Energetic Investigation and Economic Feasibility for a University Campus in Romania towards Becoming an Energy Supplier

Ali Al Dabbas1*, Laith Al-Hyari2, Ahmad D. M. Al Awana3, Mohammad Fawaier2

1 Department of Engineering Geology and Geotechnics, Faculty of Civil Engineering, Budapest University of Technology and Economics, H-1111 Budapest, 3 Műegyetem rkp., Hungary
2 Department of Building Service and Process Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, H-1111 Budapest, 3 Műegyetem rkp., Hungary
3 Department of Mechanical Engineering, Faculty of Mechanical Engineering and Mechatronics, University Politehnica of Bucharest, 060042 Bucharest, 313 Splaiul Independenței, Romania

* Corresponding author, e-mail: ali.al.dabbas@emk.bme.hu

Received: 15 October 2020, Accepted: 26 November 2020, Published online: 15 February 2021

Abstract
This research investigates and evaluates the University Politehnica of Bucharest (UPB) possibilities to become an energy self-supplying by building up its own power plant and becoming an energy distributor. The campus has already been connected to the national natural gas supplying pipe and the local district heating and electrical network.

A set of criteria was used to evaluate the feasibility of this project. Technical, financial, and environmental considerations were taken into account to determine the most suitable solution. The feasibility study assumed three proposals of an energy supply system considered for the university buildings/campus. Gas-fired heating plant, gas-fired Internal Combustion Engine cogeneration plant and gas fired Internal Combustion Engine for cogeneration with an Organic Rankine Cycle ORC.

The details of each proposal were discussed to obtain the optimum solution. Elaborate. It was found from a financial and environmental perspective that the most feasible project is gas-fired Internal Combustion Engine cogeneration, considering profit revenue from selling/exporting power to the domestic electricity grid. And the Net Present Value was around one million euros for 15 years life.

Keywords
energy efficiency, economical analysis, Internal Combustion Engine (ICE), recuperative cycle

1 Introduction
Balancing between energy consumption/production and levels of emitted Greenhouse Gases GHG is important to meet the produced energy. Optimum efficiency is the key performance indicator of energy efficiency, keeping in mind fulfilling the growing demand for energy in urban society. Carbon dioxide CO2 is the primary member of the GHG. CO2 saving should be considered in the energy production process to minimize the impact of environmental pollution as low as possible [1]. However, due to fossil fuel prices daily growth, designing energy-efficient buildings will conserve the required energy and attempt to lower the costs of energy bills. Which is considered a target should be reached from the energy efficiency point of view [2].

Energy efficiency, climate comfort, and evaluating actual building energy consumption have been studied significantly by different feasibility studies to provide perfect building patterns [3]. Construction engineering and many of such evaluation studies were performed on university buildings/campus to give additional academic vision value of applying energy management/efficiency concepts on construction [4].

University Politehnica of Bucharest (UPB) is the largest technical university in Romania, located at 21° Eastern Longitude and 45° Northern Latitude, Covering a total area of 100 ha (hectare). UPB has almost 10,000 students, consisting of six major buildings of administrative services, classes, and laboratories. All planes area under the building's roof is around 120,000 m2 [5].

Currently, the campus is importing electricity and thermal energy from the local specialized distributor...
The thermal energy is used for space heating, domestic hot water, electricity for lighting, cooling, electronic appliances, and essential building utilities. The campus has also been connected to natural gas distribution pipes and the local district heating and electricity grid. This situation has encouraged the university to explore the possibilities of becoming an energy supplier by building its own energy supply system. UPB would become self-sufficient in energy supply and sometimes could export its excess energy to the electricity grid, i.e., energy distributor.

Researchers highlighted previous work in this paper to specify the progress and development of implying different energy supply systems. Bayoumi [6] developed a comprehensive energy plan for a campus in Saudi Arabia to achieve possible results to reduce energy consumption. Kalina [7] studied three different proposals (allothermal wood gasifier, Solid Oxide Fuel Cell (SOFC) and Internal Combustion Engine (ICE) and Organic Rankine Cycle (ORC) for waste heat recovery) for elective utility station. It was found that the proposed integrated biomass gasification small-scale cogeneration plant with allothermal wood gasifier, SOFC, ICE, and ORC for waste heat recovery could be an attractive technological alternative for reduction of consumption of fossil fuels and global CO$_2$ emission.

