Preliminary evaluation of operational results of RES systems integrated in students’ residences in Xanthi, Greece

P N Botsaris\textsuperscript{1*}, K Lymperopoulos\textsuperscript{1} and A Pechtelidis\textsuperscript{1}

\textsuperscript{1} Lab of Mechanical Design, Faculty of Materials, Processes and Mechanics, Production and Management Engineering, School of Engineering, Democritus University Thrace, Greece

Email: klympero@pme.duth.gr

Abstract. This paper discusses the techno-economic performance of installed renewable energy technologies in students’ residences of Democritus University of Thrace, in Kimmeria, Xanthi, North Greece. The students’ residences building complex includes eleven (11) buildings of total area of 14,819.09 m\textsuperscript{2} and accommodate 630 students. The RES technologies installed, include a hybrid solar thermal/biomass system for heating, cooling and domestic hot water of the students’ residences buildings and one amphitheater, a geothermal heat pumps system for heating and cooling of a restaurant, an autonomous PV system and one small vertical axis wind turbine. The above interventions were accomplished under “REUNI” project that was funded by EEA and Norway Grants program – GR03-Renewable Energy Technologies. The present study elaborates the operational results of almost two years of the RES technologies installed and highlights their techno-economic performance, through analysis of the collected operational data. The building complex of the students’ residences of DUTH in Kimmeria has managed to operate for its thermal and cooling energy demand with hundred per cent (100\%) renewables throughout a year, resulting in significant energy costs and CO\textsubscript{2} reduction. However, the operation and maintenance cost of the installed systems has been underestimated, resulting in increased number of days of unavailability. The results highlight the need to increase solar energy penetration, as well as the need for subsidy in order to compete with the fossil fuel technologies. The development of such systems that utilize renewable energy sources is considered as a priority for the increase of share of RES in the building sector. The experience from the operation of such system is valuable for the promotion of renewable energy in the built environment.

1. Introduction
The building sector is without doubt an important sector towards the ultimate target of energy transition. Accounting more than forty per cent (40\%) of the total energy consumption in Europe and worldwide, the building sector holds a significant role in the climate change mitigation activities that has been acknowledged by European Commission and member states [1]. Through recent years, renewable energy sources (RES) are considered as conventional technologies and as inevitable replacement of fossil fuels. The integration of RES technologies in buildings has been extensively investigated, with numerous installations already in place [2]. Since the majority of the future building stock has already been constructed, the integration of RES technologies into existing buildings constitutes an opportunity for reducing primary energy consumption of the building sector.
2. Site and systems description

2.1. The building complex
The site of RES installations includes a building complex located near Kimmeria, northeast of the city of Xanthi, in northern Greece. The building complex is owned by Democritus University of Thrace and it is used for the accommodation of its students. The total built is 14,819.09 m$^2$ and consists of 8 students’ residence buildings, 1 amphitheater, 1 restaurant and 1 building that houses the central electromechanical facilities. The building complex is constructed in two phases, one completed in 1990 and one completed in 1999. The students’ residences include 535 double rooms, 24 single rooms and 9 rooms for disabled students. All buildings of the building complex are poorly thermally insulated following the Greek Thermal Insulation Regulation that was in force during the both construction periods of the students’ residences.

The heating and domestic hot water (DHW) of the buildings comprising the building complex is performed centrally within the “Energy Centre” and through extensive not insulated piping network. This network serves all students’ residences and the amphitheater, while restaurant has a specific heating and domestic hot water system. The heating network consists of 5 branches that utilize a specific circulation pump. Each student’s residences building have a hot water storage tank of 2,500 lt in order to cover the domestic hot water demand. Amphitheatre is the only building that is covered in terms of cooling from the “Energy Centre” central cooling systems.

The existing central heating system of the “Energy Centre” includes 3 heating oil boiler of 1.16 MW$_{th}$ each (one used as backup). The heating system of the restaurant includes a heating oil boiler of 395.42 KW$_{th}$ and the cooling system of the “Energy Centre” includes 2 water-cooled chillers of 316.71 KW$_{c}$ each that were not in operation. Each students’ building has a domestic hot water tank of 2,500 lt, besides buildings B1 and D1 that have a 4,000 lt DHW tank.

