple.xls - workbook for the analysis of systems with an industrial gas turbine and a water heat recovery boiler.

These materials belong to the advisor of this thesis and have been shared with the author of this work for the purpose of creating a software. Most of the equations used in the spreadsheets have been cited from [7]. Some of the equations have been changed as they have been updated and some of the them have been adjusted due to specific needs of the written program.

The description of the software part of the thesis focuses rather on explaining the algorithm implemented in the written program instead of presenting all of the equations used with respective units in details. The most important equations are presented, rest is discussed. Such approach allows to keep the work more concise and orderly. For the comfort of describing the algorithm and reading the equations, a repetition of the shortcuts from abbreviation is present. In case of figures that present values calculated throughout the lifetime, the screenshots are adjusted and present the values only for a few years.

2.1. Input data

The first tab requires from the user to insert a data file which will serve as basis to perform calculations. A user needs to input the name of the file (optionally with the directory but for the purpose of the simulation which will be presented in this work, a file has been already placed in an appropriate folder) and choose the type of data. Input file needs to contain hourly time, outside temperature in °C and heat demand in kW. Type of data determines whether the file works with data put in columns (figure 15) or rows. A file with sample data is presented in figure 15 (data only for 24 hours). Inputfile.csv uses historical data for power plant supplying district heating grid. It is required from the user to provide heat demand for given facility as the program does not support a database. These data could be gathered from historical performance of a plant (which is the approach used in case of Inputfile.csv) or from external software predicting future energy demand on given area/facility. The file contains 8760 rows as the simulation is performed for the whole year. If a file did not have 8760 rows and the user would be interested in performance of CHP for the shorter period (e.g. six months) or longer period (e.g. two years), the calculations would be performed, however one should keep in mind that all the references in further tabs are made assuming one year period. For technical and environmental assessment inserting a file with data for other period than one year would not cause a problem, in case of economic assessment a shorter period could be assumed, for instance in case of the CHP working only for nine months during the year, but for longer period than one year, the some part of economic analysis could be a source of confusion and therefore it would not be a recommended approach.


*INPUTFILE — Notatnik
Plik Edycja Format Widok Pomoc

```
Time;Outside temperature;Heat demand
0;-20;74909
1;-19,3;73660,76
2;-18,8;72769,16
3;-18,5;72234,2
4;-17,7;70807,64
5;-17,7;70807,64
6;-17,6;70629,32
7;-17,4;70272,68
8;-17;69559,4
9;-16,9;69381,08
10;-16,8;69202,76
11;-16,7;69024,44
12;-16,5;68667,8
13;-16,5;68667,8
14;-16,4;68489,48
15;-16,4;68489,48
16;-16,4;68489,48
17;-16;67776,2
18;-16;67776,2
19;-15,9;67597,88
20;-15,8;67419,56
21;-15,7;67241,24
22;-15,5;66884,6
23;-15,3;66527,96
24;-15,3;66527,96
```

Figure 15. Input file to the software.

Input file could be a .csv file (comma-separated values) or a .txt file. Between the values, semicolons or commas can be used, in the case of sample file, semicolons are used. Inputfile.csv uses values of heat demand which are organized in a list from maximum to minimum value. Such organization is not the general case, however it is in such form that these data have been delivered to the author of this work and it has not been changed (same data as used in spreadsheets serving as base for this software). Organization of data does not affect the calculations.

Input data tab allows the user to visualize the data and choose the type of performance. Figure 16 presents a screenshot of first tab of the software (and shows other tabs).

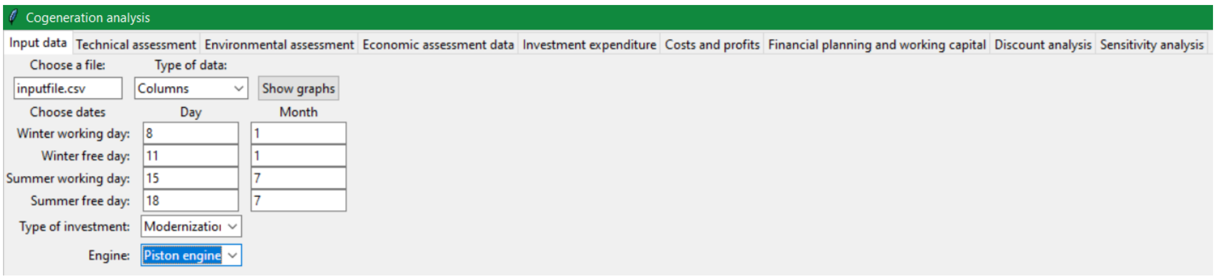


Figure 16. Input data tab (and list of other tabs).

Visualization of the data is performed by Show graphs option. It creates an additional tab which shows two types of graphs: daily graphs of characteristic days and load duration curve. First graph presents heat load as a function of 24-hour time for winter working and free days, second presents summer working and free days. A user has an option to indicate which days should be considered what naturally depends on the data. Since in the case of sample simulation, which uses a file with data ordered annually, those graphs do not represent respective days and therefore these are not helpful to use. The third graph which shows the load duration curve, which is the name for the curve of annually ordered data, is presented in figure 17.

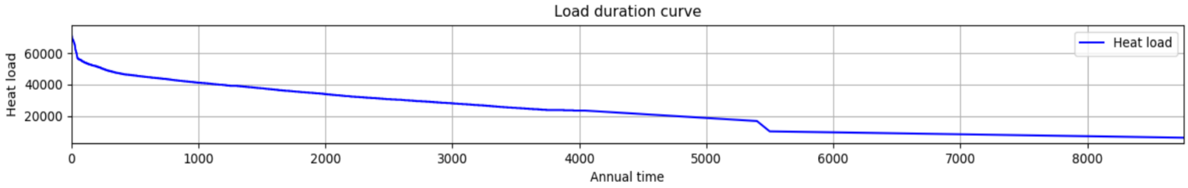


Figure 17. Load duration curve.

Visualization of the data helps the user to assess the size of equipment required to match the demand. CHP units can work in different modes in terms of their operation. Heat tracking mode has been implemented meaning that its aim is to cover the demand for heat, which is the case if the CHP unit is designed to supply the heat for district heating grid. Beside heat tracking, an electrical energy tracking mode (CHP is programmed to cover the demand for electrical energy) and economical type of operation (CHP is programmed according to the most profitable type of operation, prices according to tariffs are included for each iteration) could be implemented depending on specific investment considered. In the software designed for the purpose of this thesis, a heat tracking has been implemented due to the fact that it is considered to be the most favorable type of operation (since program was prepared having in mind that development of district heating is one of the main goals of Polish energy policy).

Input data defines also type of investment and engine used for analysis. Type of investment supports two options:

- Modernization – gas fueled CHP unit is being built on the site of coal powered unit but the coal unit is not removed and it can work. As for the calculations the importance of this is that it is assumed that in case of the demand which cannot be covered by engine and peak-reserve boiler, a coal unit operates in order to support CHP system and meet the demand.
- New investment – gas fueled CHP unit alone is considered.

As for the engine a user can choose between piston engine and turbine engine. The engines are the same as discussed in chapter 1.2.2, shown in figures 1 and 2.

2.2. Technical assessment

2.2.1. Input data for technical assessment

Technical analysis performs a simulation of working of cogeneration unit with a step of 1 hour for a period of one year (discrete model). Energy balance is performed according to overall equation:

$$\dot{P} * LHV + N_G = \dot{Q}_D + \dot{Q}_S + N_{CHP} \tag{7}$$

where: $\dot{P} * LHV$ – total amount of energy delivered by fuel to CHP system, stream of fuel multiplied by lower heating value of fuel (in case of modernization type of investment, it also accounts for energy stream from coal i.e. fuel stream of coal multiplied by caloricity of coal), N_G – electrical power delivered to CHP unit from the grid, $\dot{Q}_D$ – heat power produced by CHP to district heating grid, $\dot{Q}_S$ – heat power produced by CHP dissipated to the atmosphere, N_{CHP} – electrical energy produced by CHP.

Technical assessment tab is divided into a series of subsections. First section, technological system, provides statistical technical information about the CHP. In order to perform the calculations, it is required from to user to define some of the variables. Technological system requires from the user to introduce:

- Heat power of engine – program allows to include up to three engines in a system. If no value is introduced, by default the software treats it as zero, meaning that this engine is not included into consideration. Referred in kW.
- Minimum electrical load of engine – minimum load for which the engine can operate, referred to electrical load in percentage.
- Captive power consumption – power consumption that can be understood as used for own needs of CHP system. Referred in percentage.

Second section is the load of engine, where the user is obligated to define maximum electrical load at which CHP will be operating (typically 100%), referred in percentage.

Figure 18 presents technological system and load of engine data provided by technical assessment tab for the case of sample simulation.

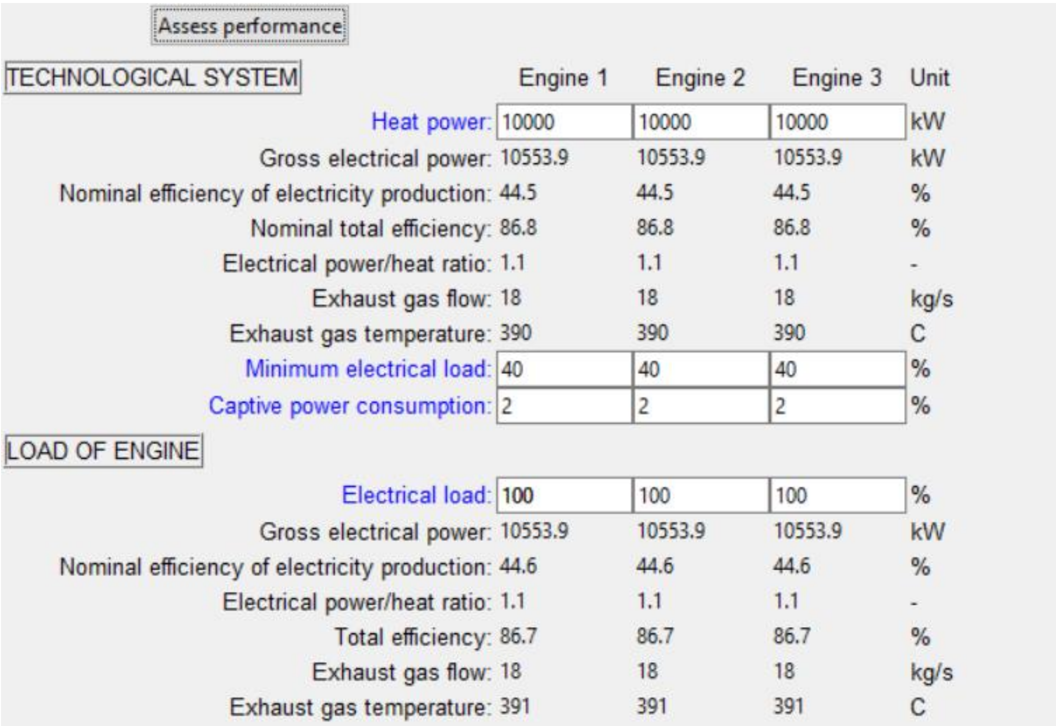


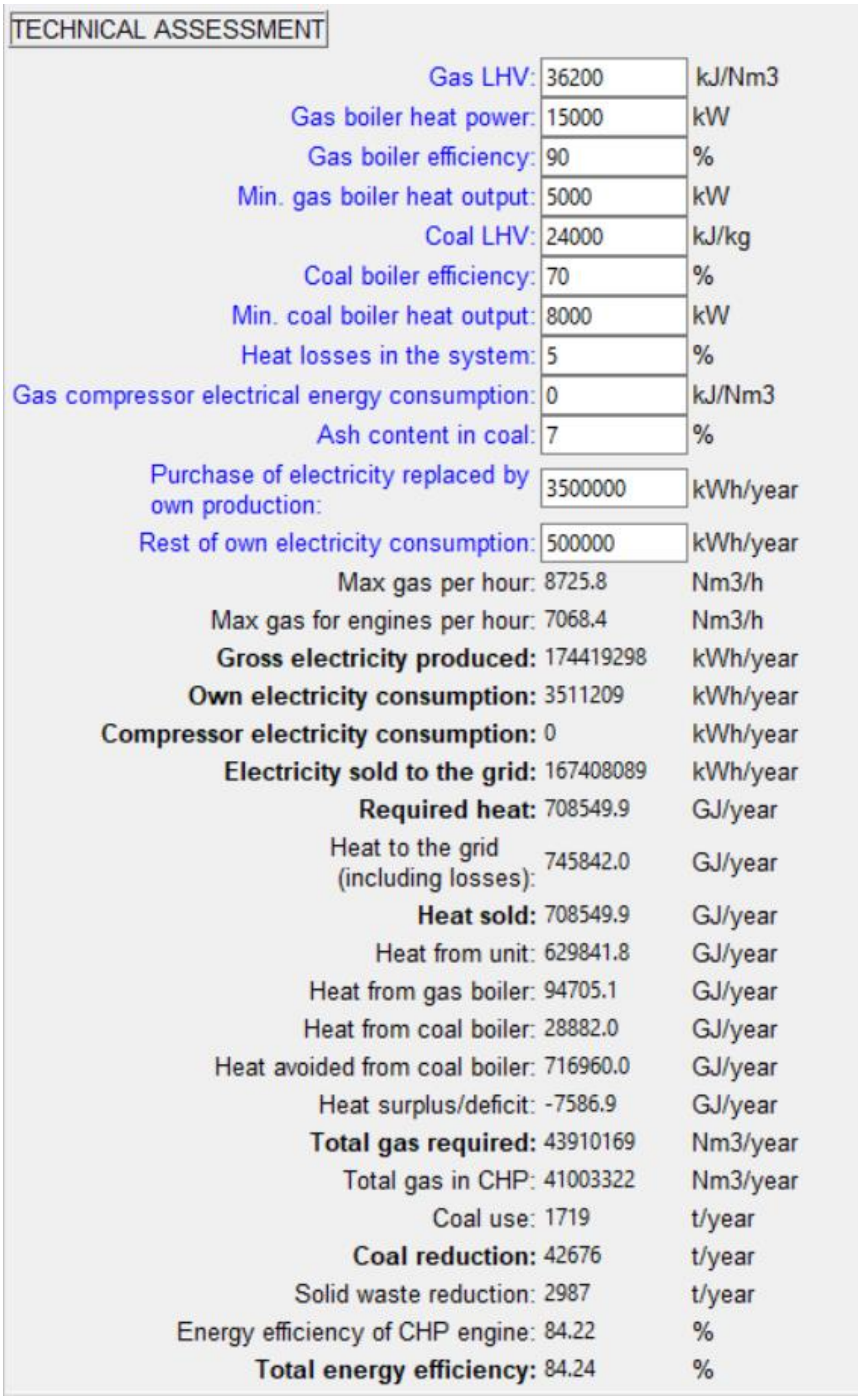
Figure 18. Technical assessment, technological system and load of engine.

Third section is technical assessment, where user needs to input following data:

- Gas LHV – lower heating value of natural gas used for analysis, referred in kJ/Nm^3.
- Gas boiler heat power – power of peak-reserve gas boiler, referred in kW.
- Gas boiler efficiency – efficiency from technical specification of the boiler, referred in percentage.
- Minimum gas boiler heat output – minimum power at which a boiler can operate, referred in kW.
- Coal LHV – LHV of coal, referred in kJ/kg.
- Coal boiler efficiency – efficiency from technical specification of the boiler, referred in percentage.

- Minimum coal boiler heat output – minimum power at which coal unit can operate, referred in kW.
- Heat losses in the system – amount of heat losses occurring between plant and end-users, referred in percentage (heat losses are considered to be constant).
- Gas compressor electrical energy consumption – consumption of electrical energy for the purpose of supplying gas compressor. Looking at schemes of analyzed engines, as in figure 1 and 2, compressors are linked to turbines through common shaft and therefore are included in efficiency of turbines (in case of piston engine, it is included in electrical efficiency of whole engine), however in case of multi-stage compressors, electrical engines are used to supply those units. Since it could be a considerable amount of electrical energy (especially in case of gas turbines), user has a possibility to declare such consumption referred in kJ/ Nm_3. For sample simulation this is assumed to be 0 kJ/ Nm_3.
- Ash content in coal – mass percentage of ash in coal, referred in percentage, based on proximate analysis.
- Purchase of electricity replaced by own production – estimated amount of electrical energy that the plant requires and which will be supplied from new CHP unit. Referred in kWh/year.
- Rest of own electricity consumption – estimated amount of electrical energy that the plant requires and which will be purchasing from the grid, referred in kWh/year.

Figure 19 presents technical assessment section for the case of sample simulation. In general, the labels describing variables which are to be defined by the user use blue font color. Once the data are delivered, a user should click “Assess performance” button (shown in figure 18) in order to obtain the results.