Rosato et al. [8] simulated the energy performance that is integrated with the micro-cogeneration system by a TRNSYS simulation software. They compared the proposed plan with a conventional system. The results showed that, in comparison to the traditional design, it allows saving more energy than the conventional system.

Dragomir-Stanciu [9] proposed a solution to increase a Combined Heat and Power (CHP) plant's efficiency incorporated with Internal Combustion Engines by using the available thermal energy produced from hot water to generate electricity in an Organic Rankine Cycle (ORC). A numerical model was applied based on two assumptions made by Mărcuş et al. [10] using the lower heating value and the higher heating value of the natural gas. The results showed that the efficiency values from the model determine the efficiency with a very close approximation to the actual model ($R^2 = 0.9443$). Besides, the variation trend of thermal and global efficiency increases with the increasing of the partial load.

Kalantzis et al. [11] presented an energy model for an Internal Combustion Engine (ICE) for cogeneration (heat and electricity) systems that were simulated using MATLAB. The engine model results were found to be adequate in predicting the measured engine outputs.

Experimental and numerical analysis of combined heat and power equipped with a biomass, gas purification system, and gas piston engine was studied by Elsner et al. [12]. It was found that it is more feasible to use the generated electricity and heat for its self-consumption rather than selling it on the market.

In this work, there are three different schemes on how UPB could develop its energy supply system. However, all of them are based on the use of natural gas as a primary fuel. The proposed schemes are:

1. Build up classical/condensation gas-fired heating plants (boilers) and keep buying electricity from the local distributor.
2. Build up a classical/condensation gas-fired heating plant (boilers) together with a gas-fired Internal Combustion Engine cogeneration plant to supply electricity and heat as well.
3. Build up as the previous schemes but with additional Organic Rankine Cycle (ORC) recuperative cycle.

This work’s novelty is to highlight the most suitable solution schemes to be utilized for future plans in such cases.

2 Methodology

The following procedure was applied to select the best proposal for the campus

1. Estimate the heating and electricity demands of the buildings.
2. Define equipment characteristics used in each proposal, such as boilers, cogeneration engine, and turbine.
3. Estimate the amount of energy delivered, fuel consumption, and emission.

The study analyzed each proposal’s economic feasibility and performed strategic planning to identify each proposal’s strengths and weaknesses to ensure the maximum efficiency for the primary/peak load. Special operations on the plant components were performed using RETScreen software. The study takes into consideration calculating pollutants and CO$_2$ emission of the system along with a one-year operation. It acquired electric energy considering that this coal-fired produced energy at a general efficiency of 35%. Three solutions have been compared from both the technical efficiency and the financial point of view, including the green certificates policies, before selecting the most suitable proposal.
3 Heating and electricity demands

The first step in setting up an energy supply system is determining the energy demand, i.e., heating and electricity demands. There are several methods to estimate heating and electricity demands. The most common way is by calculating the heat load of a building based on tabulated climate data. The electricity demand can also be estimated by knowing the total electricity load. Another method, which is more straightforward and more practical, is by analyzing the energy bills. Using data from energy bills, one can simply figure out the actual energy consumption of a building representing the heating and electricity demands. In this project, heating demand was determined using both methods mentioned above; electricity demand was estimated using energy bills data.

3.1 Heating demand

There are two critical parameters to be calculated when one estimates the heating demand. The first parameter is the total annual heat demand. Two kinds of heating loads are considered to estimate the total annual heat demand of a building, 1. $Q_{H}$, the sum of the energy use for space heating, and 2. $Q_{DHW}$, and the energy use from domestic water heating,

$$Q_{H} = Q_{H} + Q_{DHW}$$

The energy use for space heating can be calculated using heating degree-days, which depends on climate conditions. The energy use for domestic water heating was 3,400 MWh, depending on the technical calculation performed previously by the university's building facility team. The calculation using this concept was performed using RETScreen software [13] to simplify the analysis; the whole building is a single cluster building. Based on this method, the energy use for space heating was estimated to be 13,673 MWh. Therefore, the total annual heat demand of the building was 17,448 MWh.

The second parameter to estimate is the peak heating load by determining using the building heating chart, as shown in Fig. 1. The peak load for space heating occurs under very cold conditions. In this project, the peak heating load was estimated at approximately 6.75 MW, using the heating design temperature of 25 °C and the building heating load of 75 W/m², based on the medium type of insulation used in the building.