2.2. Renewable energy systems
The renewable energy technologies utilised in “REUNI” project include biomass, solar thermal energy, photovoltaics, geothermal energy and wind energy. The installed technologies are considered as conventional RES technologies. Figure 1 presents the technologies installed in Kimmeria, Xanthi. The objective of the RES technologies installed is to create a decentralized RES system for collective production and generation of energy. The installed system can be considered as a pilot installation for the investigation of the feasibility of retrofitting districts towards zero energy. The detailed information about the RES technologies installed has been presented by the authors in previous work [3].

2.2.1. Hybrid biomass/solar thermal system. The main renewable energy system installed in DUTH’s students’ residences is a hybrid system that utilises a biomass boiler and a solar thermal system for the heating, cooling and domestic hot water of the buildings’ complex. Figure 2 presents the one-line diagram of the hybrid system. The main components of the system include 740 selective flat plate solar collectors of 2.58 m$^2$ each, 4 solar stations with plate heat exchangers, one biomass boiler of 1.15 MW$_{th}$, a underground metallic biomass storage tank of 35 m$^3$, an absorption chiller of 316.52 KW$_{c}$ coupled with cooling tower of 720.5 KW and 4 outdoor hot water tanks of 10 m$^3$ each.

The solar field consists of 4 identical solar collectors loops. Each loop consists of 40 parallel solar strings with 4 or 5 collectors each. A “reverse-return” connection is selected in order to achieve hydraulic balance. Solar collectors are supported on an aluminium system utilizing trembling. Each loop is controlled by a specific solar station that utilises speed variation in order to maintain a stable $\Delta T$ between the solar collectors and the thermal energy storage (TES) system. Water/glycol mixture is used as heat transfer medium in order to prevent freezing conditions.
Figure 1. Photo (aerial view) of renewable systems installed

The biomass boiler is accompanied with an economizer of 50kW, a multicyclonic ash filter, a bag filter (<10mg/Nm$^3$) and a chimney with diameter of 640mm and height of 12m. The biomass boiler is installed in parallel with the existing oil boilers, which are used as a back up heating system.

As shown in Figure 2, thermal energy produced in solar field is transmitted to the TES system. The external plate heat exchangers included in the solar stations are used to transfer the heat for the water/glycol mixture to the water stored within the tanks. TES system is inline connected with the biomass boiler. During thermal energy demand, the water stored in TES is circulated to the consumptions (buildings) after is heated up to 90°C – if required – in biomass boiler. During summer, solar energy is utilized to satisfy the demand for domestic hot water of the students’ buildings and for the cooling demand of amphitheater. Cooling is produced by the absorption chiller by using the available heat of the solar thermal. In case the temperature of the water stored is below 80°C, biomass boiler is used to raise the temperature to 90°C.

2.2.2. Geothermal heat pumps. This RES technology is utilised for solely heating and cooling the restaurant of DUTH’s students’ residences. The main parts of the installed system constitutes the geothermal heat exchanger that consists of 34 wells of 94m each, two twin water chilled heat pumps of 135KW$_a$, 94.6KW$_c$ each, and a buffer tank of 1m$^3$. In order to increase the efficiency of the system, a new air handling unit was installed within “REUNI” project. The geothermal heat pumps are installed in parallel with the existing heating oil boiler, which is used as a backup system. Figure 3 presents the simplified one-line diagram of the geothermal heat pumps system. The geothermal heat exchanger is constructed with polyethylene pipes (PE-HD 16) in U-tube formation. According to the thermal response test, the geothermal heat exchanger delivers about 66.6 W/m of thermal energy.