TECHNICAL ASSESSMENT

Gas LHV:	36200	kJ/Nm3
Gas boiler heat power:	15000	kW
Gas boiler efficiency:	90	%
Min. gas boiler heat output:	5000	kW
Coal LHV:	24000	kJ/kg
Coal boiler efficiency:	70	%
Min. coal boiler heat output:	8000	kW
Heat losses in the system:	5	%
Gas compressor electrical energy consumption:	0	kJ/Nm3
Ash content in coal:	7	%
Purchase of electricity replaced by own production:	3500000	kWh/year
Rest of own electricity consumption:	500000	kWh/year
Max gas per hour:	8725.8	Nm3/h
Max gas for engines per hour:	7068.4	Nm3/h
Gross electricity produced:	174419298	kWh/year
Own electricity consumption:	3511209	kWh/year
Compressor electricity consumption:	0	kWh/year
Electricity sold to the grid:	167408089	kWh/year
Required heat:	708549.9	GJ/year
Heat to the grid (including losses):	745842.0	GJ/year
Heat sold:	708549.9	GJ/year
Heat from unit:	629841.8	GJ/year
Heat from gas boiler:	94705.1	GJ/year
Heat from coal boiler:	28882.0	GJ/year
Heat avoided from coal boiler:	716960.0	GJ/year
Heat surplus/deficit:	-7586.9	GJ/year
Total gas required:	43910169	Nm3/year
Total gas in CHP:	41003322	Nm3/year
Coal use:	1719	t/year
Coal reduction:	42676	t/year
Solid waste reduction:	2987	t/year
Energy efficiency of CHP engine:	84.22	%
Total energy efficiency:	84.24	%

Figure 19. Technical assessment results.

2.2.2. Algorithm of technical assessment

All the discussed parameters are shown in figures 18 and 19.

2.2.2.1. Technological system

Gross electrical power and nominal efficiency of electricity production are calculated from assumed heat power through empirical equations cited in spreadsheets.

Nominal total efficiency is calculated according to overall equation for efficiency:

$$\eta = \frac{\dot{Q}_{chp} + N_{chp}}{\dot{Q}_{fuel}} \tag{8}$$

where: η – nominal total efficiency, $\dot{Q}_{chp}$ – heat power of CHP, N_{chp} – gross electrical power of CHP, $\dot{Q}_{fuel}$ – chemical energy from delivered fuel as stream of energy (same meaning as power).

Chemical energy from delivered fuel as stream of energy is obtained by:

$$\dot{Q}_{fuel} = \frac{N_{chp}}{\frac{\eta_{el}}{100}} \tag{9}$$

where: η_{el} – nominal efficiency of electricity production.

Electrical power to heat ratio (association indicator) is formulated analogically as in equation (5). Exhaust gas flow and exhaust gas temperature are estimated based on gross electrical power through empirical equations.

2.2.2.2. Load of engine

Introduced load of engine is the basis for new value of gross electrical power. This is the value that serves to calculate reduced, new values of: nominal efficiency of electricity production, electrical power to heat power ratio (association indicator), total efficiency, exhaust gas flow and exhaust gas temperature. Since the equations are vital for further calculations these are presented below [7] distinguishing between piston and turbine engine.

a. Piston engine

Reduced gross electrical power:

$$N_{chpl} = N_{chp} * L \tag{10}$$

where: N_{chpl} – reduced value of gross electrical power, N_{chp} – gross electrical power, L – introduced load of CHP unit.

Reduced efficiency of electricity production:

$$\eta_{ell} = \eta_{el} * (0.0025 * L^3 - 0.2341 * L^2 + 0.587 * L + 0.6447) \tag{11}$$

where η_{ell} – reduced value of efficiency of electricity production, η_{el} – basic value of efficiency of electricity production.

Reduced electrical power to heat power ratio:

$$\sigma_l = \sigma * (0.8147 * L^3 - 1.9848 * L^2 + 1.7756 * L + 0.3968) \tag{12}$$

where: σ_l – reduced electrical power to heat power ratio.

Reduced total efficiency:

$$\eta_l = \eta_{ell} * (1 + \frac{1}{\sigma_l}) \tag{13}$$

where: η_l – reduced total efficiency.

Reduced exhaust gas flow:

$$G_{fgl} = G_{fg} * (0.9318 * L + 0.069) \tag{14}$$

where: G_{fg} – exhaust gas flow, G_{fgl} – reduced exhaust gas flow.

Reduced exhaust gas temperature:

$$T_{fgl} = T_{fg} * (1.0004 * L^{-0.0457}) \tag{15}$$

where: T_{fg} – exhaust gas temperature, T_{fgl} – reduced exhaust gas temperature.

b. Gas turbine

Reduced gross electrical power :

$$N_{chpl} = N_{chp} * (-2.6934 * {T_r}^2 + 3.653 * T_r + 0.0404) * L \tag{16}$$

where: T_r – reduced outdoor temperature (temperature of air supplying gas turbine).

Reduced outdoor temperature:

$$T_r = \frac{(T_{out} + 273.15)}{288.15} \tag{17}$$

where: T_{out} – outdoor temperature.

Reduced efficiency of electricity production:

$$\eta_{ell} = \eta_{el} * (1.2918 * L^3 - 3.142 * L^2 + 2.851 * L) * (48.511 * {T_r}^4 - 190.85 * {T_r}^3 + 278.45 * {T_r}^2 - 178.88 * T_r + 43.796) \tag{18}$$

Reduced electrical power to heat power ratio

$$\sigma_l = \sigma * (0.7854 * L^3 - 2.0368 * L^2 + 2.1337 * L + 0.1492) * (-0.1774 * {T_r}^3 - 1.6136 * {T_r}^2 + 2.4171 * T_r + 0.3736) \tag{19}$$

Reduced exhaust gas flow

$$G_{fgl} = G_{fg} * (-0.0007 * L^2 + 0.0122 * L + 0.9885) * (-1.5778 * {T_r}^2 + 2.1063 * T_r + 0.4722) \tag{20}$$

Reduced exhaust gas temperature

$$T_{fgl} = T_{fg} * (-0.1147 * L^2 + 0.7589 * L + 0.354) * (1.0681 * {T_r}^2 - 1.7503 * T_r + 1.6826) \tag{21}$$

Reduced total efficiency for gas turbine case is calculated the same as in equation (13). Outdoor temperature of 15 °C is used for technological system and load of engine, simulation uses data about temperature from the input file.

2.2.2.3. Technical assessment

Information presented in technological system and load of engine present statistical data about piston and turbine engines. The stage of actual simulation takes place in technical assessment subsection.

First, maximum gas for CHP system and maximum gas for engines of CHP (without peak-reserve boiler), are calculated based on respective powers and efficiencies (as in equations (8,9)). Then an algorithm, programmed as heat tracking type, defines the distribution of heat generation between CHP engine, peak-reserve boiler and a coal unit in case of modernization type. It compares demand for given hour with powers of respective units and defines at what level each of the equipment operates. CHP engine is the primary source of heat generation with possibility of operation in between its minimum (defined by user) and maximum load. If the energy demand is higher, a peak-reserve boiler is launched, if energy heat demand is still not met, a coal unit supports the CHP system (both gas boiler and coal unit are also capable of working between their minimum and maximum load). Program stores the values of generation of respective equipment in lists (which is a convenient form considering Python as programming language). Based on heat balance, lists including instantaneous heat loads (ratio of instantaneous value of CHP generation to maximum CHP generation) , electrical power to heat power ratios (eq. (12) or (19)), electrical energy generation (eq. (5)), own electrical energy consumption (active electrical energy multiplied by captive power consumption value), electrical efficiencies (eq. (11) or (18)) and fuel demands (eq. (9)) for respective hours are created. Once such lists are completed, numerical integration is performed in order to obtain annual values. An example of total value of heat generated by CHP engine over a year can be used for presenting implemented numerical integration.

Heat generated over time:

$$Q_{CHP} = \sum_{i=1}^{8760} 0.5 * \left(\dot{Q}_{CHP,i} + \dot{Q}_{CHP,i-1}\right) * (t_i + t_{i-1}) \tag{22}$$

which corresponds to trapezoidal rule of numerical integration, where $\dot{Q}_{CHP,i}$, $\dot{Q}_{CHP,i-1}$ are respective bases of trapezium (heat power of CHP engine), $t_i + t_{i-1}$ is a height of trapezium (time),

This approach has been used to obtain values of: gross electricity produced, own electricity consumption, required heat (and heat with losses), generated heat and gas requirements (optionally also coal) by respective equipment and heat surplus/deficit (value with minus is a surplus, as such amount of heat is not used and it is dissipated to the atmosphere). Based on these values, rest of the parameters are obtained.

Electricity sold to the grid is calculated according to equation:

$$N_{ELS} = N_{ELA} - N_{cap} - N_{compr} - N_{rep} \tag{23}$$

where: N_{ELS} – electrical energy sold to the grid, N_{ELA} – electrical energy produced from active power, N_{cap} – electrical energy for captive power consumption, N_{compr} – electrical energy consumed by compressor, N_{rep} – purchase of electricity replaced by own production (avoided cost).

Heat sold is the amount of heat that reaches customers (end users), which is the same number as heat demand, if analyzed system allows to cover the demand. For new investment type of operation, if CHP engine and gas boiler are not capable of meeting the demand, a heat deficit is included and heat sold is lower than the heat required.

Gas requirements from CHP and peak-reserve boiler allow to obtain total gas requirement which is a basis for the estimation of compressor electricity consumption. Gas requirement for peak-reserve boiler is calculated according to equation:

$$F_{gb} = \frac{Q_{gb}}{\frac{\eta_{gb}}{100}} * \frac{10^6}{LHV_{gas}} \tag{24}$$

where: F_{gb} – amount of gas for peak-reserve boiler, Q_{gb} – energy from gas peak-reserve boiler (from integration), η_{gb} – efficiency of gas boiler, LHV_{gas} – LHV of natural gas. Such approach assumes the efficiency of the gas boiler to be constant despite the load of boiler.

Such approach assumes the efficiency of the gas boiler to be constant despite the load of boiler.

For modernization type of investment, reduction of coal use (amount of coal which is saved by implementing CHP, additionally heat avoided from coal boiler is shown) with solid waste reduction and coal still in use are also included. Coal requirement (coal use) and savings are obtained by equations constructed by the same analogy as equation (24). Solid waste reduction is obtained from:

$$SWR = F_{CS} * \frac{Ash}{100} \tag{25}$$

where: SWR – solid waste reduction, F_{CS} – amount of coal which is saved due to CHP installation, Ash – ash content in coal.

Finally, technical assessment presents efficiency in CHP engine and total system efficiency. Efficiency of in CHP engine is calculated the same way as in equation (7), but annual values of CHP engine of generated active electrical energy, heat energy and fuel consumed are used.

Total system efficiency accounts for whole energy balance and it is obtained according to equation (for new investment type, a coal part is not included):

$$\eta_{total} = \frac{N_{ELA} + Q}{F_{gtotal} * LHV_{gas} + F_{Ctotal} * LHV_{coal}} \tag{26}$$

where: Q – total amount of heat energy input to the grid, F_{gtotal} – total value of gas used, F_{Ctotal} – total amount of coal used, LHV_{coal} – lower heating value of coal.

2.3. Environmental assessment

2.3.1. Input data for environmental assessment

Parameters calculated in technical assessment tab allow to perform environmental assessment of CHP system. In the first subsection, fuels data, user needs to introduce the following data:

- Coal and gas benchmarks and LHVs – since operators of power plants participate in the UE emissions trading system the companies receive or buy CO_2 emission allowances. In order to calculate the amount of emitted CO_2 for this purpose, there are standardized benchmarks for fuels, referenced in kg CO_2/GJ with corresponding lower heating values referenced in MJ/kg for coal and MJ/Nm^3 for natural gas. In case of simulation the values are taken from [48].
- Biomass and biogas shares in coal, before and after investment – since operators of power plants aim to reduce their emissions, biomass and biogas are introduced. The user defines

biomass share by the percentage of energy coming from biomass in reference to total energy required which without the biomass would be coming from coal in total. Analogical approach is implemented for biogas. Biomass is defined both before and after investment, biogas only after investment.

- Biomass and biogas lower heating values – biomass LHV is referenced in kWh/kg, biogas in MJ/Nm^3.
- Sulfur content in coal – mass percentage of sulfur in coal based on ultimate analysis.
- Ash content in biomass – mass percentage of ash in biomass based on proximate analysis.
- Sulfur content in gas – mass share of sulfur in gas, referenced in mg/Nm^3.

Flue gas cleaning systems is a section where the user defines the efficiency of flue gas cleaning installations considering each compound respectively. That accounts for equipment to capture: CO_2, SO_x, NO_x, CO, dust and b(a)p. References are set in percentages. Flue gas cleaning installations are considered to be working both before and after investment, although in the economic analysis, the cost of flue gas systems is included to expenditure. It is treated that previous gas systems installed for coal unit will be working with coal unit and new, separate one is purchased for gas system, while both systems will have the same efficiency.

Next subsection is called emission prices, where the user sets the price values for respective compounds. Reference is PLN/kg (since program is designed for Polish market) with the exception of CO_2 price as it uses a reference of PLN/t.

Final section is named comparison as it compares the emissions before and after installation of CHP system. Total values of annual costs for respective emissions, total prices, values of emission rights and profit are presented in figure 21.

Fuels data, flue gas cleaning systems and emission prices are seen in figure 20.

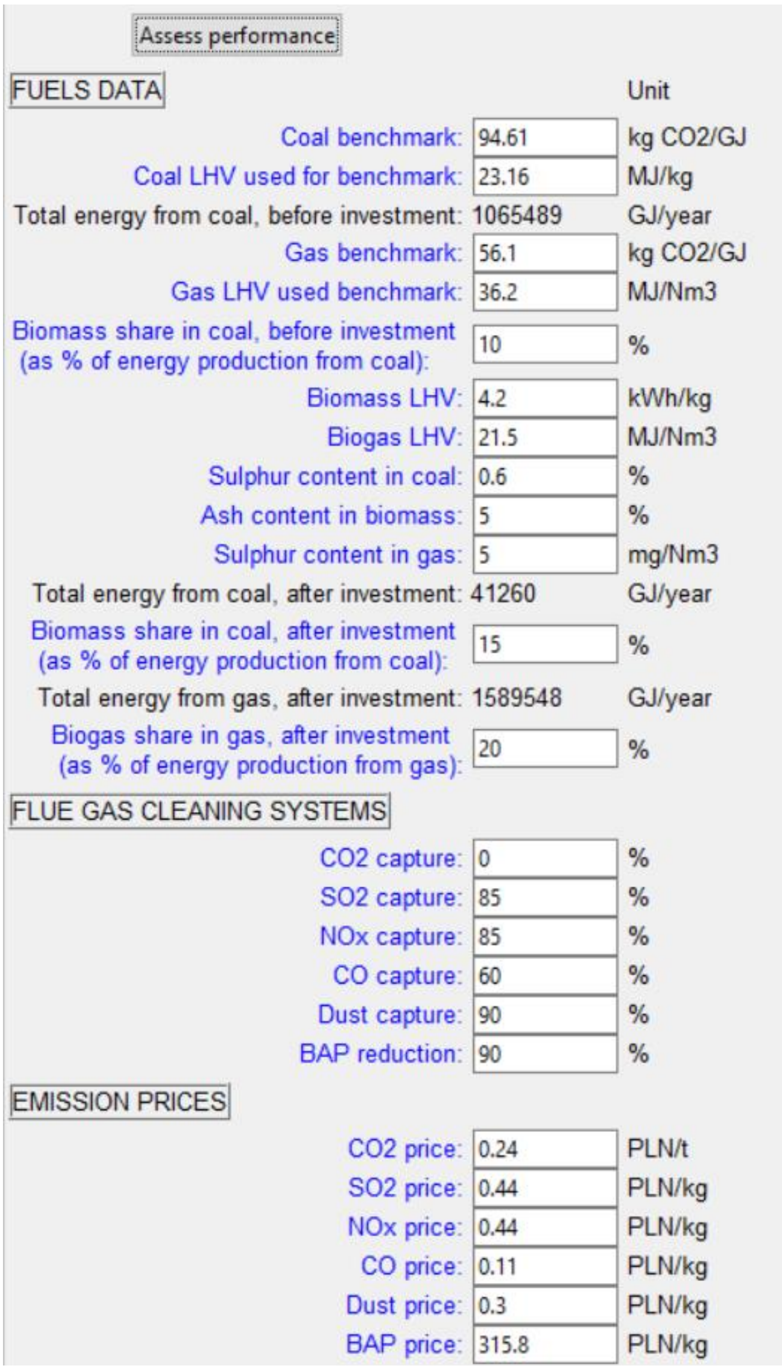


Figure 20. Environmental assessment input data.

2.3.2. Algorithm of environmental assessment

Total values of energy from coal and gas are known from technical assessment. Introducing information about the share of renewable sources to generation process and respective calorific values of these sources, allow to obtain final values of used coal, biomass, gas and biogas. The concept of delivering information about biomass and biogas at environmental assessment stage, instead of technical assessment stage, allows to keep technical assessment simpler in terms of calculations as well as required data, since the user can more easily assess the amount of renewable generation after seeing the annual energy requirements from conventional sources. However, one should keep in mind that all the data from technical assessment tab are referred only to usage of coal and natural gas in CHP system (e.g. solid waste reduction that can be affected by exploitation of biomass).

Input data in economical assessment tab deliver sufficient information in order to calculate emissions. Basic equation for estimating emissions [49]:

$$E_{X,Y} = F_X * W_Y * \frac{100 - \eta_Y}{100} \tag{27}$$

where: $E_{X,Y}$ – emission of a given compound (y) from considered fuel (x), F_X – amount of used fuel, W_Y – emission factor of given compound, η_Y – value of emission reduction (capture). Analyzed fuels "x" are coal, biomass, natural gas, biogas. Analyzed compounds "y" are CO_2, SO_x, NO_x, CO, dust and b(a)p.

Analyzed fuels "x" are coal, biomass, natural gas, biogas. Analyzed compounds "y" are CO_2, SO_x, NO_x, CO, dust and b(a)p. Emission factors are referenced in kg/Mg for coal and biomass and kg/10^6m^3 in case of natural gas and biogas.

