# Software for techno-economic assessments of gas CHP

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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.

Keywords: combined heat and power (CHP), renewables, techno-economic assessment, software

## 1. Introduction

Development and promotion of highly efficient technologies and renewables sources of energy is an integral part of the European Union energy policy. That is due to the strong dependence of current energy industry on fossil fuels which are a source of considerate number of problems, especially their negative impact on the environment. As a response to international policy, membership countries have prepared the strategies serving to complete those goals. Polish government have prepared a PEP2040 describing energy strategy and its goals for Poland until 2040 [1]. The act stresses development of renewable and clean energy technologies. This is required also due to the fact that Poland is facing environmental issue known as “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. 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 1.

Table 1. Criteria for annual assessment of PM10 concentrations [2].

| 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 | - |

Distribution of PM10 concentrations across Poland as 24-hours concentrations, expressed as 36$^{th}$ maximum daily concentration, is presented in figure 1.

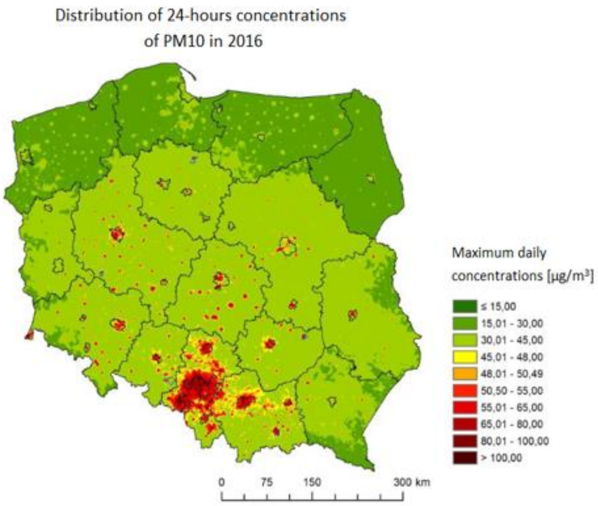


Figure 1. Maximum 24-hours PM10 concentrations concentration in Poland, 2016 [2].

Since the pollution of PM10 is directly harmful for human's life e.g. due to the emission of benzo(a)pyrene, which has been classified as the most carcinogenic factor by the International Agency of Research on Cancer, neutralizing the "superficial emission" occurrence is one of the key goals to achieve as soon as possible. One of the ways to improve environmental condition as well as fulfill the concepts of policy strategies is the development of gas fueled CHP systems. 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 [3,4]. 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. Strategy of gradually reducing the share of coal and switching to natural gas has several benefits. Firstly, natural gas power plants allow to decrease undesirable emissions [5]. Apart from that, decreasing price of natural gas over recent years stimulates the investments and more dynamic nature of gas plants (possibility of launching or stopping in a short period) benefits in terms of operation as it can help to balance the grid more appropriately and minimize heat losses [5].

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 CHP 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 user can choose between two types of engine, piston (reciprocating) or turbine presented in figure 2. Additionally, the software allows the user to include renewable generation as a concept fulfilling the strategic plans. 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 theoretically used coal and biogas in theoretically used natural gas. Introducing biomass and biogas has several advantage, the major ones are that co-firing coal with biomass and gas with biogas requires little additional investments [6]. and that, in general, $CO_2$ emissions are considered to be zero.