As a countermeasure for the first method, the energy bills were also used to estimate the heat demand. The energy bills were reflecting the thermal energy consumption in UPB. The summary of this data is shown in Table 1.

Table 1 The thermal energy consumption of University Politehnica of Bucharest selected building campus

| Month       | Thermal energy usage (MWh) | Heat load (kW) |
|-------------|----------------------------|----------------|
| January     | 5,236,653                  | 7,039          |
| February    | 5,341,154                  | 7,948          |
| March       | 3,204,692                  | 4,307          |
| April       | 1,228,465                  | 1,706          |
| May         | 362,270                    | 487            |
| June        | 354,142                    | 492            |
| July        | 181,135                    | 243            |
| August      | 29,028                     | 39             |
| September   | 328,597                    | 456            |
| October     | 1,236,593                  | 1,662          |
| November    | 3,169,859                  | 4,403          |
| December    | 4,539,981                  | 6,102          |

The total annual heat demand was around 25,213 MWh, and the average heating load was around 2,100 kW. It appears that the energy bill gave a higher heat demand compared to the previous method. The different result is due to the simplification used in the first method, which may not represent the actual condition. Thus, the heating demand calculation from the energy bills shall be used as a basis for the next analysis.

3.2 Electricity demand

The electricity load was determined from the monthly electricity bills of UPB University for the selected buildings in the year 2018. Table 2 shows the monthly average load of electricity.

Based on Table 2 data, the total electricity consumption and the power peak load can be determined. The total annual electricity use was 5,779 MWh, and the power peak load was around 1,000 kW.
Equipment sizing

4.1 Gas fired heating plant

In the first stage, a review of the most relevant boiler available in the market was performed. The selection process is based on the availability of information on the capacity, as indicated in the current bill and its price for the financial review.

The high efficient boiler Weil McClain manufacturer is selected, an ultra commercial boiler 94 series, the description of this boiler is shown in Appendix (Table 6). The selection is based on the current bill, which indicates the energy use of 25 MWh. After the review and the boiler's selection, the next step is to establish the best approach to determine the natural gas consumption in the selected boiler and the university's available data. The best approach found up to now is provided by RETScreen software [13], which has considered these factors in its calculation:

- Area covered for space heating and its heat load per square meter.
- A direct calculation to obtain natural gas consumption in m³.
- A proportion of heat water demand.
- Heat delivered to the system.

The boiler efficiency is 80 % and seasonal efficiency 75 %, along with its operations. The result is obtained, as shown in Appendix (Table 6). Other assumptions used in this case are:

- The total number of boilers required is five, with four boilers in operation and one standby.
- One boiler will be used to meet the base load capacity, and four boilers will be used in peak load capacity.

4.2 Gas fired internal combustion engine for cogeneration

The cogeneration plant's basic principle is using the energy from natural gas to generate electricity and recover the flue gas thermal energy for heating purposes.

The IC engine's sizing calculation is based on the electricity peak load capacity at 1,000 kW and the average heat load at 2,100 kW. To fulfill this energy demand, two units of GE JGS 320 were selected. Each unit of GE JGS 320 has an electrical and thermal output of 1,064 kW and 1,222 kW, respectively. The cogeneration system's technical performance is indicated by the overall efficiency, total annual electricity, thermal energy production, and fuel consumption.

To ensure the maximum utilization rate, the engines are running at full capacity mode. The IC engines can deliver the total annual electricity and total annual heat recovery of 18,641 MWh and 21,409 MWh, respectively, with an overall maximum efficiency of 85.94 %.

Since the annual electricity production is larger than the annual power demand, the excess power of 12,862 MWh can be exported to the grid. On the other hand, the total annual heat recovery is insufficient to cover the heat demand during the peak period. Thus, the natural gas-fired heating plant indicated by the blue bar in Fig. 2 should cover the remaining heat demand of 3,804 MWh. Since the IC engine runs at full capacity mode, it produces a constant heat recovery for the whole year. Thus, a heat excess during the summer period must be considered, either as a potential thermal energy or heat loss indicated by the yellow bar in Fig. 2.

The total annual fuel consumption can be estimated by adding the natural gas consumption of cogenerating engines and the auxiliary boilers used during peak season.