Amount of fuel used is known from technical assessment tab and input data about share of biomass and biogas. Reduction of emission is input variable. The values of emission factors are shown in [49]. It is assumed that emission factors for wood represent emission factors for biomass.

2.3.2.1. Coal emission factors

Carbon dioxide emission factor is obtained according to benchmark [49]:

$$WC_{CO2} = W_{CB} * LHV_{CB} \tag{28}$$

where: WC_{CO2} – CO_2 emission factor from coal, W_{CB} – CO_2 coal benchmark, LHV_{CB} – LHV of coal used for benchmark.

Emission factors for SO_x, NO_x, CO, dust are presented in table 6.

Table 6. Coal emission factors [49].

Emission factor/Heat power	Q >= 12 MW	Q < 12 MW and Q > 3 MW	Q =< 3 MW
WC_{SO2}	17*x	16*x	16*x
WC_{NOx}	4	4	4
WC_{CO}	5	10	20
WC_{DUST}	3*a	2.5*a	2*a

where: x – sulfur content in coal, a – ash content in coal (declared by user).

Benzo(a)pyrene emission factor is assumed to be (from the spreadsheets):

$WC_{B(a)P}$ = 0.004.

2.3.2.2. Biomass emission factors

Values used in case of biomass are presented below. CO_2 emission factor is considered to be zero. B(a)p emission factor is assumed to be the same as in case of coal.

WB_{CO2} = 0.

Table 7. Biomass emission factors [49].

Emission factor/Heat power	Q >= 5.5 MW	Q < 5.5 MW and Q > 1 MW	Q =< 1 MW
WB_{SO2}	0.02	0.11	0.11
WB_{NOx}	0.8	0.95	1
WB_{CO}	11	16	26
WB_{DUST}	2.5*a	1.5*a	1.5*a

where: a – ash content in biomass (both declared by user).

$WB_{B(a)P}$ = 0.004.

2.3.2.3. Natural gas emission factors

Approach used in case of natural gas is analogical as to coal and biomass. The difference is in the b(a)p which is considered to be zero for gas and biogas (on the contrary to solid fuels [50]).

$$WG_{CO2} = W_{GB} * LHV_{GB} \tag{29}$$

where: WG_{CO2} – CO_2 emission factor from gas, W_{GB} – gas benchmark, LHV_{GB} – LHV of gas used for benchmark.

Table 8. Natural gas emission factors [49].

Emission factor/Heat power	Q >= 30 MW	Q < 30 MW and Q > 5.5 MW	Q < 5.5 MW and Q > 1.4 MW	Q =< 1.4 MW
WG_{SO2}	2*x	2*x	2*x	2*x
WG_{NOx}	7500	3700	1920	1280
WG_{CO}	270	270	270	360
WG_{DUST}	12	14.5	14.5	15

where: a – ash content in biomass (declared by the user).

$WG_{B(a)P}$ = 0.

Emission factors for natural gas are considered to be the same in case of biogas which is an implemented simplification as the paper [49] does not support specific emission factors for biogas (apart from emission factor of CO_2 which is zero). Emission factors for B(a)P from coal is taken from spreadsheets. The same value is used for biomass. Although B(a)P is a part of dust, not a separate emission, due its strongly toxic nature, additional cost for emitting this compounds is included.

2.3.3. Environmental assessment results

Sum of emissions from respective sources generates the comparison between emissions for old coal unit and new unit. It is shown in figure 21. In case of new type of investment the “Before” section is empty and therefore profit has a minus value, since the emissions are treated solely as a cost.

COMPARISON

	Before	After	
CO2 emission:	87549.9	74540.9	t
SO2 emission:	57.6	2.2	t
NOx emission:	24.8	28.6	t
CO emission:	190.8	13.0	t
Dust emission:	78.7	3.1	t
BAP emission:	0.0019	0.0001	t
Total price:	102462.08	33845.8	PLN
Emission rights:	87549.9	74540.9	t
Profit:	68616.28	PLN	

Figure 21. Environmental assessment results.

2.4. Economic assessment data

Economical assessment in the program is divided into series of tabs as the software presents detailed information for the user about cash flows and investment assessment.

In the first tab the user introduces the following variables in accordance to subsections.

2.4.1. Initial data

- Lifetime – number of years included for economical assessment.
- Acquisition and modernization year – year during which acquisition of the plant and modernization takes place. It can be treated as a year “0” as first year of the analysis is the first year of operation.
- Depreciation rate of fixed current assets – rate of depreciation (depreciation is a cost that represents how much of asset’s value has been used) related to the acquisition of a plant (current assets). Referenced in percentage/year.
- Depreciation rate of fixed new assets – depreciation related to modernization of a plant (new assets). Referenced in percentage/year.
- Income tax rate – referenced in percentage.
- Excise duty rate for electricity – referred in PLN/MWh.

2.4.2. Acquisition financing

- Net subsidies – subsidies (e.g. from government) that cover part of the investment for acquisition. It is referenced between 0 to 1. Acquisition financing refers to the cost of purchasing land and actual acquisition cost (shown in equation 57).
- Equity – own financial resources of the investor, referenced the same as net subsidies.
- Assumed return on equity – assumed variable describing profitability of used capital (return on investment is defined as ratio between net operating profit to invested capital) which in this case is equity, referenced in percentage.
- Credit 1 – credit that covers part of the investment, referenced as net subsidies.
- Credit 1 repayment period – number of years that will serve to repay the credit.
- Credit 1 interest rate – interest rate of the credit in percentage.

- Credit 2 – same definitions as for credit 1. Program allows to include up to 2 credits serving to cover the investment. Part of the investment that is covered by second credit is calculated from the equation:

$$credit2 = 1 - netsub - equity - credit1 \tag{30}$$

where: $credit2$ – part of the investment covered by second credit, $netsub$ – part of the investment covered by net subsidies, $equity$ – part of the investment covered by equity, $credit1$ – part of the investment covered by first credit.

If the user wants to define only one credit, he should set the value of credit 1 to be zero.

- Inflation rate – annual rate of inflation (rate at which price level of goods and services increase over a period), referenced in percentage.
- Discount rate – a rate that allows to converse future value of the capital to its present value (indicator allowing to express the change in value of money), referenced between 0 to 1. The user can use the discount rate calculated by the cost method according to equation:

$$r_d = \frac{(netsub + equity) * (r_e - inf)}{1 + inf} + \frac{credit1 * (r_{c1} - \mathrm{inf})}{1 + inf} + \frac{credit2 * (r_{c2} - inf)}{1 + inf} \tag{31}$$

where: r_d – discount rate, r_e – assumed return on equity, r_{c1} – interest rate of credit 1, r_{c2} – interest rate of credit 2, inf – inflation rate.

Initial data and acquisition financing are presented in figure 22.

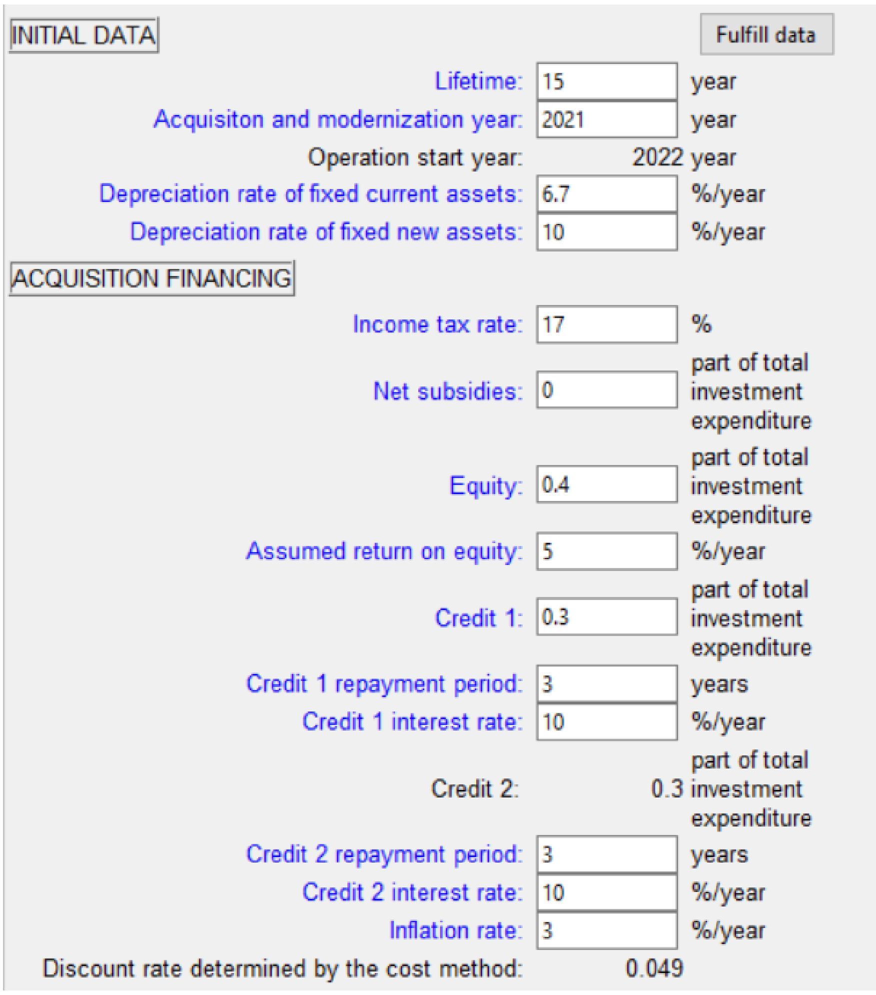


Figure 22. Economical assessment input data, initial data and acquisition financing.

2.4.3. Modernization financing

Rest of the parameters are defined the same way as in case of acquisition but these are referred to financing of modernization process.

2.4.4. Fuel tariff

If the user knows the tariff for the natural gas, he can fulfill the table that will serve to obtain final price of natural gas, according to the equation:

$$P_{ng} = \frac{12 * S + F_{gtotal} * (P_{rng} + P_{dng}) + F_{gmax} * R_{gmax} * 8760}{F_{gtotal}} \tag{32}$$

where: S – monthly subscription for gas delivery, P_{rng} – raw price for the natural gas, P_{dng} – distribution price for natural gas, F_{gmax} – maximum gas for CHP system, R_{gmax} – rate for maximum gas delivery, F_{gtotal} – total amount of natural gas used in CHP system.

From these values the user needs to declare:

- Price of fuel – raw price of fuel in PLN/Nm^3.
- Subscription – the monthly payment for subscription from gas delivery in PLN.
- Rate max gas – rate for maximum gas delivery in PLN/(m$_3$/h).

- Distribution – distribution price for natural gas in PLN/Nm3.

If the user does not have sufficient information about fuel tariff at this stage of analysis, he can leave this section empty and set the estimated price for natural gas in the next section (described below). Modernization financing and fuel tariff are shown in figure 23.

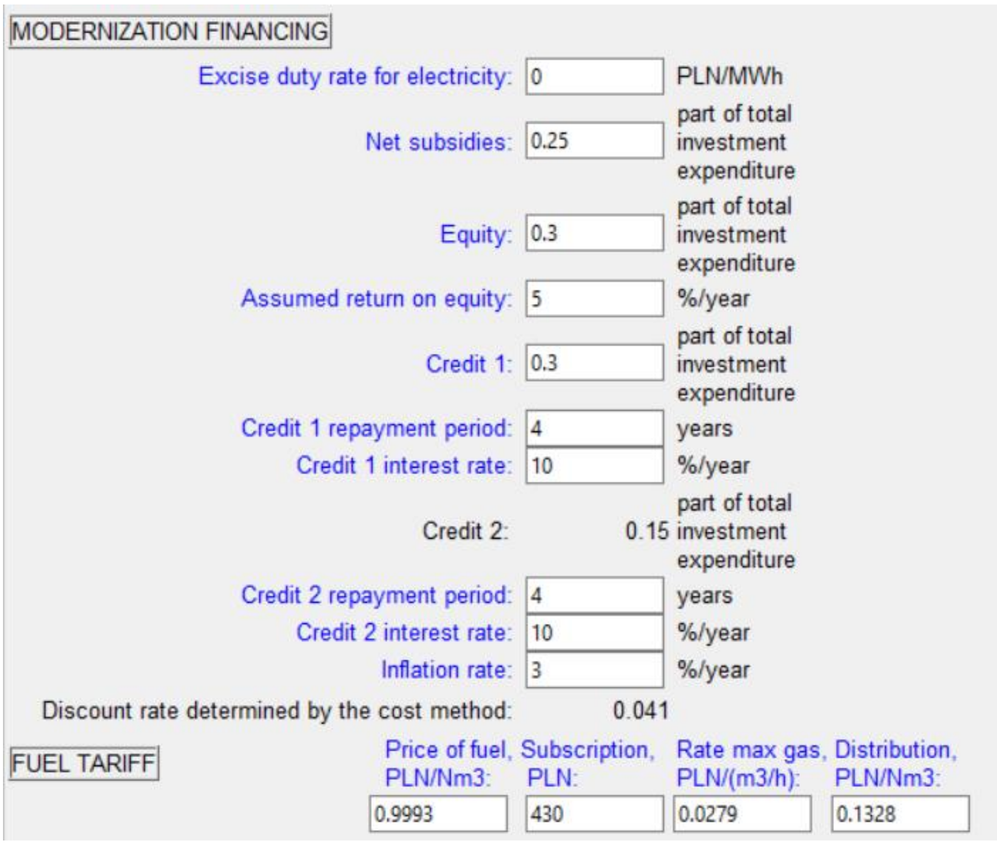


Figure 23. Economical assessment input data, modernization financing and fuel tariff.

2.4.5. Base prices

- Natural gas price – price of purchasing natural gas referred in PLN/Nm3. This variable should be introduced by the user in case he does not have knowledge about the fuel tariff.
- Biogas price – price of purchasing biogas referred in PLN/Nm3.
- Coal and biomass price – price of purchasing coal and biomass referred in PLN/t.
- Heat price – price of selling the heat to end users, referred in PLN/GJ.
- Cost of electricity purchased from the grid – price of purchasing electrical energy from the grid, referred in PLN/MWh.
- Electricity sales to the grid price – price for selling produced electrical energy to the grid, referred in PLN/MWh.
- Price of MWh for capacity market – price for ensuring delivery of electrical energy (capacity market), referred MWh.
- Price of CO_2 emission certificate – price for obtaining CO_2 emission allowance (the EU emission trading system).
- Waste disposal cost – price for waste disposal, referred in PLN/t.

2.4.6. Cost increase rates

The user can define annual increase of the following costs: electrical energy (included both in purchasing and selling), heat, gas, biogas, coal, biomass, remuneration, materials and maintenance, referred in annual %.

2.4.7. Exchange rate

The user defines actual exchange rates between PLN and USD as some of the empirical equations serving to assess investment expenditures are based on USD currency and the final values obtained are in PLN.

2.4.8. Investment expenditure index

If the user knows investment expenditure index (reflects changes in prices of expenditures realized in given period compared to the prices in the corresponding period of the previous year) for the year of modernization (known from government statistical office), he can introduce the value (value of 1 means that no increase or decrease in the price of expenditures is speculated).

Discussed subsection is presented in figure 24.

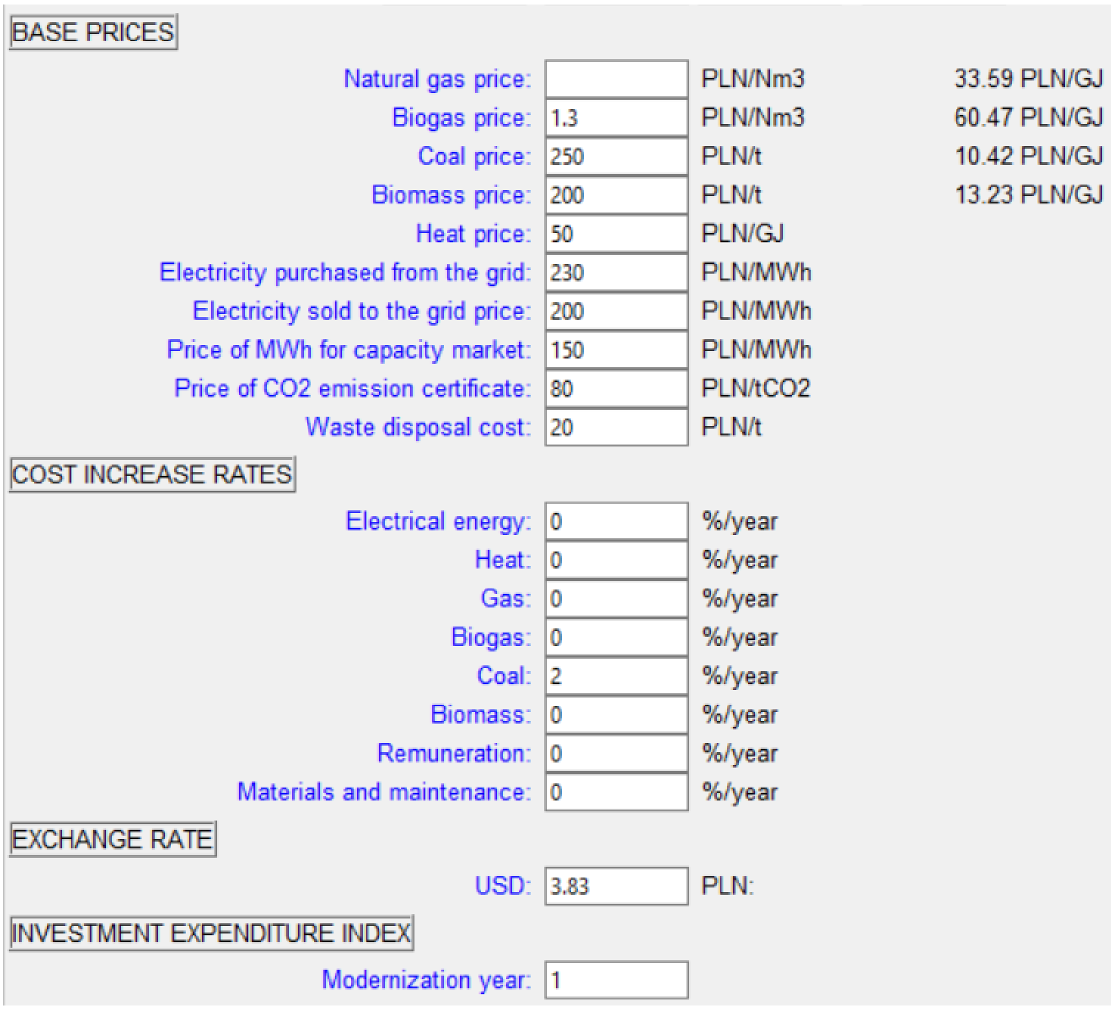


Figure 24. Economical assessment input data, base prices, cost increase rates, exchange rate.