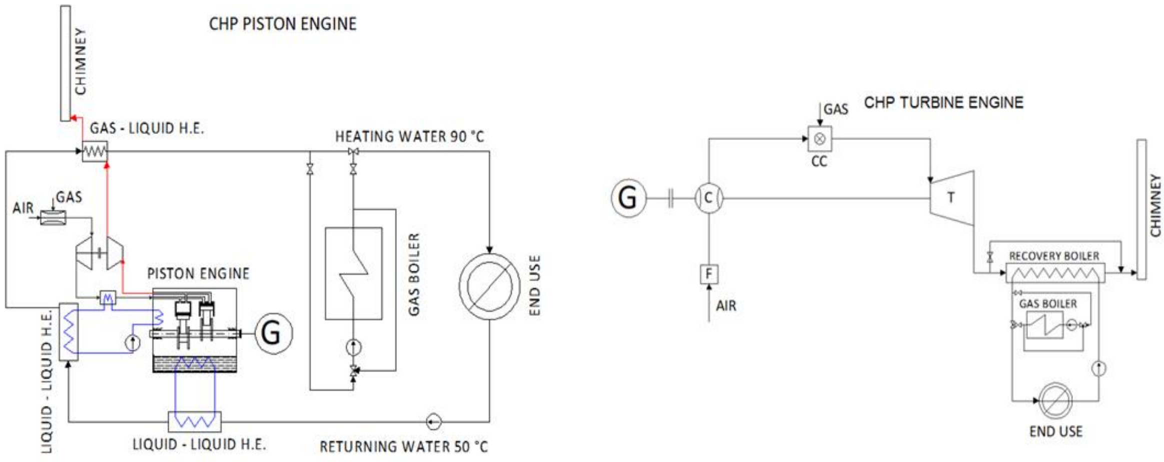


Figure 2. CHP system with piston engine (left side) and turbine engine (right side) implemented in the software.

## 2. Commercial software

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. Some of the tools which allow to analyse CHP systems are *Balmoral, BCHP Screening Tool, Compose, EnergyPLAN, eneryPRO* and *RETScreen*. The software with the highest number of downloads is *RETScreen*. *RETScreen* (Clean Energy Management Software) is a software which offers the a vast range of analyses for various technologies including highly efficient and renewable units. 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 [7]. Program has been developed by Natural Resources Canada (contributions from government and industry) and it used to be free of 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).

## 3. Literature Review

The issue of fossil fuels and their impact on the environment has been discussed by authors Gaete Morales, Carlos & Gallego Schmid, Alejandro & Stamford, Laurence & Azapagic, Adisa. (2019) [8] as they 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. An informative paper regarding coal to gas switch, proposed in mentioned work [8] 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) [9]. 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) [10]. Article discussing pollution ($CO_2$, $NO_2$, 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) [11]. Advantages of introducing biomass has been analyzed by Loha, Chanchal & Karmakar, Malay & Chattopadhyay, Himadri & Majumdar, Gautam. (2019) [6]. Cogeneration technology has been described based on book from Skorek J., Kalina J. “Gas cogeneration systems” (2004) [3] as the paper focuses on criteria serving to assess CHP unit in terms of profitability and shows some specific examples of techno-economic analyses. More recent publication has been delivered by Breeze Paul “Combined Heat and Power” (2018) as it 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 [4]. 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) [12]. The authors examine gas mixing ratio and heat sales ratio in terms of the costs of electrical energy and heat produced concluding that higher proportion of natural gas makes CHP plant more susceptible to economic factors. An informative paper regarding software modelling energy systems has been delivered by Connolly, D. & Lund, Henrik & Mathiesen, Brian & Leahy, Martin (2010) [7] 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.

## 4. 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 [13]. 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 an example of such technology for Polish market. Depending on evaluation criteria which are the basis for objective function, different solution might be indicated as the most favourable. In case of private investment, local analysis aiming to maximize net present value or internal rate of return might be the most favourable, however public energy projects could prioritize environmental benefits e.g. through achieving minimum hazardous and GHG emissions (PM10 and PM2.5) or maximum fuel chemical energy savings.

## 5. 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 3.

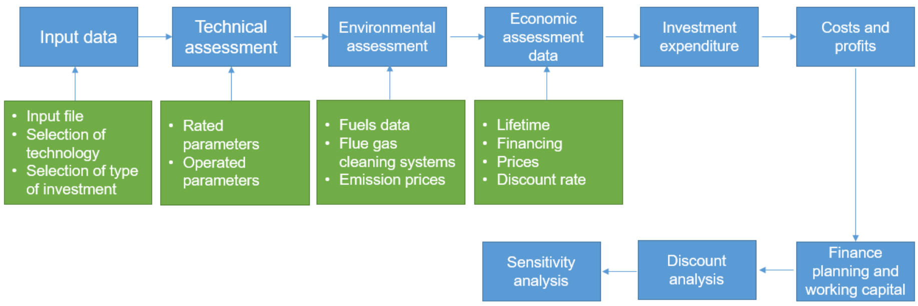


Figure 3. General structure of the software.

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. 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 and 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 [3]. 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. General outlook of the software with first tab is presented in figure 4.