![Table 2 The electricity consumption of University Politehnica of Bucharest selected buildings campus](image)

| Month    | Electricity Usage (MWh) | Power Load (kW) |
|----------|-------------------------|-----------------|
| January  | 594                     | 958             |
| February | 620                     | 923             |
| March    | 590                     | 793             |
| April    | 582                     | 808             |
| May      | 579                     | 778             |
| June     | 423                     | 588             |
| July     | 375                     | 504             |
| August   | 123                     | 165             |
| September| 256                     | 356             |
| October  | 487                     | 655             |
| November | 563                     | 782             |
| December | 587                     | 789             |

![Fig. 2 The heat energy profile of cogeneration engine](image)
Using the gas lower heating value of 10.8 kWh/m$^3$, the total annual fuel consumption is estimated as follow:

- Natural gas consumption of cogenerating engines
  \[ \text{Cogeneration Engine Heating} \]
  \[ \left( \frac{\text{Calorific value of natural gas}}{\text{Electrical Efficiency} \left( \mu_e = 40.1 \% \right)} \right) = 4,315,111 \text{ m}^3 \]

- Natural gas consumption of Auxiliary Boiler
  \[ \text{Auxiliary Boiler caloric value} \]
  \[ \left( \frac{\text{Calorific value of natural gas}}{\text{Auxiliary Boiler thermal efficiency} \left( \mu_r = 80 \% \right)} \right) = 1,462,417 \text{ m}^3 \]

The Total Natural gas consumed is 5,777,528 m$^3$. The summary of the technical performance of cogeneration engine system is shown in Appendix (Table 7).

### 4.3 Gas fired internal combustion engine for cogeneration with an ORC recuperative cycle

The basic principle of an ORC addition to the cogeneration engine is to recover the thermal energy production excess or waste heat during summer. In this proposal, the cogeneration system and boilers capacity remain the same as the second proposal. ORC's sizing calculation is based on the excess thermal energy during the summer period, which is equal to 8,689 MWh. This amount of heat can be converted into electricity by using a unit of Cogeneration Engine with the model Turbogen 4 HR with an electrical efficiency of 18%. The electrical output of the engine is 400 kW.

The Turbogen engine can deliver the total annual electricity of 1,581 MWh, exported to the electricity grid. This system's main drawback is its low utilization rate since it only runs in the summer. Since the ORC system's energy input is waste-heat from cogeneration engine. The addition of an ORC turbine in the cogeneration system does not increase the fuel consumption. The summary of cogeneration's technical performance with an ORC recuperative cycle is shown in Appendix (Table 8).

### 5 Financial analysis

Many parameters were engaged in calculating the financial assessment for each case presented earlier. The parameters used in our analysis are:

1. Operating cost is the recurring expenses to the operation of facilities/equipment. For this analysis, the parameter is fuel cost.
2. Revenue is income received by a business from its normal business activities. In case 1, there is no revenue. In case 2, revenue is the sum of the export of electricity from CHP to the grid and the potential saving of electricity and thermal consumption, as indicated in the current bill. In case 3, revenue is the same as case 2, plus the export of electricity by utilizing gas waste.

3. Profit is gross profit less all operating expenses. In case no 1, profit is taken from the potential saving of fuel consumed by the boiler and the current bill annually. In case 2, profit is generated from the difference between its revenue and the fuel cost annually. In case 3, the profit is produced as case 2 Net Present Value (NPV). The net present value is the indicator used for the financial assessment. It is a time series of cash flow, both incoming and outgoing, defined as the sum of the individual cash flows' present values. All the values used for NPV calculation are taken from Europe's Energy portal, as indicated in Table 3.

Along with the NPV calculation, these assumptions are applied:

1. The lifetime expectation for each equipment is 15 years.
2. The depreciation method used is linear depreciation.
3. The tax rate for exporting electricity in Romania is 35%.
4. The discount rate in Romania for investment is 16%.
5. Technician's salaries are not included in the calculation since they do not reflect the changes before and after the implementation of cases.

The financial assessment result for all the proposed cases is shown in Fig. 3.

As shown in Fig. 3, the expected loss for case 1 is negative, and obviously, the net present value shows negative as well. The second proposed system can generate considerable revenue due to the electricity sold to the grid. It also confirms that both saving and net present value are positive. The massive saving is made, besides selling electricity, because the equipment's investment is small compared to the output. Therefore, it can be concluded that the project is promising for further study as long as it is allowed to export or sell the electricity to the grid.