2.4.9. Cost indicators of operating

a. Fixed costs

- Annual write-offs for maintenance (coal part) – annual write-offs for maintenance of coal unit (depreciation rate of maintenance), referred in percentage of acquisition expenditure.
- Annual write-offs for maintenance (gas part) – annual write-offs for maintenance of gas unit, referred in % of expenditure (expenditure understood as total expenditure minus cost of acquisition and current assets).
- General factory cost ratio – cost for factory expenses, referred in percentage of total expenditure.
- Administrative cost ratio – cost for administrative expenses, referred in percentage of total expenditure.
- Others (licenses, taxes etc.) – additional cost the user can introduce for other licenses, taxes etc.
- Employment rate – number of employees.
- Personnel costs ratio – monthly payment for individual employee in PLN.

b. Variable costs

- Auxiliary materials and operation service for cogeneration modules costs – these are costs calculated through empirical equations cited in spreadsheets [50] which use gross electrical power and exchange rate of currency to estimate the values.
- Other costs of service (coal part) – costs of service of coal unit, referred in PLN/GJ (GJ of heat produced).
- Complementary water cost – cost for complementary water, referred in PLN/GJ.
- Wastewater disposal cost – cost for wastewater disposal, referred in PLN/GJ.

2.4.10. Interest rates

- Interest rate for short-term financing – interest rate used for short-term loans which the user can also include at the stage of finance planning,
- Interest rate for retained capital – interest rate for the capital that the user decides to retain during next year (used in equation (52)).

2.4.11. Discount rates

- Discount rate for "0" year – discount rate used for the analysis for the year of acquisition and modernization.
- Discount rate for operational years – discount rate used for the analysis of operational years.

Cost indicators of operating, interest and discount rates are presented in figure 25.

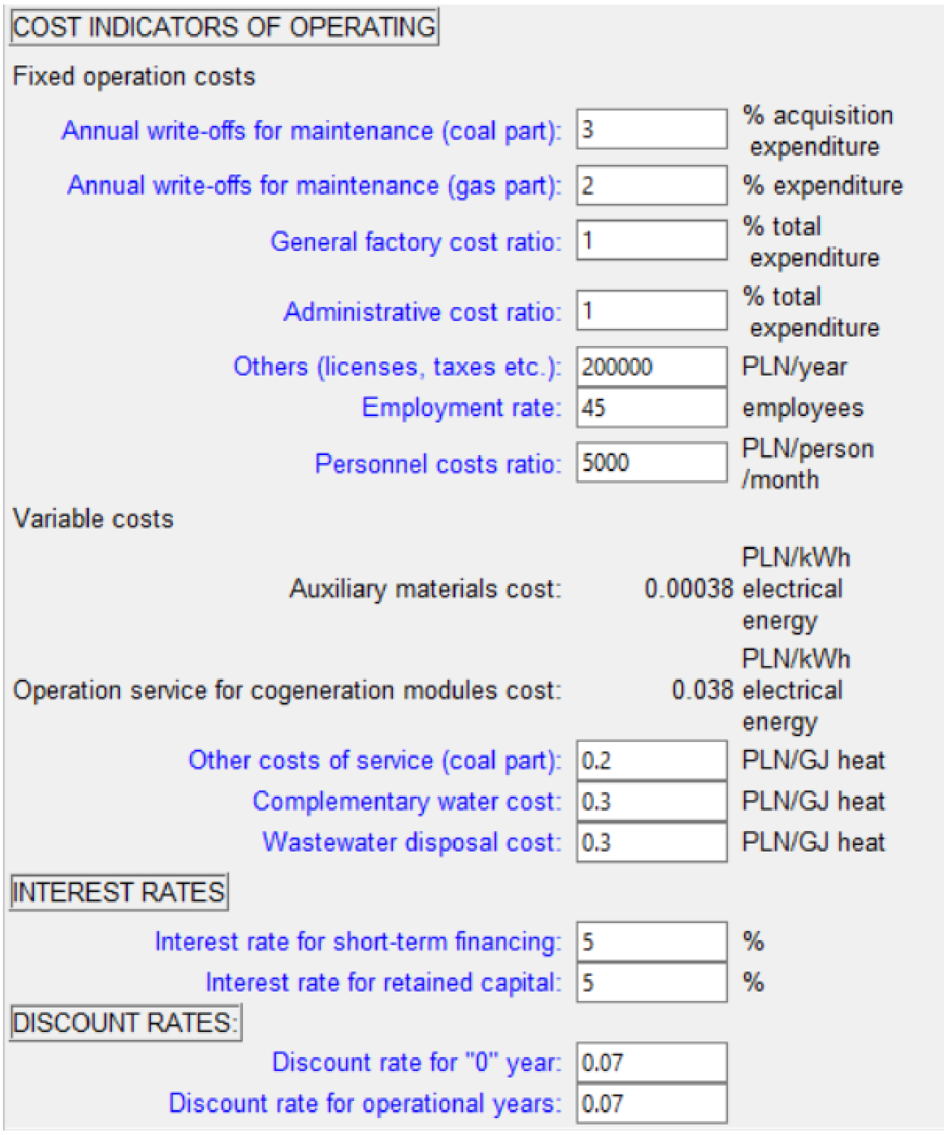


Figure 25. Economical assessment cost indicators of operating, interest and discount rates.

Discount rates estimated by the cost method can serve as reference which discount rate should be used for the discount analysis.

Once these values are introduced, the user should click “Fulfill data” button. Program shows: operation start year (acquisition and modernization year plus one), shares of credits 2, discount rates estimated by cost method (if the user wants to change discount rate accepted for analysis, he should do it at this stage and again click the button), auxiliary materials and operation and service for cogeneration modules cost.

2.5. Investment expenditure

Next tab presents estimated expenditures related to investment. All the values are in PLN.

2.5.1. Input data for investment expenditure

The user introduces following variables:

- Land (purchase) – cost of purchasing a land for investment (PLN).
- Cost of acquisition – cost of acquisition of existing unit (PLN).

- Other expenditures – any other costs not assessed by the program that refer to expenditures for fixed assets.

Once these data are completed, the user should click “Fulfill data” button. The program estimates indicators shown in figure 26.

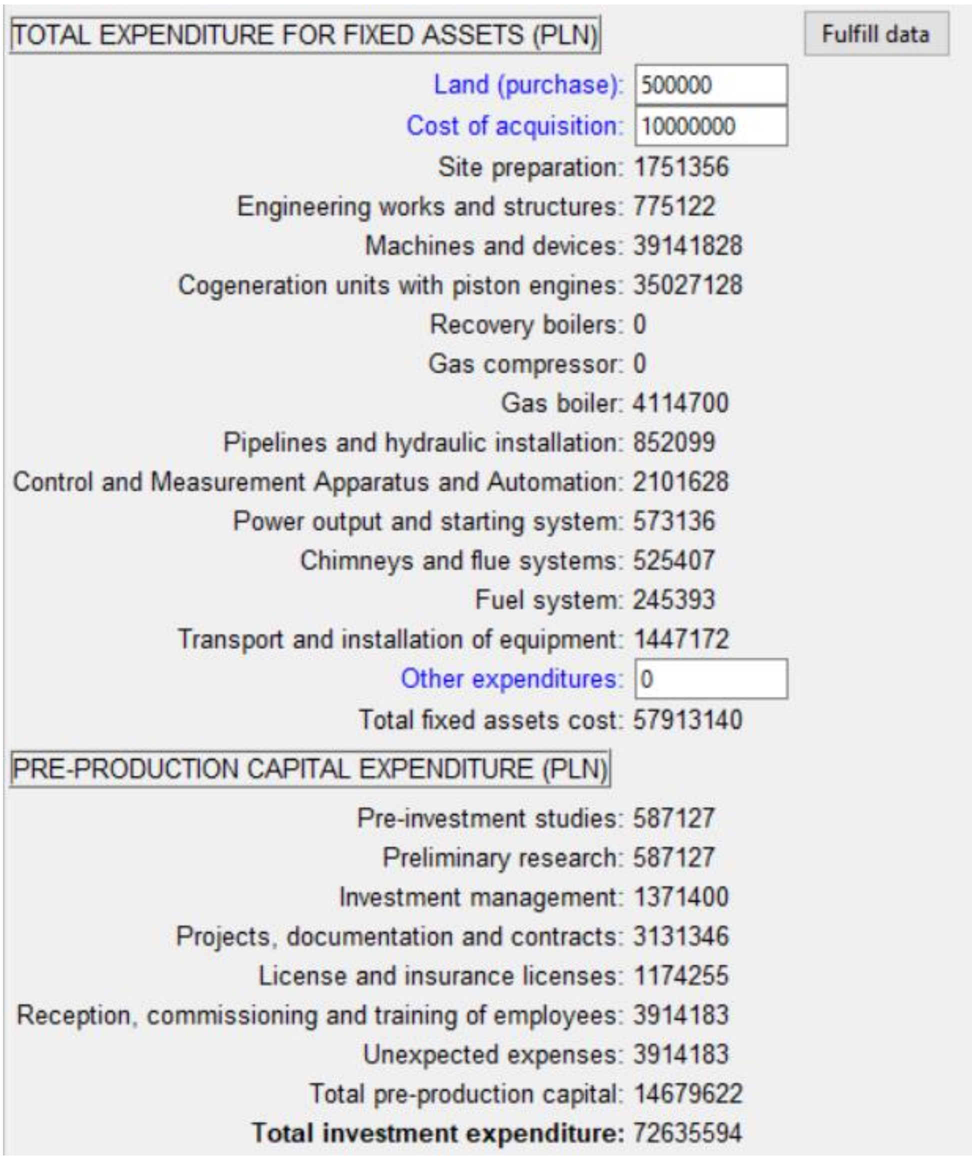


Figure 26. Investment expenditure, fixed assets and pre-production capital.

2.5.2. Algorithm of investment expenditure

Most important equations which determine the size of the costs are presented. The approach is to estimate these values based on empirical equations derived from historical and statistical data about such costs.

2.5.2.1. Total expenditure for fixed assets

Piston engine cost:

$$GT = \sum_{i=1}^{n} USD * inv * \ N_{chp,i} * 0.75 * (-195.9 * ln_{N_{chp,i}} + 2200) \tag{33}$$

Gas turbine cost

$$GT = \sum_{i=1}^{n} USD * inv * ((3 * 10^{-9} * {N_{chp,i}}^3) - 0.0013 * {N_{chp,i}}^2 + 365.43 * N_{chp,i} + 10^6) \tag{34}$$

where: GT – estimated value of cogeneration unit with piston engines, USD – exchange rate between PLN and USD, $N_{chp,i}$ – gross electrical power of given unit (up to three units, n=3 in case of simulation with maximum number of three engines), inv – investment expenditure index.

Recovery boiler (only for gas turbine, since piston engine CHP system do not use recovery boiler, the value is 0).

$$RB = \sum_{i=1}^{n} USD * inv * \ Q_{chp,i} * 0.75 * 450 * {Q_{chp,i}}^{-0.18} \tag{35}$$

where: RB – estimated cost of recovery boiler, $Q_{chp,i}$ – heat power of given engine.

Gas compressor cost (both for piston and turbine engine):

$$GC = USD^2 * 0.15 * \ GT * 28.073 * \left(\frac{USD * GT}{1000}\right)^{-0.585} \tag{36}$$

where: GC – estimated cost of gas compressor.

Gas boiler cost ((both for piston and turbine engine):

$$GB = USD * \ Q_B * 0.75 * 250 * {Q_B}^{-0.13} \tag{37}$$

where: GB – estimated cost of peak-reserve gas boiler, Q_B – heat power of gas boiler.

All of the parameters shown in figure 27 are estimated through empirical equations which are based on cost of cogeneration engine (GT). Following costs are shown: site preparation, engineering works and structures, machines and devices (sum of cogeneration unit engine, recovery boiler, gas compressor and gas boiler), pipelines and hydraulic installation, control and measurement apparatus and automation, power output and starting system, chimney and flue gas cleaning systems, fuel economy, transport and installation of equipment. Sum of all is in the value of total.

A representative equation of estimating these values can be shown for transport and installation of equipment. Its cost is calculated according to:

$$INSTALLATION = 600 * \left(\frac{USD * GT}{1000}\right) * 0.185 * \left(\frac{USD * GT}{1000}\right)^{-0.2117} + 5.9114 * \left(\frac{USD * GT}{1000}\right)^{-0.3527} \tag{38}$$

where: $INSTALLATION -$ estimated cost for transport and installation of equipment.

2.5.2.2. Pre-production capital expenditure

Using the same approach all the expenditures related to pre-production phase are estimated. This includes: pre-investment studies, preliminary research, investment management, projects, documentation and contracts, license and insurance licenses, reception, commissioning and training of employees, unexpected expenses. Total is a sum of these values.

2.5.2.3. Total investment expenditure

Total investment expenditure is a sum of pre-production capital expenditure, expenditure for fixed assets and current assets.

Current assets are defined according to equation:

$$CA = ST + RE + CASH \tag{39}$$

where: CA – current assets, ST – stock inventory, RE – accounts receivable, $CASH$ – cash.

Since for the year of modernization there are no receivables and cash, only stock inventory is included. Stock inventory is understood as the value of stocks of solid fuels and materials and raw resources (raw resources as resources that are not used for energetic purposes). Stock inventory is included to the stage of investment as it is the value of resources that the plant already owns (supplies for the period of one month in case of coal, biomass and other materials as turnover of these resources is twelve months). Since coal, biomass and other materials are stored and managed at plant site, these are treated differently than gas and biogas which are not included to the current assets. It is important for the purpose of completing balance sheet which is a financial statement that a company is obliged to prepare. In the program this is shown when defining the working capital and finance planning (other tab). Costs of supply for coal, biomass and materials and raw resources are obtained according to equation (40).

Cost of supply for coal:

$$S_{coal,i} = \frac{C_{coal,i}}{To_{coal,i}} \tag{40}$$

where: $S_{coal,i}$ – cost of supply of coal (monthly in this case) in given year i, $C_{coal,i}$ – cost of coal for given year i, $T_{coal,i}$ – period of turnover of coal in given year (12 months).

$$To_{coal,i} = \frac{360}{D_{coal,i}} \tag{41}$$

where: $D_{coal,i}$ – days of coverage of coal in given year (30 days).

Cost of coal for given year:

$$C_{coal,i} = F_{coal} * P_{coal} * (1 + r_{coal})^{i-i_1} \tag{42}$$

where: $C_{coal,i}$ – cost of coal in given year i, F_{coal} – quantity of used coal, P_{coal} – cost of purchasing coal, r_{coal} – cost increase rate of price of coal, i_1 – first year of operation, i – analyzed year (for the first year of operation cost increase rate is zero, it impacts the result from the second year of operation).

Analogical approach is used to obtain the cost of supply of biomass but with particular values referring to biomass exploitation. Cost for supply of materials and raw resources is based on cost for auxiliary materials and active electrical energy produced. Sum of these is the value of stock inventory for the modernization year.

Next section of investment expenditure tab is the credits service seen in figure 27. According to information delivered from the user, the program presents loans taken for acquisition and modernization purposes and shows respective years with the values of total value of given credit, installment and charged interest payments. Total values subsection presents sum of installments and charged interest for considered years.

LOANS ACQUISITION (PLN)

Credit 1

Total value of credit 1:	3150000		
Years:	2022	2023	2024
Credit 1 installment:	1050000	1050000	1050000
Credit 1 value:	3150000	2100000	1050000
Credit 1 charged interest:	315000	210000	105000

Credit 2

Total value of credit 2:	3150000		
Years:	2022	2023	2024
Credit 2 installment:	1050000	1050000	1050000
Credit 2 value:	3150000	2100000	1050000
Credit 2 charged interest:	315000	210000	105000

LOANS MODERNIZATION (PLN)

Credit 1

Total value of credit 1:	18640678			
Years:	2022	2023	2024	2025
Credit 1 installment:	4660170	4660170	4660170	4660170
Credit 1 value:	18640678	13980509	9320339	4660170
Credit 1 charged interest:	1864068	1398051	932034	466017

Credit 2

Total value of credit 2:	9320339			
Years:	2022	2023	2024	2025
Credit 2 installment:	2330085	2330085	2330085	2330085
Credit 2 value:	9320339	6990254	4660170	2330085
Credit 2 charged interest:	932034	699025	466017	233008

TOTAL VALUES (PLN)

Year:	2022	2023	2024	2025
Total installment:	9090254	9090254	9090254	6990254
Total installment value:	34261017			
Total charged interest:	3426102	2517076	1608051	699025
Total charged interest value:	8250254			

Figure 27. Investment expenditure, loans.