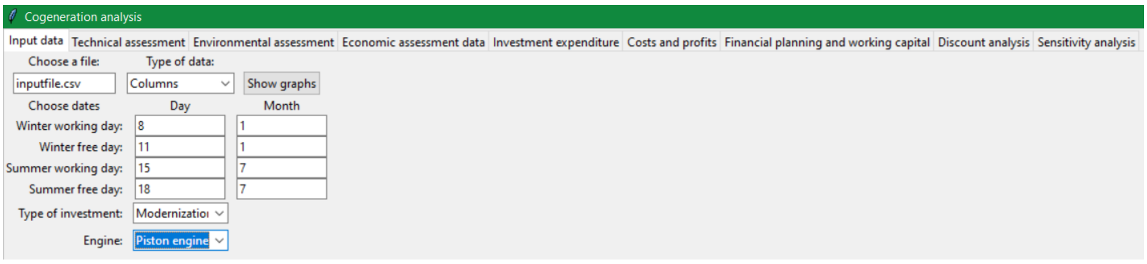


Figure 4. Input data tab with list of other tabs.

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:

$$\dot{P} * LHV + N_G = \dot{Q}_D + \dot{Q}_S + N_{CHP} \tag{1}$$

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.

Input file for the software requires heat demand as the software performs the simulation according to heat tracking mode. Technical assessment allows the user to obtain the annual values of performance of CHP such as: gross electricity produced, electricity sold to the grid, required heat, heat sold, total gas required and system efficiency. Environmental assessment allows to compare the total values of emissions of $CO_2$, $SO_x$, $NO_x$, CO, dust and b(a)p and the profit in terms of avoided cost (user declares prices for particular compounds). Economic assessment allows the user to declare lifetime, financing (acquisition and modernization projects are included separately) with the division by net subsidies, equity and credits. Subsequent tabs present respectively the results. Investment expenditure shows all the expenditures associated with the project calculating it through a set of empirical equations and credit service. Costs and profits tab present detailed information about annual costs of production and incomes, working capital and finance planning present further information about the predicted cash flows, finally discount analysis allows to obtain the economic investment indicators such as net present value, net present value ratio (ratio of net present value to total investment expenditure), internal rate of return, simple and discounted payback period, as seen in figure 5. Sensitivity analysis calculates the values of economic indicators in case of different values of particular prices (the user can change the values of natural gas, biogas, coal, biomass, sold heat, electricity and total investment prices).

| 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 5. Discount analysis.

The results seen in figure are taken from sample simulation performed in order to present the possibilities of the software. 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%, as seen in figures 18, 19, 20 and 21 of the thesis. Technical assessment indicates significant coal save (comparing to current coal use). Total energy efficiency achieves very good value as it is over 80%. Environmental assessment uses assumption 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. Evaluating results (figure 21) 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 22, 23, 24 and 25 of the thesis. The summary of results is presented in table 2.

Table 2. Results of simulation (annual values).

| | |
|---|---|
| Gross electricity produced | 174 419 298 kWh |
| Electricity sold to the grid | 167 408 089 kWh |
| Heat sold to the grid | 708659.9 GJ |
| Total gas required | 43 901 169 $Nm^3$ |
| Coal reduction | 42676 t |
| Coal use | 1719 t |
| Total energy efficiency | 84.24 % |
| $CO_2$ emission | 74540.9 t |
| Profit from change in emissions | 68616 PLN |
| NPV | 71 946 130 PLN |
| NPVR | 0.991 |
| IRR | 0.192 |
| SPB, DPB | 5.95, 7.22 |

Sensitivity analysis has been performed comparing the scenarios presented in table 3. The results are presented further in table 4. 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.

Table 3. Scenarios with varying prices of sold/purchased goods.

| Parameter/<br>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 4. 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. For given simulation the price of natural gas impacts the investment in the strongest way as it is the highest cost among the fuels. 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. The results of other simulations (modernization type for turbine engine and new investment type for both piston and turbine engines) are presented in the thesis.

## 6. Conclusions and comments

Extension of district heating grids corresponds to Polish policy goals, therefore tools allowing to assess such investments are of special help for potential investors in the process of decision making. The software has several advantages if comparing to other programs which could also serve for the purpose of analysis of the CHP units. It's easy to use, does not required a lot of data in order to perform calculation and it delivers quite detailed analysis within its scope. 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 lists of incomes and outcomes. 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.

As for the limitations of the software, first thing is that model uses heat demand values based on input data file, which might not be accurate in following years. Another assumption is 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 is required which might not be feasible to achieve. 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% [20]. 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. 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. 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 working type. 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 year.

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