### Table 3 Energy prices in Romania [14]

| Parameter                        | Unit    | Value  |
|----------------------------------|---------|--------|
| Fuel rate – base case            | Eur/kWh | 0.0200 |
| Electricity rate – base rate     | Eur/kWh | 0.0847 |
| Fuel rate – proposed case        | Eur/kWh | 0.0198 |
| Electricity export rate          | Eur/kWh | 0.0700 |
| Electricity rate – proposed case | Eur/kWh | 0.0847 |
The third case makes savings during its operation annually, but the net present value calculation is the opposite. This happens due to the high investment cost on the ORC system, and its saving cannot cover it for 15 years of operations. Hence, it is not recommended for further development.

6 Emission analysis
In Section 6, the greenhouse gas emission will be analyzed to assess the overall greenhouse gas (GHG) impacts of fuel and to calculate the total reduction of CO₂ when implementing the proposed cases in this work.

This project's greenhouse gas emission analysis method is based on the RETScreen GHG Analysis Reduction model [13].

\[
\Delta R_{GHG} = \left[ FC \times tCO_2 \right]_{Heating} - \left[ FC \times tCO_2 \right]_{Electricity} \tag{2}
\]

For base case emission analysis, it is considered that the electricity is produced by a coal-fired power plant with general efficiency of 35 %, and thermal energy is produced by a gas district heating system with boiler efficiency of 70 %. The GHG emission factors are taken from the RETScreen database [13]. The overall annual GHG emission for the base case is estimated at around 26,063 tCO₂. In the first proposed case, the GHG emission has resulted from the combustion of natural gas in boilers and the electricity purchased from the coal-fired power plant. The overall annual GHG emission for the first case is estimated at around 24,862 tCO₂. In the second proposed case, the GHG emission results from the combustion of natural gas in the cogeneration engine and the transportation and distribution losses of electricity exported to the grid. The T&D loss is estimated at around 8 %. The overall annual GHG emission for the second case is estimated at 7,740 tCO₂.

The third proposed case GHG emission similarly results from the combustion of gas in the cogeneration engine and the transportation and distribution losses of electricity exported to the grid. But in this case, the T&D loss is higher than the second case since the quantity of electricity exported to the grid is also higher due to the addition of an ORC turbine. The overall annual GHG emission for the second case is estimated at around 7,875 tCO₂.

By using GHG emission analysis, it appears that the second proposed case produces the least amount of annual greenhouse gases emission. This result should be taken into considerations for technology selection. The detail of the GHG emission calculation is shown in Table 4.

7 Conclusion
In determining the building's heat supply, many factors should be considered, i.e., heating degree days of the location, coverage area, building insulation, the proportion of water and space heating, total hours, and seasonal efficiency. Technology selection should also consider the equipment efficiency factor and the Technical, financial, and environmental feasibility.

To select the most feasible energy system proposal, strategic planning was used to identify each proposal analysis's strengths and weaknesses are elaborated to compare all option's viability. By comparing each proposal's strengths, weaknesses, opportunities, and threats using technical, financial, and environmental criteria, one can decide which proposal is to be selected. The detailed analysis is shown in Table 5.

From a financial and environmental point of view in this case study. It is concluded that the most feasible project is gas-fired Internal Combustion Engine cogeneration, considering profit revenue from selling/exporting power to the domestic electricity grid that will support the financial feasibility of this choice.
Table 5: Strategic planning to identify strengths, weaknesses of each proposal (SWOT analysis)

| Proposal          | Case 1                                                                 | Case 2                                                                 | Case 3                                                                 |
|-------------------|------------------------------------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------|
| **Strength**      | High efficiency for heating system                                     | 1- Higher overall efficiency                                            | 1-Higher overall efficiency                                            |
|                   |                                                                       | 2-Relatively low GHG emission                                           | 2-Relatively low GHG emission                                           |
|                   |                                                                       |                                                                       |                                                                       |
| **Opportunity**   | Excess thermal energy during the summer period can be utilized         | 1-Excess of thermal energy during the summer period can be utilized     | 1-Excess of thermal energy during the summer period can be utilized     |
|                   |                                                                       | 2-able to generate revenue from electricity exported to the grid        | 2-more electricity exported to the grid due to additional ORC           |
| **Weakness**      | Not economically feasible due to the high investment of heating system  | T&D losses to electric grid contribute to GHG emission                  | 1-Not financially feasible due to the high investment of ORC turbine   |
|                   | and high operating cost                                               |                                                                       | 2-T&D losses to electric grid contribute to GHG emission               |
| **Threat**        | Lack of gas supply in time of shortage may disrupt the operation       | Lack of gas supply in time of shortage may disrupt the operation        | Lack of gas supply in time of shortage may disrupt the operation        |

Acknowledgments
Stipendium Hungaricum Scholarship Programme is highly acknowledged for supporting the PhD study and research.