2.6. Costs and profits

2.6.1. Input data

A table is presented that shows particular costs for each of the year within the lifetime of analysis. First step is to click “Prepare table” button. Windows where user can introduce following variables appear.

- Production capacity – assumed production capacity of plant for given year, referred in percentage. If production capacity is 90% it can be understood as that plant operates for 90% time during the year. Rest 10% could be used for maintenance, repairs etc.
- Other emissions and other variable costs – the user can declare some additional costs for emissions, not included in the software, optionally if the real costs are expected to be higher than estimated by the program, the difference can be included here. Other variable costs is general for any other cost for given year that the user would like to introduce.

The estimated values are shown in figure 28. These are obtained through the series of equations presented below (equations refer to obtain a value for single year of operation).

ANNUAL COSTS OF PRODUCTION (PLN) | Prepare table | Assess performance

Years:	2022	2023	2024	2025	2026	2027
Production capacity in %:	100	100	100	100	100	100
Annual write-offs for major and ongoing repairs:	1551855	1551855	1551855	1551855	1551855	1551855
Personnel costs:	225000	225000	225000	225000	225000	225000
Factory expenses:	726356	726356	726356	726356	726356	726356
Administrative expenses:	726356	726356	726356	726356	726356	726356
Others (licenses, taxes, etc.):	200000	200000	200000	200000	200000	200000
Fixed operation costs:	3429567	3429567	3429567	3429567	3429567	3429567
Coal:	365323	372629	380082	387684	395437	403346
Biomass:	81865	81865	81865	81865	81865	81865
Gas:	41906346	41906346	41906346	41906346	41906346	41906346
Biogas:	19222442	19222442	19222442	19222442	19222442	19222442
Materials and raw resources:	66803	66803	66803	66803	66803	66803
Wasterwater disposal complementary water:	449960	449960	449960	449960	449960	449960
Total resources and materials:	62092739	62100045	62107498	62115100	62122853	62130762
Electricity for plant needs:	115000	115000	115000	115000	115000	115000
Current maintenance and service:	5087139	5087139	5087139	5087139	5087139	5087139
CO2 emission:	17890	17890	17890	17890	17890	17890
SO2 emission:	959	959	959	959	959	959
NOx emission:	12597	12597	12597	12597	12597	12597
CO emission:	1434	1434	1434	1434	1434	1434
Dust emission:	942	942	942	942	942	942
BAP emission:	24	24	24	24	24	24
Other emissions:	0	0	0	0	0	0
Total emissions:	33846	33846	33846	33846	33846	33846
CO2 emission allowances:	5963268	5963268	5963268	5963268	5963268	5963268
Other variable costs:	0	0	0	0	0	0
Variable operation costs:	73291992	73299299	73306751	73314353	73322107	73330015
Total operation costs:	76721559	76728866	76736318	76743920	76751674	76759582
Depreciation of current assets:	670000	670000	670000	670000	670000	670000
Depreciation of new assets:	3316096	3316096	3316096	3316096	3316096	3316096
Financial expenses (interest):	3426102	2517076	1608051	699025	0	0
Excise tax on electricity:	0	0	0	0	0	0
Total sold production costs:	84133757	83232038	82330465	81429041	80737770	80745678

Figure 28. Costs and profits, costs.

2.6.2.Algorithm of annual costs of production

Annual write-offs for major and ongoing repairs:

$$AWR = \frac{a_{wmc}}{100} * AQ + \frac{a_{wmg}}{100} * (T - AQ - CA_0) \tag{43}$$

where: AWR – cost of annual write-offs for major and ongoing repairs, a_{wmc} – annual write-offs for maintenance (coal part), a_{wmg} – annual write-offs for maintenance (gas part), T – total investment expenditure, AQ – cost of acquisition, CA_0 – value of current assets for the year of modernization.

Personnel costs:

$$PCC = ER * PCR * (1 + r_{rem})^{i-i_1} \tag{44}$$

where: PCC – personnel cost, ER – employment rate, PCR – personnel cost ratio, r_{rem} – cost increase rate of remuneration, i_1 – first year of operation, i – analyzed year.

Factory expenses:

$$FE = \frac{GFCR}{100} * T \tag{45}$$

where: FE – factory expenses, $GFCR$ – general factory cost ratio.

Administrative expenses are calculated the same way as in equation (45), however administrative cost ratio is used. Others (licenses, taxes) are the same values as introduced by the user in economic assessment data tab (included for each year). These five values are classified as fixed operation costs.

Costs for coal, biomass, gas, biogas, materials and raw resources, wastewater disposal and complementary water are calculated by equation analogical to equation to (42) using respective values of fuel usage, price and cost increase rates. Wastewater disposal and complementary water use complementary water cost and wastewater disposal cost which are multiplied by the amount of heat delivered to the grid and use cost increase rate for materials and maintenance. Same approach is used to determine electricity for plant needs but using the value of rest of own electricity consumption (the electricity the plant purchases from grid), price for purchasing the electricity and cost increase rate for electrical energy are used. The difference is that one additional factor is included to the calculations, which is production capacity for given years. That is shown e.g. for cost for current maintenance and service as it is obtained according to the equation:

$$CMS = PC_i * (os * N_{ELA} + ocs_c * Q_{coal} - AWR) * (1 + r_{mat})^{i-i_1} \tag{46}$$

where: CMS – cost for current maintenance and service, PC_i – production capacity for i year, os – operation service for cogeneration modules cost, N_{ELA} – electrical energy produced from active power, ocs_c – other costs of service (coal part), Q_{coal} – heat produced by coal unit, r_{mat} – cost increase rate for materials and maintenance.

Cost for emissions of particular compounds is based on quantity of emissions after installation and declared price. If the investment cause more CO_2 comparing to the before investment condition, a fee for additional CO_2 allowances is charged. It is added to the first year of operation.

Costs for total resources and materials, electricity for plant needs, current maintenance and service, total emissions and other variable costs are classified as variable operation costs. Total operation costs are sum of fixed and variable operation costs.

Depreciation of current assets is calculated according to:

$$Dca = \frac{r_{dca}}{100} * AQ \tag{47}$$

where: Dca – depreciation of current assets, r_{dca} – depreciation rate of fixed current assets.

Depreciation of new assets is obtained through:

$$Dna = \left(T_{fixed} - land - AQ - SP - INSTALLATION\right) * \frac{r_{dna}}{100} * (1 - netsubpm) \tag{48}$$

where: Dna – depreciation of new assets, T_{fixed} – expenditure for fixed assets, $land$ – cost of purchasing of the land, SP – site preparation, r_{dna} – depreciation rate of fixed new assets, $netsubpm$ – part of the investment expenditure for modernization project which is covered by net subsidies.

Financial expenses are values of charged interest from loans (same as in investment expenditure tab).

Excise tax on electricity is calculated from plant's electrical energy that is generated in CHP system and consumed onsite (sum of electrical energy for captive power consumption and amount of electrical energy that would be purchased if no CHP was installed) and excise duty rate for electricity.

Sum of total operation costs, depreciation costs, financial expenses and excise taxes is a value of total sold production cost as in equation (49). Shares subsection presents the share of particular component on the overall value of production cost (presented in the next figure 29). Total sold production costs:

$$TSPC = T_{oc} + D_c + FIE + ETE \tag{49}$$

where: $TSPC$ – total sold production cost, T_{oc}– total operation cost, D_c – cost for depreciation, FIE – financial expenses, ETE – excise tax on electricity.

2.6.3. Algorithm of annual income

Second part of the tab presents table with annual incomes. The user can introduce the value of:

- other sale – sale not estimated by the program which should be included into the revenues.

The results are presented in figure 29.

Shares						
Share of fixed operating costs	0.04	0.04	0.04	0.04	0.04	0.04
Share of variable operating costs	0.87	0.88	0.89	0.9	0.91	0.91
Depreciation share	0.05	0.05	0.05	0.05	0.05	0.05
Share of financial costs	0.04	0.03	0.02	0.01	0.0	0.0
Excise duty share	0.0	0.0	0.0	0.0	0.0	0.0
ANNUAL INCOME (PLN)						
Heat sale:	35427495	35427495	35427495	35427495	35427495	35427495
Sale of electricity to an external distributor:	33481618	33481618	33481618	33481618	33481618	33481618
Income from capacity market:	26162895	26162895	26162895	26162895	26162895	26162895
Other sale:	0	0	0	0	0	0
Total revenues:	95072007	95072007	95072007	95072007	95072007	95072007
Financial income (interest):	0	198729	443128	735083	1181565	2024775
Variable costs:	73291992	73299299	73306751	73314353	73322107	73330015
Variable surplus:	21780015	21971438	22208384	22492738	22931466	23766767
Fixed costs:	3429567	3429567	3429567	3429567	3429567	3429567
Depreciation:	3986096	3986096	3986096	3986096	3986096	3986096
Operational surplus:	14364352	14555775	14792721	15077075	15515803	16351104
Financial expenses (interest):	3426102	2517076	1608051	699025	0	0
Excise tax on electricity:	0	0	0	0	0	0
Gross profit:	10938251	12038699	13184670	14378050	15515803	16351104
Income tax:	1859503	2046579	2241394	2444268	2637686	2779688
Net profit:	9078748	9992120	10943276	11933781	12878116	13571417
Gross profit/income ,%:	11.51	12.66	13.87	15.12	16.32	17.2
Net profit/income, %:	9.55	10.51	11.51	12.55	13.55	14.27
EBIT:	14364352	14555775	14792721	15077075	15515803	16351104
EBITDA:	18350448	18541871	18778817	19063171	19501898	20337200

Figure 29. Costs and profits, profits.

Heat sale is calculated by the same approach as in equation (42) using amount of heat sold, heat price and cost increase rate of heat price. Same approach applies for sale of electricity to an external distributor which uses the amount of electricity sold to the grid, price of electricity sold to the grid and cost increase rate of electrical energy.

Income from capacity market is obtained through equation:

$$INCC = P_{cm} * N_{ELA} \tag{50}$$

where: $INCC$ – income from capacity market, P_{cm} – price of MWh for capacity market, N_{ELA} – electrical energy produced from active power.

Total revenues are calculated according to equation:

$$TR = HS + SE + INCC + OSE \tag{51}$$

where: TR – total revenue, HS – heat sale, SE – sale to external distributor, OSE – other sale.

If financial income is added to the total revenues and variable operation costs are subtracted, variable surplus is obtained. Further subtracting fixed operation costs, costs for depreciation and other variable costs from variable surplus allows to obtain operational surplus. From operational surplus, financial expenses and costs for excise tax are subtracted and gross profit is obtained. Including the amount of income tax, net profit is calculated. Gross and net profit divided by income respectively, are presented further.

Financial income is obtained according to:

$$FI_i = r_{rc} * CVI_{i-1} \tag{52}$$

where: FI_i – financial income for i year, r_{rc} – interest rate for retained capital i year, CVI_{i-1} – cumulated value of investment (from previous year).

Earnings before interest and taxes is calculated according to equation:

$$EBIT = TR + FI - T_{oc} - D_c - OVC - ETE \tag{53}$$

where: TR – total revenues, FI – financial income, T_{oc} – total operation costs, D_c – cost for depreciation, OVC – other variable costs, ETE – excise tax for electricity.

Earnings before interest, taxes, depreciation and amortization is calculated the same as EBIT but cost for the depreciation is not included in the equation. Excise tax for electricity is included to the EBIT and EBITDA indicators as these are a measure of cash flows within a company without including the income tax and it is the approach implemented in [50]. This could however be treated differently i.e. value of excise tax would not be used in the equations.

Cumulated value of investment is defined as:

$$CVI_i = CVI_{i-1} + EBITDA_i - L_{ins,i} - L_{ch,i} - inctax_i \tag{54}$$

where: CVI_i – cumulated value of investment for i year, $L_{ins,i}$ – total value of installments for loans for i year, $L_{ch,i}$ – total value of charged interest payment for i year, $inctax_i$ – value of income tax for i year.

Definition of working capital is presented in the discussion of the next tab.

2.7. Financial planning and working capital

For the purpose of deeper understanding of cash flow simulation that is performed by the software and comfort of presenting the data, a tab presenting working capital (measure of company's liquidity) and financial planning is presented.

2.7.1. Working capital

Working capital uses values obtained in earlier calculations. It is presented in figure 30.

WORKING CAPITAL (PLN) Assess performance

Current assets	Days of coverage	Turnover	2021	2022	2023	2024
Coal:	30	12	30444	30444	31052	31674
Biomass:	30	12	6822	6822	6822	6822
Materials and raw resources:	30	12	5567	5567	5567	5567
Receivables:	30	12	0	7843441	7843441	7843441
Cash:	30	12	0	79227	79227	79227
Total current assets:	0	0	42833	7965500	7966109	7966730
Current liabilities						
Liabilities for deliveries:	0	0	0	5728966	5729575	5730196
Factory expenses:	30	12	0	60530	60530	60530
Administrative expenses:	30	12	0	60530	60530	60530
Cost of materials and electricity:	30	12	0	5183978	5184587	5185208
Current maintenance and service:	30	12	0	423928	423928	423928
Liabilities for taxes, duties and others:	0	0	0	6171730	6171730	6171730
License fees, land taxes and other fixed fees:	360	1	0	200000	200000	200000
Excise tax on electricity:	30	12	0	0	0	0
Emission of pollution:	90	4	0	8461	8461	8461
CO2 emission allowances:	360	1	0	5963268	5963268	5963268
Payroll liabilities:	30	12	0	18750	18750	18750
Total current liabilities:	0	0	0	11919446	11920055	11920676
Working capital:	0	0	42833	-3953946	-3953946	-3953946
Increase in working capital:	0	0	42833	-3996778	0	0

Figure 30. Working capital.

Current assets have been already explained and shown in equation (39).

Receivables are calculated according to equation:

$$RE = \frac{TR - OSE}{To_{rec}} \tag{55}$$

where: To_{rec} – turnover for receivables, defined the same as in equation (41) with the same number of days of coverage.

Cash is determined as:

$$CASH = 0.01 * RE \tag{56}$$

The final value of RE is the value subtracted by the cash. Liabilities for deliveries is a sum of factory expenses, administrative expenses, cost of materials and electricity and current maintenance and service. Factory and administrative expenses are calculated analogically as in costs and profits tab with implementation of respective turnovers (12), as in equation (55). Cost of materials and electricity uses values of total resources and materials and electricity for plant needs, again divided by turnover of 12. Same applies for current maintenance and service.

Liabilities for taxes, duties and others is a sum of license fees, land taxes and other fixed fees, excise tax on electricity, emission of pollution and fee for granting additional CO_2 emission allowances. License fees, land taxes and other fixed fees is the value introduced by the user as others in economic assessment tab at cost indicators of operating subsection (turnover equals 1 as seen in the figure 30). Excise tax on electricity is calculated analogically as in equation (55) using turnover of 12. Liabilities for emission of pollution use value of total emissions from costs and profits tab and use the turnover of 4 as the number of days of coverage is 90. Fee for granting additional emission allowances use turnover of 1. Payroll liabilities are personnel costs divided by respective turnover.

Liabilities for deliveries, taxes, duties and others and payroll liabilities are total current liabilities. Difference between current assets and current liabilities is known as working capital. Increase in working capital is the difference between the value of working capital for given year and previous year.

Respective values of turnovers and days of coverage are fixed and based on spreadsheets and represent typical values (seen in figure 30). If given asset or liability use the value of turnover of 12, it means that payment for it is performed on monthly basis. As such, for example receivables for given year do not represent all the income for given year, but the amount of money that a company will receive monthly basis from particular source in a given year. This approach allows to obtain the value of working capital.

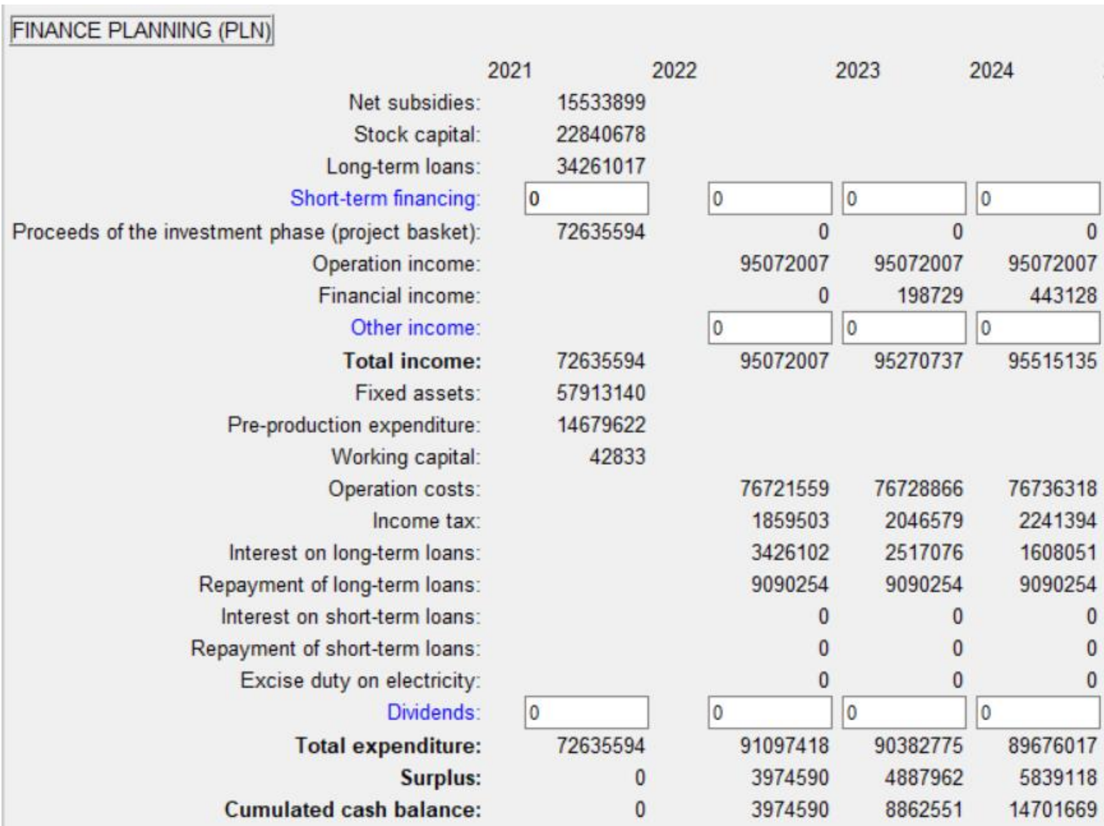
Working capital can be treated as a measure of company's liquidity. If it is positive, it means that the company will have a potential to develop and grow. If it is negative, it means that company will have issues with paying back all the creditors and could mean bankrupting in a long term.

2.7.2. Finance planning

The user can introduce:

- Short-term financing – additional short-term loans that the user can make in given year.
- Other income – value of additional income (it can be declared only for operational time).
- Dividends – payment to the stockholders of the company.

The tab is presented in the figure 31.



FINANCE PLANNING (PLN)

	2021	2022	2023	2024
Net subsidies:	15533899			
Stock capital:	22840678			
Long-term loans:	34261017			
Short-term financing:	0	0	0	0
Proceeds of the investment phase (project basket):	72635594	0	0	0
Operation income:		95072007	95072007	95072007
Financial income:		0	198729	443128
Other income:		0	0	0
Total income:	72635594	95072007	95270737	95515135
Fixed assets:	57913140			
Pre-production expenditure:	14679622			
Working capital:	42833			
Operation costs:		76721559	76728866	76736318
Income tax:		1859503	2046579	2241394
Interest on long-term loans:		3426102	2517076	1608051
Repayment of long-term loans:		9090254	9090254	9090254
Interest on short-term loans:		0	0	0
Repayment of short-term loans:		0	0	0
Excise duty on electricity:		0	0	0
Dividends:	0	0	0	0
Total expenditure:	72635594	91097418	90382775	89676017
Surplus:	0	3974590	4887962	5839118
Cumulated cash balance:	0	3974590	8862551	14701669

Figure 31. Finance planning.

Tab is structured in a way that the user notices particular components of expenses and incomes that appear in given years. That is the reason why e.g. long-term loans are shown solely for the year of modernization as the loans are made in this year and operating income appears for years of operation.

Net subsidies is the total value of subsidies for the acquisition and modernization. It is calculated according to formula:

$$NS = netsub * (land + AQ) + netsubpm * (T - (land + AQ)) \tag{57}$$

where: NS – total value of net subsidies, $netsub$ – part of acquisition expenditure that is covered by net subsidies, $land$ – cost of purchasing land, AQ – cost of acquisition, SP – site preparation, T – total investment expenditure.

Stock capital is a value of total investment expenditure subtracted by value of long-term loans and net subsidies. Long-term loans is a value of loans for acquisition and modernization.

Sum of net subsidies, stock capital, long-term loans and short-term financing is known as project basket which can be treated as proceeds of investment phase. It also considered to be the value of total income for the project for the year of modernization (financial resources input to the investment).

Operating income is the value of total revenues from costs and profits, financial income is defined the same in previous tab. Total income is the sum of these two and any other additional income declared.

Fixed assets and pre-production expenditure are corresponding to values of obtained in investment expenditure tab. Working capital for the year of modernization is the value of current assets in the same year. Operation costs, income tax, interest on long-term loans, repayment of long-term loans, excise duty on electricity correspond to total operation costs, income tax, financial expenses (or total charged interest in investment expenditure tab), total installment (from investment expenditure tab), excise tax on electricity, respectively.

Interest of short-term loans is calculated according to:

$$I_{STL} = r_{stl} * STF \tag{58}$$

where: I_{STL} – interest of short-term loans, r_{stl} – interest rate for short-term financing, STF – value of short-term financing.

Repayment of short-term financing is the value of short-term financing appearing as cost in the next year (short-term loans are to be paid back within a single year).

Total expenditure for the year of modernization is the sum of fixes assets, pre-production expenditure and working capital. For operational years it is a sum of costs mentioned between operation costs and excise duty on electricity. Total income minus total expenditure is a value of surplus. Cumulated cash balance is a sum of cash balance from previous year and current surplus.

2.8. Discount analysis

Discount analysis for the investment project is shown in subsection discount analysis. The tab is presented in figure 32.

ECONOMIC INVESTMENT INDICATORS	Assess performance
NPV (PLN):	**71946130**
NPVR:	**0.991**
IRR:	**0.192**
SPB (years):	**5.95**
DPB (years):	**7.22**

DISCOUNT ANALYSIS (PLN)							
Year:	2021	2022	2023	2024	2025	2026	2027
Total income:	15533899	95072007	95270737	95515135	95807091	96253572	97096783
Total expenditure:	72635594	91097418	90382775	89676017	86877468	79389360	79539270
Discount rate:	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Discounting factor at:	0.935	0.873	0.816	0.763	0.713	0.666	0.623
Net cash balance CF:	-57101696	3974590	4887962	5839118	8929623	16864212	17557513
Cumulated cash balance:	-57101696	-53127106	-48239144	-42400027	-33470404	-16606192	951321
Discounted cash balance CF*at:	-53366071	3471560	3990033	4454635	6366698	11237337	10933936
Cumulated NPV:	-53366071	-49894510	-45904477	-41449843	-35083145	-23845808	-12911872

Figure 32. Discount analysis.

Total income and expenditure are the same as in financial planning and working capital tab. Income for the modernization year in previous tab is positive as it represents the amount delivered to investor in order to cover the expenditure. It is not an actual income from the operation of plant as the loans need to paid back. Income in discount analysis tab for this case is positive only in case net subsidies are delivered to an investor. Otherwise it is treated to be zero and the income is included when the plant starts operating.

Discount rates are the same introduced by the user. Discounting factor is calculated as:

$$a_{t,i} = a_{t,i-1} \frac{1}{(1 + r_{at,i})} \tag{59}$$

where: $a_{t,i}$ – discounting factor for i year, $r_{at,i}$ – discount rate for i year, $a_{t,i-1}$ – discount factor for previous year.

Net cash flow CF is obtained according to:

$$CF = TI - TE \tag{60}$$

where: CF – net cash flow, TI – total income, TE – total expenditure.

Cumulated cash balance:

$$CCB_i = CF_i + CCB_{i-1} \tag{61}$$

where: CCB_i – cumulated cash balance for i year.

Discounted cash balance:

$$DCB_i = a_{t,i} * CF_i \tag{62}$$

where: DCB_i – discounted cash balance for i year.

Cumulated value of NPV:

$$CNPV_i = DCB_i + CNPV_{i-1} \tag{63}$$

where: $CNPV_i$ – cumulated value of NPV for i year.

Discount analysis serves to obtain the values of economic investment indicators.

Net present value (NPV) of a project is a value of cumulated value of NPV for the final year of analysis.

$$NPV = CNPV_n \tag{64}$$

where: NPV – net present value, $CNPV_n$ – cumulated net present value for final year of analysis.

Net Present Value Ratio (NPVR) is a ratio of NPV to total investment expenditure.

$$NPVR = \frac{NPV}{T} \tag{65}$$

where: T – total investment expenditure.

Internal rate of return (IRR) is calculated through iterative approach using general equation:

$$0 = NPV = \sum_{i=1}^{n} \frac{CF_i}{(1 + IRR)^i} - T \tag{66}$$

where: IRR – internal rate of return, i – given year, n – number of years for the analysis.

Simple payback (SPB) is a time after which cumulated cash balance reaches positive value. Discount payback (DPB) is a time after which cumulated value of NPV reaches positive value. Both SPB and DPB are obtained through linear interpolation of cumulated cash balance and cumulated NPV, respectively.

2.9. Sensitivity analysis

Sensitivity analysis allows the user to obtain the values of economic indicators when changing respective prices without running the whole simulation again. The user introduces the change of given parameter in percentage as reference to base price. The change is possible for:

- Natural gas price.
- Biogas price.
- Coal price.
- Biomass price.
- Sold heat price.
- Electricity purchased from the grid.
- Electricity sold to the grid.
- Total investment.

Sensitivity analysis assuming positive change in the market (the prices of purchasing goods are lower by 20% and the price of sold heat increases by 20%) in seen in figure 33. Rest of the values is not changed i.e. these are set to be 100%.

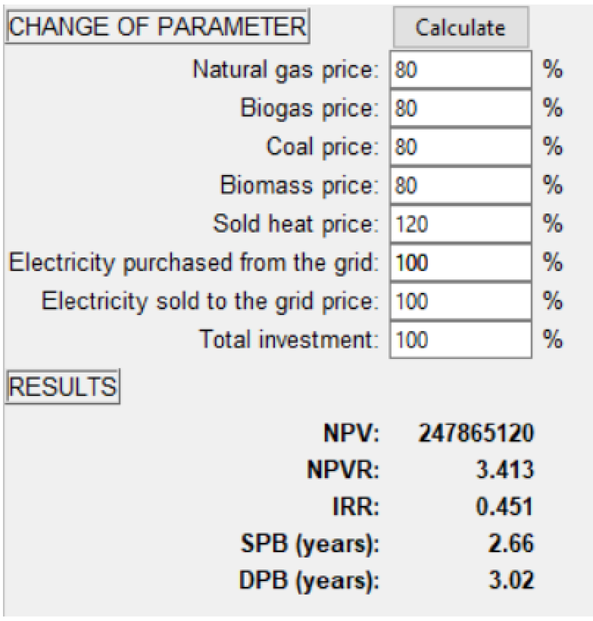


Figure 33. Sensitivity analysis.

3. Results of simulation

Sample simulation performed in the software allows the user to assess given investment through NPV, NPVR, IRR, SPB and DPB indicators.

Net present value can be understood as difference between discounted incomes and discounted outcomes (net cash balance, cash-flows). If NPV > 0 it means that project is profitable as the investment is recovered and surplus is obtained. In case of NPV = 0 the assessment of the project is not straightforward as it does not provide any surplus, however such investment is feasible i.e. it recovers the costs. If NPV < 0 it means that the profitability is not achieved. The value of NPV strongly depends on discount rate used for the analysis since discount rate determines the rate at which future incomes and outcomes can be converted to present value (discounting). Discount rate depends on the company and its way of funding. Required rate of return (minimum return which will satisfy the investor for owning company's stock) can serve for the purpose of discounting. In the case of the software, discount rate determined by the cost method can be understood as the cost of capital, since all of the sources of financing the investment with respective interest rates are included in the value [51, 52, 53].

Another useful index when assessing the projects is the internal rate of return (IRR). It is a discount rate which sets the value of NPV to 0, as seen in equation (66). IRR portrays real rate of return of the project and it is often compared to cost of the capital. If IRR is higher than cost of capital, the investment is beneficial. Another indicator to which IRR is often compared is the required rate of return (RRR). It is considered that the higher the difference between IRR and RRR, the higher the profits [51, 54].

Net Present Value Ratio (NPVR) is a measure which represents what part of the investment expenditure is associated to value of NPV. It is a useful indicator in terms of designed software, in case the user would like to create a set of scenarios comparing different engines with different powers as these factors strongly affect the investment expenditure.

Simple payback period (SPB) is a time after which the incomes recover the investment (break-even point is reached). Short payback period (few years) is a desired criterion for the investors.

Discounted payback period (DPB) is understood the same as SPB but it refers to discounted cash balance i.e. including the change in value of money over time, therefore it is more informative than SPB.

Sample simulation is a modernization type of investment which considers three piston engines of heat power of 10 MW and gas peak-reserve boiler of power 15 MW. Other values are based on typical values one can expect for this kind of analysis of equipment, fuels and demands of power plant with the assumption of production capacity of 100%. Looking at technical results of the simulation, there is small difference in results of technological system and load of engine, despite the fact that 100% load is assumed (figure 18). That is due to the fact that other empirical equations are used for technological system and load of engine and the difference is due to rounding error. Technical assessment indicates significant coal (comparing to current coal use) and waste reduction. Heat surplus is relatively low. Total energy efficiency, as well as energy efficiency of CHP engine, achieve very good values as these are over 80% (figure 19).

Environmental assessment uses coal and gas benchmarks and LHV's taken from [49]. It is assumed that before investment 10% of total required energy from coal is substituted by biomass, after investment it is 15% of energy from biomass and 20% of biogas. Rest of the parameters are statistical values. Evaluating results (figure 22) installment of new CHP system improves environmental conditions as there is a decrease in emissions and therefore a profit in terms of avoided cost. Fuel chemical energy savings, primary energy savings and decrease in emissions are obtained.

Economic assessment evaluates the investment using 15 years of lifetime and finance the modernization assuming 25% of net subsidies. Credits, their interest rates, inflation, depreciation and discount rates as well as assumed prices, cost increase rates and other costs are presented in figures 23, 24, 25 and 26.

In order to present information that can be concluded based on the possibilities of the software a set of simulations have been performed. Modernization type of investment with piston and turbine engine is compared and the same analysis is done for new investment type. The same technical parameters and type of financing of the investments are assumed.

3.1. Modernization investment

3.1.1. Piston engine

The comparison of different scenarios of prices is presented in table 9. Scenario 1 is the most positive scenario in which the prices of purchased goods decrease (as in figure 33) and sold heat increase by 20%. Scenario 2 uses the difference of 10%. Scenario 3 is a base scenario which presents the same results as simulation. Scenario 4 and scenario 5 use 10% and 20% difference, respectively, as increase of price. Results from simulation are presented in tables 10, 11, 12 and 13.

Table 9. Scenarios with varying prices of sold/purchased goods.

Parameter/ Change of parameter in %	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Natural gas	80	90	100	110	120
Biogas	80	90	100	110	120
Coal	80	90	100	110	120
Biomass	80	90	100	110	120
Sold heat	120	110	100	90	80
Electricity purchased from the grid	100	100	100	100	100
Electricity sold to the grid	100	100	100	100	100
Total investment	100	100	100	100	100

Table 10. Results from scenarios for piston engine, modernization investment.

Scenario/indicator	NPV	NPVR	IRR	SPB	DPB
Scenario 1	247 865 120	3.413	0.451	2.66	3.02
Scenario 2	159 905 625	2.202	0.323	3.96	4.46
Scenario 3	71 946 130	0.991	0.192	5.95	7.22
Scenario 4	-	-	-	-	-
Scenario 5	-	-	-	-	-

It is seen that the most positive variant, scenario 1, allows to obtain around three and a half times higher NPV and two times higher IRR and lower SPB with DPB comparing to base case scenario 3. In the same time, the variants which use a decrease in prices by 10% and 20%, estimates the NPV and other indicators to be negative. Based on that, it is seen that the profitability of the investment strongly depends on the market situation and delivered contracts. Since a change in base price by 10% strongly affects the final results, the considered investment is susceptible to changes and should be assessed carefully. The values of electricity purchased from and sold to the grid have not been changed as typically a bilateral contract known to the investor is made. Total investment is assumed to be the same as obtained through the software.

Even though scenarios 4 and 5 are not profitable from the investors perspective, the final decision whether to launch this kind of project, depends on the objectives to achieve. If the economic conditions provided the set of prices corresponding to scenario 5, but the power plant was financed completely through public resources with the main objective aimed to achieve maximum possible coal savings (according to decarbonisation policy), local financial analysis would serve only to predict how the plant should be managed in terms of its financing.

Considering figure 28 it is apparent that for given simulation the price of natural gas impacts the investment in the strongest way as it is the highest cost among the fuels. The user should consider potential correlations between the factors available in sensitivity analysis tab (e.g. increase in the price of coal might decrease the price of biomass) and be aware which of these factors are the most crucial for given simulation. In general, the price of natural gas, biogas (if the share of biogas is high) and the price of the heat sold to the grid would dominate the investment assessment.

3.1.2. Turbine engine

Table 11. Results from scenarios for turbine engine, modernization investment.

Scenario/indicator	NPV	NPVR	IRR	SPB	DPB
Scenario 1	45 571 598	0.451	0.130	7.63	9.95
Scenario 2	-	-	-	-	-
Scenario 3	-	-	-	-	-
Scenario 4	-	-	-	-	-
Scenario 5	-	-	-	-	-

In case of turbine engine simulation, the results are apparently worse in terms of economic indicators compared to piston engine. Only scenario no. 1 is profitable. The main reason for this fact is the association indicator (electrical power to heat ratio), which is around 0.5 for gas turbine and around 1 for piston engine. As the result, less electrical energy is produced and therefore sold to the grid, what strongly affects the annual balance (table 12). Comparison of technical and environmental performance of piston and turbine engine is presented in table 12.