Nomenclature

- \( Q_H \): Total Heating Demand of a Building (MWh)
- \( Q_{SH} \): Heating Demand for Space Heating (MWh)
- \( Q_{DHW} \): Domestic Hot Water Heating (MWh)
- \( \mu \): Efficiency
- \( \Delta R_{GHG} \): Annual GHG emission reduction (tCO\(_2\))
- \( FC \): Fuel consumption (MWh)
- \( tCO_2 \): GHG emission factor (tCO\(_2\)/MWh)
- \( PC \): Proposed Case
- \( BC \): Base Case

References

[1] Kassai, M. "Heat Pump Heating System Development of Educational Building based on Energy, Economical and Environmental Impacts", Periodica Polytechnica Mechanical Engineering, 63(3), pp. 207–213, 2019. https://doi.org/10.3311/PPme.13872

[2] Derzsi, I., Takács, J. "Hydraulic Analyze of Risers of Heating System in High-rise Building", Periodica Polytechnica Mechanical Engineering, 63(2), pp. 156–163, 2019. https://doi.org/10.3311/PPme.13320

[3] Flucker, S., Tozer, R. "Data Centre Energy Efficiency Analysis to minimize total cost of ownership", Building Services Engineering Research and Technology, 34(1), pp. 103–117, 2013. https://doi.org/10.1177/0143624412467196

[4] Kóvári G., Kitselegdi I. "Optimized Building Automation and Control for The Improvement of Energy Efficiency and Climate Comfort Of Office Buildings", Pollack Periodica, 10(1), pp. 71–82, 2015. https://doi.org/10.1556/pollack.2015.10.1.7

[5] University Politehnica of Bucharest "History and faculties of the university", [online] Available at: https://upb.ro/en/ [Accessed: 13 January 2019]

[6] Bayoumi, M. "Potential of integrating power generation with solar thermal cooling to improve the energy efficiency in a university campus in Saudi Arabia", Energy & Environment, 31(1), pp. 130–154, 2020. https://doi.org/10.1177/0958305x18787271

[7] Kalina, J. "Options for using solid oxide fuel cell technology in complex integrated biomass gasification cogeneration plants", Biomass and Bioenergy, 122, pp. 400–413, 2019. https://doi.org/10.1016/j.biombioe.2019.06.014

[8] Rosato, A., Sibillo, S., Scorpio, M. "Dynamic performance assessment of a residential building-integrated cogeneration system under different boundary conditions. Part I: Energy analysis", Energy Conversion and Management, 79, pp. 731–748, 2014. https://doi.org/10.1016/j.enconman.2013.10.001

[9] Dragomir-Stanciu, D. "Improving the energy efficiency of an internal combustion engine cogeneration system using ORC as bottoming cycle", Procedia Manufacturing, 22, pp. 691–694, 2018. https://doi.org/10.1016/j.promfg.2018.03.099

[10] Mărcuş, G., Jordache, V., Iordache, F., Ilie, A. "Energy analysis of a CHP plant with internal combustion engines, for a district heating system, based on the information from the annual database", E3S Web of Conferences, 85, Article Number: 01012, 2019. https://doi.org/10.1051/e3sconf/20198501012

[11] Kalantzis, N., Pezouvanis, A., Ebrahimi, K. M. "Internal Combustion Engine Model for Combined Heat and Power (CHP) Systems Design", Energies, 10(12), Article Number: 1948, 2017. https://doi.org/10.3390/en10121948

[12] Elsner, W., Wysocki, M., Niegošdajew, P., Borecki, R. "Experimental and economic study of small-scale CHP installation equipped with downdraft gasifier and internal combustion engine", Applied Energy, 202, pp. 213–227, 2017. https://doi.org/10.1016/j.apenergy.2017.05.148
### Appendix