Table 12. Comparison of technical and environmental results for modernization investment.

Parameter/engine	Piston engine	Turbine engine
Gross electricity produced	174 419 298 kWh	91 571 834 kWh
Electricity sold to the grid	167 408 089 kWh	86 228 416 kWh
Heat required	708549.9 GJ	708549.9 GJ
Heat sold to the grid	708549.9 GJ	708549.9 GJ
Total gas required	43 901 169 Nm^3	37 238 121 Nm^3
Coal reduction	42676 t	42641 t
Coal use	1719 t	1755 t
Total energy efficiency	84.24 %	77.37 %
CO_2 emission	74540.9 t	63767.3 t
Profit from change in emissions	68616 PLN	73088 PLN

The ultimate judgment of this technology should be however performed stating the objectives which the investor aim to achieve. Scenario 3 is a basis scenario for which the value NPV for the analysis is negative (other indicators are not evaluated in this case). However looking at total gas required (table 12), which is lower by approximately 6.5 million Nm^3, and CO_2 emissions, lower by around 11 thousands of tons, it is apparent that environmental benefits are achieved. If the objective function would aim to minimize the usage of fossil fuels or GHG emissions, this technology would be more attractive than piston engine, despite the results of local financial analysis performed for the specific conditions of predicted outcomes and incomes.

3.2. New investment

New investment type of project differs from modernization by the cost of acquisition that is not included.

3.2.1. Piston engine

Table 13. Results from scenarios for piston engine, new investment.

Scenario/indicator	NPV	NPVR	IRR	SPB	DPB
Scenario 1	262 922 899	4.200	0.558	2.04	2.26
Scenario 2	175 531 889	2.804	0.402	3.03	3.47
Scenario 3	88 104 878	1.407	0.246	4.97	5.79
Scenario 4	695 868	0.011	0.072	10.00	14.81
Scenario 5	-	-	-	-	-

New investment of CHP with piston engine is the most profitable type of investment as it achieves better results than in case of modernization investment which is due to the lack of cost for acquisition. Relations between respective results of scenarios are similar as to in modernization type, however scenario 4 achieves profitability. The results are strongly susceptible to changes depending on cost definition as the decrease of prices by 10% cause NPV to be around 100 times lower and other indicators respectively worse.

3.2.2.Turbine engine

Table 14. Results from scenarios for turbine engine, new investment.

Scenario/indicator	NPV	NPVR	IRR	SPB	DPB
Scenario 1	60 440 384	0.664	0.159	6.78	8.51
Scenario 2	-	-	-	-	-
Scenario 3	-	-	-	-	-
Scenario 4	-	-	-	-	-
Scenario 5	-	-	-	-	-

Table 15. Comparison of technical and environmental results for new investment.

Parameter/engine	Piston engine	Turbine engine

Gross electricity produced	174 419 298 kWh	91 571 834 kWh
Electricity sold to the grid	167 408 089 kWh	86 228 416 kWh
Heat required	708549.9 GJ	708549.9 GJ
Heat sold to the grid	697948.1 GJ	697632.1 GJ
Total gas required	44 221 258 Nm^3	37 562 349 Nm^3
Total energy efficiency	85.12 %	78.25 %
CO_2 emission	71844.3 t	61025.9 t
Profit from change in emissions	-30170 PLN	-25627 PLN

New investment with turbine engine obtains similar economic results to modernization type of investment, although the absolute values are higher. The approach to final judgment of the project is analogical to modernization type of investment, since turbine engine uses around 6.5 million Nm^3 less of natural gas and therefore emits nearly 11 thousands less of CO_2 (practically the same difference as in case of modernization type of investment), therefore in case of rapid increase of price of natural gas or emission allowances, piston engine would not necessarily turn out to be a profitable source of heat generation. Technical and environmental results for new investment type do not obtain sufficient amount of heat according to requirements due to equipment configuration. Profit from change in emissions is negative as for new investment it is treated solely as cost.

4. Conclusions and comments

Designed program allows the user to asses technical, environmental and economic performance of CHP system with piston (figure 1) or turbine (figure 2) engine with peak-reserve gas boiler. Modernization of existing heating system fueled by coal or new investment are possible to analyze. The program would be of interest for utility companies which will be responsible for development of distributed energy systems e.g. for district heating purposes through gas and biogas fueled CHP systems.

The software has several advantages if comparing to other programs which could also serve for the purpose of analysis of the CHP units. Firstly, it does not require a lot of input data in order to perform the simulation. The input file needs to contain the information only about time, temperature and heat demand. Secondly, it is easy to use as basic information about system configuration, rated and operating parameters allow to obtain the results. Another advantage is that the program is capable of delivering quite detailed analysis within its scope. Technical assessment simulates the working of CHP system presenting detailed information about the performance i.e. electrical energy and heat produced, fuel requirements, coal savings and efficiency. Environmental assessment allows to compare emissions before and after the investment and shows the change in cost for the emissions (in general case profit) due to the investment. Environmental assessment is also the stage where the program allows the user to include co-firing of coal with biomass and natural gas with biogas in a way that the user delivers information about the percentage share of biomass and biogas in total energy required from coal and natural gas, respectively. Software is capable of performing thorough economic analysis as the user introduces the way of financing, namely, equity, subsidies, credits (long-term and short-term loans) and other factors such as depreciation, cost increase rates and all costs associated to operation of power plant. Additionally, for most of the tabs the user can include additional income or outcome, what allows to achieve more precise final results, since the user can always adjust particular values (e.g. if the costs estimated by the program are too high, the user can include additional negative cost in order to balance the values). Detailed investment expenditures, service of credits, all incomes and outcomes, financial planning and working capital and discount analysis are obtained by the software. In order to validate the results and verify other cases, sensitivity analysis is available.

One of the most important features of the written program is the implementation of empirical equations estimating values of expenditure based on historical databases. If we take a look at one of the most appreciated software serving for such analyses, RETScreen Expert, the economic analysis there is based on the user definition of unit price (referred $/kW) for the equipment and operation and maintenance. Although introducing the exact unit prices allows to properly estimate the final values, in reality the values are often roughly approximated. Economic investment in the designed software uses more detailed approach, as empirical equations based solely on the system configuration present complete list of expenditures (figures 26, 27), incomes and outcomes (figures 28, 29), working capital with finance planning (figures 30, 31) and discount analysis (figure 32). RETScreen Expert does not present that detailed costs and profits as well as it does not include working capital and finance planning with short-term financing options. Other steps of analysis in both programs are similar, technical and environmental analyses can be obtained in both programs, risk analysis in RETScreen Expert uses analogical approach as sensitivity analysis in the designed software. Naturally, since RETScreen is a well-known and developed software it can account for various technologies (different type of renewable projects, PV, wind etc.) with respective databases of equipment etc. which makes it a solid option when looking for a software for assessing energy projects. Designed software is a dedicated and very specific tool allowing to analyze CHP units, therefore if one already knows that the investment in CHP is considered, designed software would be of help. Written program could be of interest especially due to its level of analysis in case of economic assessment.

The tool uses a model that performs a working of CHP system and estimates the economic analysis, however there are certain limitations affecting the final result. First thing is that model uses heat demand values based on input data file, it does not predict future values of the demand. Due to parallel development of highly efficient technologies and development of micro PV with heat pumps and solar collectors installations, the decrease of the demand over time could happen. From the perspective of the company operating CHP, such occurrence could mean less heat sold to the grid, but in the same time savings in the purchase of the fuels would appear. Other limitations come from calculations. Emission factors for respective fuels should be determined precisely, especially in case of biomass and biogas. There is an assumption that co-firing process for both coal and biomass and gas and biogas do not impact the efficiency or load of CHP system. It is not necessarily correct, as in reality an optimal mixing ratio might be required, especially in case of coal and biomass. Gas-peak reserve boiler is also assumed to have constant efficiency, independent from the its load. Technical as well as economic assessment uses a set of empirical equations in order to estimate respective values and expenditures. Due to the lack of accuracy of particular values, the final error of economic indicators might be even up to 20% [48]. The approach to economic assessment could also be adjusted to one’s specific requirements.

In order for the user to execute the calculations, a desktop application has been written, which is seen in figures in the designed software chapter. Guide user interface has been programmed using tkinter, which is not however the best choice for this kind of interactive applications due to issues with frame widget optimization for many labels. Restructuring the application into a series of sequenced modules (technical, environmental etc. assessments as separate modules, which is not the approach used in the written program), that would be managed from upper layer GUI using PyQt library, would provide more professional and optimized design. As for the calculation performance, a several improvements could be included, if the software was to be developed further. Technical assessment could include other types of operation, namely electrical energy tracking and economic type of operation. Economic type of operation would require from the software to account for local prices and costs of generation, optionally also with the participation of the plant in the electricity market (spot price). As for the algorithm improvements, since the empirical equations used in the software have been derived some years ago an upgrade to the newest databases would decrease the error in calculations. Dynamic efficiency of the boiler, impact of co-firing on the efficiency and load could, allowing the user to input emission factors or including additional databases of emissions factors could be also developed. An implemented assumption that the modernization period is one year is also not necessarily true in case of higher units, an option to define this period for the user would be useful. Integration of the program with online databases (databases of equipment, but also weather which is required when analyzing gas turbine), preferably also with the prediction of future electrical and heat demands, would be a direction in which the program could be developed. In a long term, other technologies could be added, creating a complex tool able to fully compete with other software.

As it has been stated in problem statement chapter, the problem which the development of distributed energy system encounters, is the optimal selection of technological solution depending on electrical energy, heat or specific requirements of energy carrier (e.g. steam for industrial purposes) profiles. However, since energy type of investments are generally not treated as standard business projects as the objective function for energy investment might demand other than directly economic benefits (namely environmental benefits), the final decision is not a trivial problem. Designed software can be used to complete a set of scenarios, comprising two main technologies of gas fueled CHP systems, which will serve as basis in decision making process based on heat demand.

Recapitulating, designed software corresponds to the needs of Polish situation as development of gas and biogas fueled CHP e.g. for district heating purposes is a one of the main policy goals to achieve. The utilities could use the tool in order to support the process of energy transition which is about to happen in Poland in the upcoming years.

Appendix

Figures and tables supporting the introduction part.

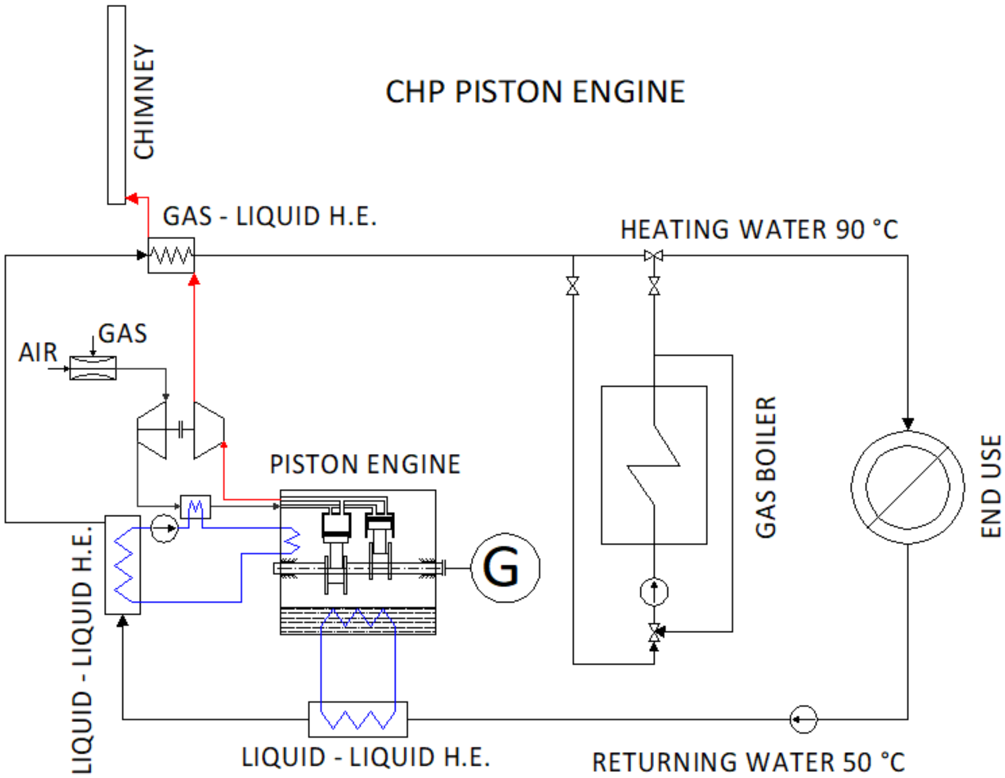


Figure 1. Scheme of CHP system with piston engine.

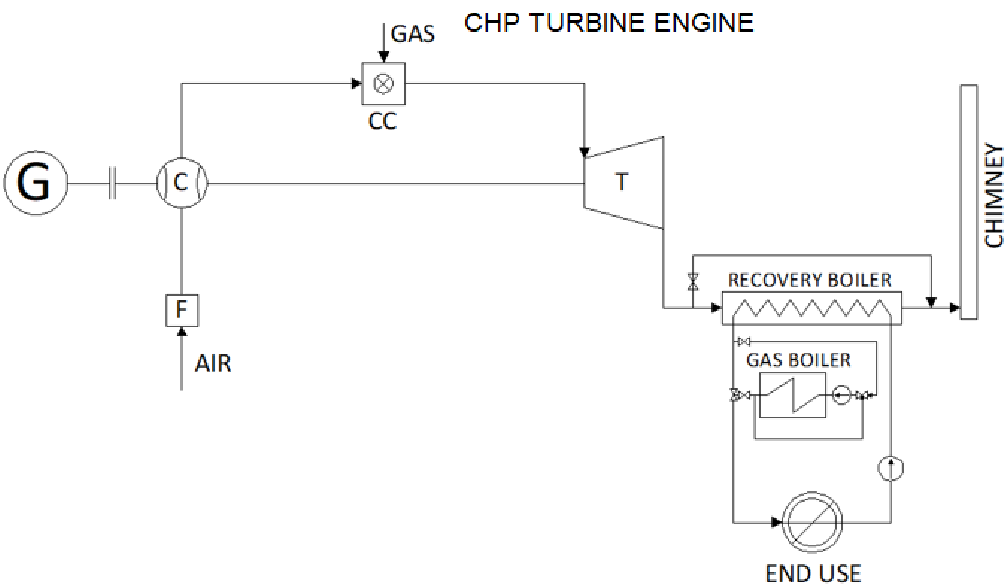


Figure 2. Scheme of CHP system with turbine engine.

Table 2. Statistical performance indicators of CHP for small scale applications [7].

Engine	Power range, MW	Electrical efficiency, η_{el}, %	Energy Utilization Factor, EUF, %	Association indicator, σ, -
Turbine	> 0.35	15 – 40	65 – 85	0.4 – 0.8
Piston engine	0.005 – 6.5	25 – 40	70 – 90	0.5 – 1.0

Table 3. Criteria for annual assessment of PM10 concentrations [15].

Averaging period	Threshold of pm10 in air [μg/m^3]	Permissible frequency of exceeding threshold dose over the year [times]
24 hours	50	35
Year	40	-

Table 4. PM10 emission, data based on KOBiZE (2017) [14].

Source	PM10 emission, %
Agriculture	12
Energy sector	7
Road transport	8
Industry	20
Superficial emission	**46**
Other	7

Table 5. Benzo(a)pyrene emission, data based on KOBiZE (2017) [14].

Source	Benzo(a)pyrene emission, %
Waste	3
Industry	10
Agirculture	2
Road transport	1
Superficial emission	**84**

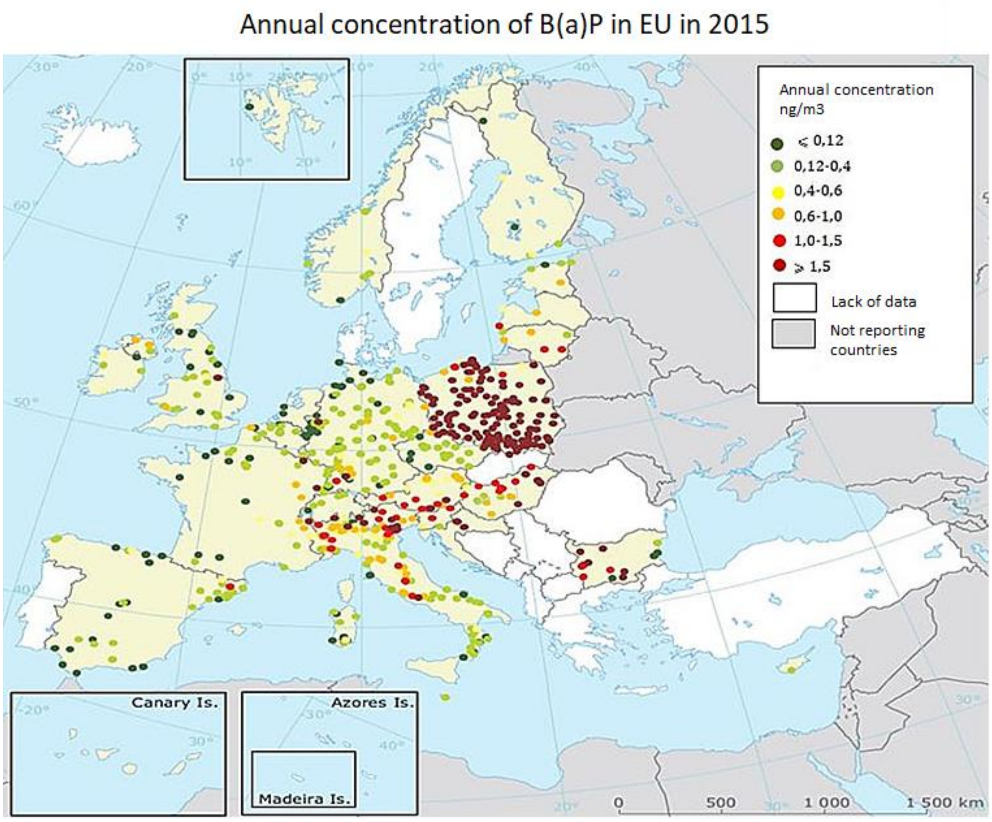


Figure 4. Annual concentration of B(a)P in EU in 2015 [16].

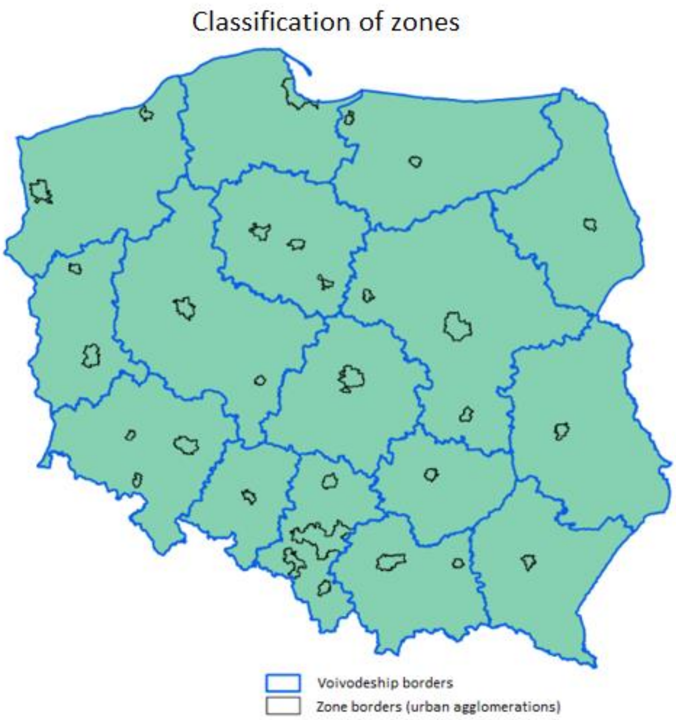


Figure 5. Classification of monitored zones in Poland 2016 [15].

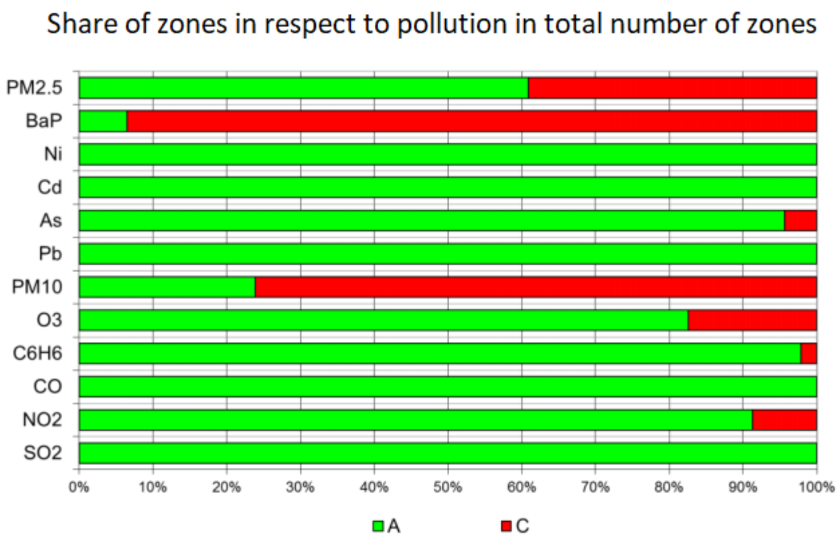


Figure 6. Share of zones in respect to pollution in total number of zones, 2016 [15].

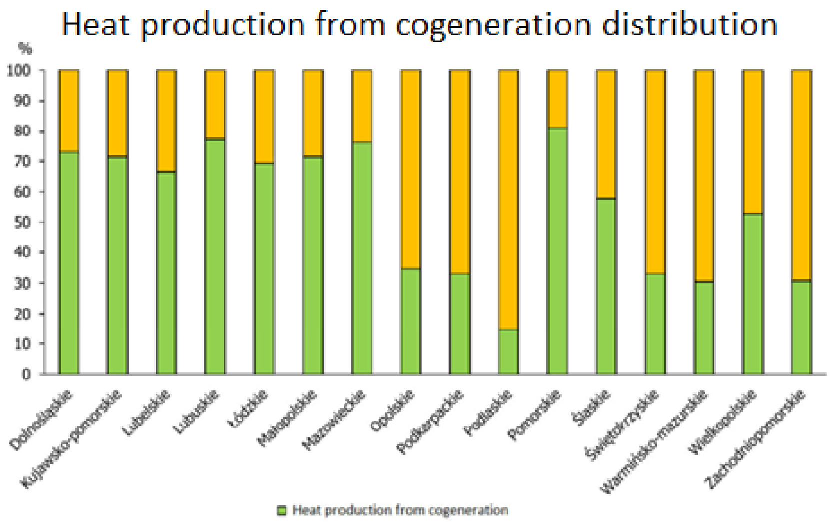


Figure 7. Heat production from cogeneration across Poland (2014) [18].

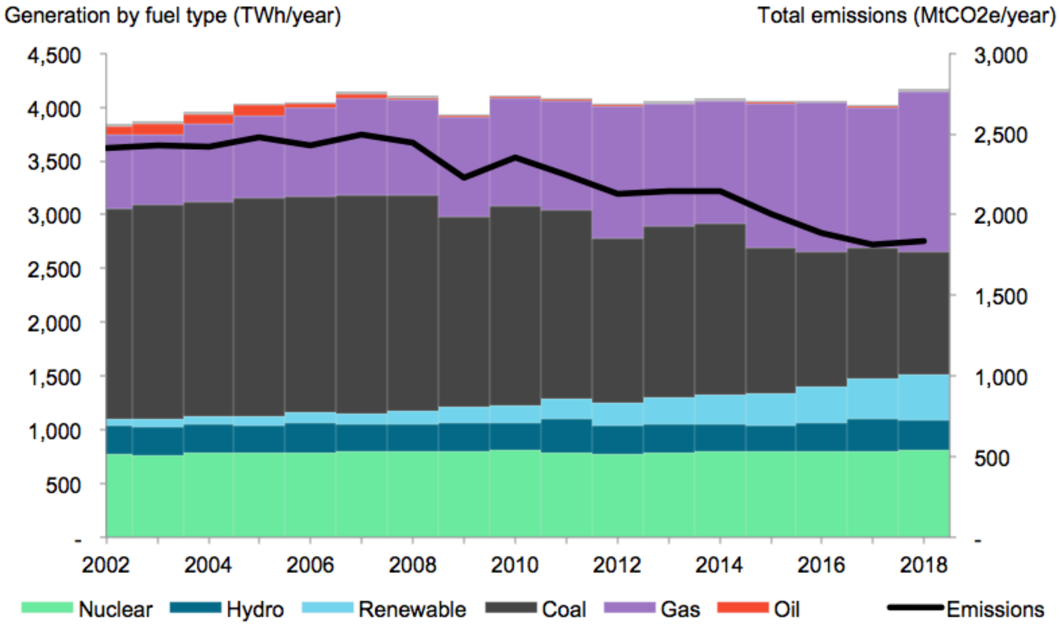


Figure 8. Change in emissions and generation of energy over recent years in the U.S. [20].

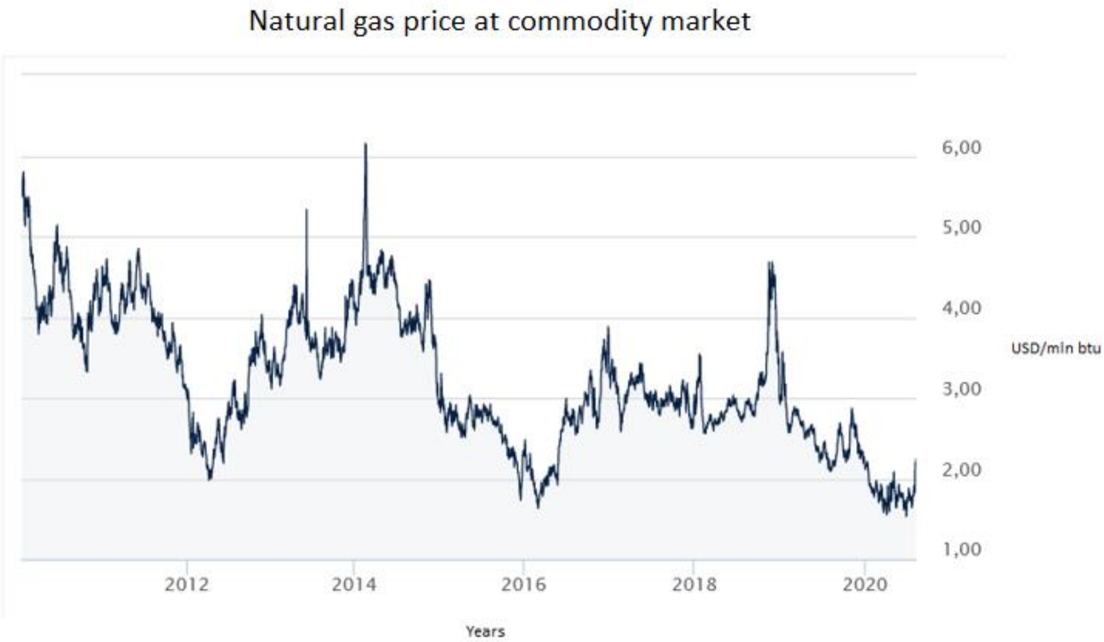


Figure 9. Change in nautral gas price at commodity market over recent years [21].

Comparison of some solid fuels

Fuel	Proximate analyses					Ultimate analyses				
	W	*A*	*V*	*FC*	Q_i	*C*	*H*	*N*	*S*	*O*
	%				kJ kg^{-1} d.m.	%				
Hard coal	3.1	8.6	32.7	55.6	25741	75.7	4.3	1.2	1.2	5.9
Tall fescue ecotype	8.8	6.6	66.7	17.8	15981	45.4	5.6	0.7	0.1	32.8
Sorghum	7.9	7.2	67.6	17.3	15829	45.6	5.7	0.9	0	32.7
Reed canary grass	8.3	8.2	65.9	17.6	15933	44.9	5.8	0.9	0.1	31.9
Miscanthus	7.4	3.6	72.4	16.6	17185	48.4	6.0	0.4	0	34.2
Brome grass	8.2	4.4	68.6	18.7	16271	46.2	6.0	0.6	0	34.6
Tall wheatgrass 33 1f	6.2	8.5	66.9	18.5	15979	44.1	5.7	0.5	0	35.0
Tall wheatgrass 35 5f	7.5	5.9	68.2	18.5	16322	46.0	5.9	0.4	0	34.3
Tall wheatgrass 35 8f	6.7	5.9	68.7	18.6	16701	46.5	5.8	0.4	0	34.6
Tall wheatgrass Bamar	6.8	5.6	69.3	18.4	16489	46.0	5.9	0.5	0	35.2
Wheat straw pellet	2.9	5.8	74.8	16.6	18130	49.4	5.6	0.6	0.1	35.7
Pellet Bamar	6.9	6.4	68.8	17.9	17043	46.7	5.9	0.6	0	33.5
LSD (p > 95%)	0.116	0.247	0.482	0.521	107.314	0.289	0.094	0.032	0.013	0.461

W – moisture content in the analysed sample, *A* – ash content in the sample, *V* – volatile matter content, *FC* – combustible solid content, Q_i – net calorific value, d.m. – dry mass.

Figure 10. Table comparing properties of different types of solid fuels [23].

Energy potential of straw for Poland

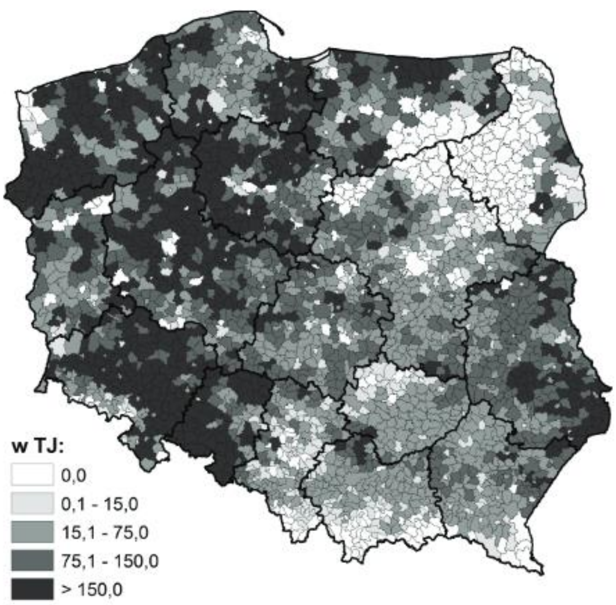


Figure 11. Energy potential of straw for Poland (2017) [26].

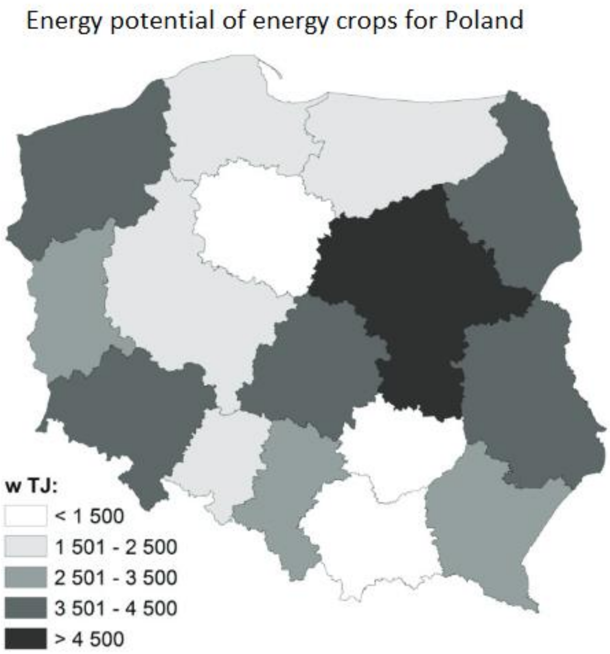


Figure 12. Energy potential of perennial energy crops for Poland (2017) [26].

Classification of tools

Tool	Type						
	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation optimisation	Investment optimisation
AEOLIUS	Yes	–	–	–	Yes	–	–
BALMOREL	Yes	Yes	Partial	–	Yes	Yes	Yes
BCHP Screening Tool	Yes	–	–	–	Yes	Yes	–
COMPOSE	–	–	–	–	Yes	Yes	Yes
E4cast	–	Yes	Yes	–	Yes	–	Yes
EMCAS	Yes	Yes	–	–	Yes	–	Yes
EMINENT	–	Yes	–	–	Yes	–	–
EMPS	–	–	–	–	–	Yes	–
EnergyPLAN	Yes	Yes	–	–	Yes	Yes	Yes
energyPRO	Yes	Yes	–	–	–	Yes	Yes
ENPEP-BALANCE	–	Yes	Yes	Yes	–	–	–
GTMax	Yes	–	–	–	–	Yes	–
H2RES	Yes	Yes	–	–	Yes	Yes	–
HOMER	Yes	–	–	–	Yes	Yes	Yes
HYDROGEMS	–	Yes	–	–	–	–	–
IKARUS	–	Yes	–	–	Yes	–	Yes
INFORSE	–	Yes	–	–	–	–	–
Invert	Yes	Yes	–	–	Yes	–	Yes
LEAP	Yes	Yes	–	Yes	Yes	–	–
MARKAL/TIMES	–	Yes	Yes	Partly	Yes	–	Yes
Mesap PlaNet	–	Yes	–	–	Yes	–	–
MESSAGE	–	Yes	Partial	–	Yes	Yes	Yes
MiniCAM	Yes	Yes	Partial	Yes	Yes	–	–
NEMS	–	Yes	Yes	–	–	–	–
ORCED	Yes	Yes	Yes	–	Yes	Yes	Yes
PERSEUS	–	Yes	Yes	–	Yes	–	Yes
PRIMES	–	–	Yes	–	–	–	–
ProdRisk	Yes	–	–	–	–	Yes	Yes
RAMSES	Yes	–	–	–	Yes	Yes	–
RETScreen	–	Yes	–	–	Yes	–	Yes
SimREN	–	–	–	–	–	–	–
SIVAEL	–	–	–	–	–	–	–
STREAM	Yes	–	–	–	–	–	–
TRNSYS16	Yes	Yes	–	–	Yes	Yes	Yes
UniSyD3.0	–	Yes	Yes	–	Yes	–	–
WASP	Yes	–	–	–	–	–	Yes
WILMAR Planning Tool	Yes	–	–	–	–	Yes	–

Figure 13. Classification of software for energy system assessment [27].

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