#### Table 6 The characteristics of boilers

| System summary | Unit Description | Unit capacity | Heating delivered | Annual fuel consumption | Manufacturer | Model | Seasonal efficiency |
|----------------|------------------|---------------|-------------------|-------------------------|--------------|-------|---------------------|
| **Baseload heating system** | | | | | | | |
| Technology | Boiler | | | | | | |
| Fuel type | Natural gas | | | | | | |
| Unit capacity | MW | 2.04 | | | | | |
| Installed capacity | MW | 2.04 | | | | | |
| Heating delivered | MWh | 14,216 | | | | | |
| Annual fuel consumption | m³ | 1,755,122 | | | | | |
| Manufacturer | Weil-MacLaine | | | | | | |
| Model | Ultra commercial boiler | | | | | | |
| Seasonal efficiency | 75% | | | | | | |
| **Peak load heating system** | | | | | | | |
| Technology | Boiler | | | | | | |
| Fuel type | Natural Gas | | | | | | |
| Unit capacity | MW | 2.04 | | | | | |
| Installed capacity | MW | 6.12 | | | | | |
| Heating delivered | MWh | 10,439 | | | | | |
| Annual fuel consumption | m³ | 1,432,073 | | | | | |
| Manufacturer | Weil-MacLaine | | | | | | |
| Model | Ultra commercial boiler | | | | | | |
| Seasonal efficiency | 70% | | | | | | |

#### Table 7 The characteristics of cogeneration engine

| System summary | Unit Description | Unit capacity | Heating delivered | Annual fuel consumption | Electricity output | Electricity efficiency | Electricity produced | Electricity delivered to load | Electricity delivered to grid |
|----------------|------------------|---------------|-------------------|-------------------------|-------------------|----------------------|-----------------------|-------------------------------|-------------------------------|
| **Baseload heating system** | | | | | | | | | |
| Technology | NG Cogeneration engine | | | | | | | | |
| Operating strategy | Full power capacity output | | | | | | | | |
| Fuel type | Natural gas | | | | | | | | |
| Annual fuel consumption | m³ | 4,315,111 | | | | | | | |
| Electricity output | kW | 2,218 | | | | | | | |
| Electricity efficiency | % | 40% | | | | | | | |
| Electricity produced | MWh | 18,641 | | | | | | | |
| Electricity delivered to load | MWh | 5,779 | | | | | | | |
| Electricity delivered to grid | MWh | 12,862 | | | | | | | |
| **Peak load heating system** | | | | | | | | | |
| Technology | Boiler | | | | | | | | |
| Fuel type | Natural Gas | | | | | | | | |
| Capacity | kW | 2,444 | | | | | | | |
| Heating delivered | MWh | 21,409 | | | | | | | |
Table 8: The characteristics of cogeneration engine + ORC

| System summary         | Unit | Description     |
|------------------------|------|-----------------|
| Overall efficiency     | %    | 89.39 %         |

**Power**

| Technology              | Description                  |
|-------------------------|------------------------------|
| Operating Strategy      | Full power capacity output   |
| Fuel type               | Natural Gas                  |
| Annual fuel consumption | m³                           | 4,315,111                   |
| Electricity output      | kW                           | 2,218                       |
| Electricity efficiency  | %                            | 40 %                        |
| Electricity produced    | MWh                          | 18,641                      |
| Electricity delivered to load | MWh                  | 5,779                       |
| Electricity delivered to grid | MWh                | 12,862                      |
| Electricity efficiency  | ORC turbogen heat recovery   |

| Thermal power load      | kW                           | 2,200                       |
| Net electric efficiency | %                            | 18 %                        |
| Electrical output       | kW                           | 400                         |
| Annual thermal output   | MWh                          | 8,689                       |
| Annual electricity output | MWh                  | 1,581                       |

**Base load heating system**

| Technology              | Description                  |
|-------------------------|------------------------------|
| Capacity                | kW                           | 2,444                       |
| Heating delivered       | MWh                          | 21,409                      |

**Peak load heating system**

| Technology              | Description                  |
|-------------------------|------------------------------|
| Fuel type               | Natural Gas                  |
| Fuel consumption        | m³                           | 467,080                     |
| Capacity                | kW                           | 4,080                       |
| Heating delivered       | MWh                          | 4,036                       |
| Manufacturer            | Weil-MacLaine                |
| Model                   | Ultra commercial boiler      |
| Boiler efficiency       | 80 %                         |