2.2.3. Autonomous photovoltaic system. This RES technology is installed for partially covering the electrical demands of building “G2” of the building complex. It constitutes 198 photovoltaic panels of 260Wp each installed on the roof of G2 and D1 buildings using an aluminium support system. PV panels are connected to an electrical energy storage system that constitutes 72 OPzS 2V batteries of 3,780Ah each. The PV system includes also 3 off-grid inverters of 8kW (SMA sunny island 8.0H) each and 2 grid inverters of 25kW each. Currently, the PV system is connected to the electric loads of the common spaces of “G2” building and an electrical bicycles charging station installed outside the “G2” building. Figure 4 presents the simplified one-line diagram of the autonomous photovoltaic system.
Figure 2. Simplified one-line diagram of hybrid biomass/solar thermal system

Figure 3. Simplified one-line diagram of geothermal heat pumps system
2.2.4. Autonomous wind turbine system. A small vertical axis, helical type, wind turbine of 1KW was installed as part of “REUNI” project within the building complex of DUTH’s students’ residences in Kimmeria, Xanthi. It also includes a battery system, an off-grid inverter and a battery charger that are used to provide with electricity to a nearby electrical bicycle charging station. The objective of this installation is to provide with insights for the smooth and safe operation of urban type wind turbine within the built environment. It is a pilot application and it is therefore not techno-economically further discussed.

2.3. Energy demand of the building complex
The building complex is constructed in two timely separate stages and according to the national regulation of thermal insulation that was in force at that period. Table 1 includes the thermal losses of each building of the complex, as well as the hours of operation per annum.

| Building | Thermal Losses (kW) | Hours of operation (h/year) |
|----------|---------------------|----------------------------|
| A1       | 137.46              | 1182.00                    |
| A2       | 111.21              | 1182.00                    |
| B1       | 168.03              | 1182.00                    |
| B2       | 109.96              | 1182.00                    |
| G1       | 137.46              | 1182.00                    |
| G2       | 111.21              | 1182.00                    |
| D1       | 168.03              | 1182.00                    |
| D2       | 109.96              | 1182.00                    |
| Amphitheater | 559.62            | 56.00                      |

For the building complex there were available real consumption data for electricity and heating oil before the integration of RES technologies. In more detail, the electrical energy consumption in 2012 was 2,317.2 MWh/y and the average heating oil consumption for years 2011 till 2013 was 2,063.2 MWh/y. The heating oil consumption does not capture the actual thermal energy demand of the building complex, since due to financial reasons the heating system operated limited hours without satisfying the
thermal comfort levels. At the same time, the limitation of the operation of the heating system resulted in increase of the electricity consumption that arises from the significant operation of electric radiators from the tenants of the buildings. Therefore, the real energy consumption of the building complex does not match with the energy demand.

The thermal energy demand of the buildings is calculated using the heating degree-days methodology [4]. The thermal energy demand for heating of the student’s residences is estimated at 1,368.8 MWh/y, while the demand for domestic hot water is estimated at 634.1 MWh/y. The thermal energy demand of the restaurant of the building complex is estimated at 194.4 MWh/y, while the thermal energy demand of the amphitheater is estimated at 55.8 MWh/y. As far as cooling demand is concerned, the estimated demand of the amphitheatre is 17.6 MWh/y and of the restaurant is 18.6 MWh/y. The cooling demand is calculated using the cooling degree days methodology described by CIBSE [5]. Electrical energy demand is not further discussed, since the completed interventions cover a small portion of the electricity consumption of the building complex.

3. Operation results and issues
The first part of this section discusses the elaboration of the operational results of the integrated renewable energy technologies from almost two years of operation. Throughout the first two years, the operation of the RES technologies was tested in real-life conditions. The second part of this section highlights the main issues that were encountered during the first two years of operation. The energy production measurements are used to feed with the required data for the techno-economic performance analysis presented later within this paper. The discussion on the issues arise supports the next steps required towards the improvement of RES integration in students’ building of DUTH, as well as towards the development of an autonomous electrical and thermal micro grid.

3.1. Renewable energy production
The integrated renewable energy systems generate thermal and electrical energy that is consumed by the building complex in Kimmeria, Xanthi of Northern Greece. Thermal energy is generated from the hybrid solar thermal/biomass system and the geothermal heat pumps, while electricity is produced from the PVs and the small wind turbine. Cooling is producing by the absorption chiller and the geothermal heat pumps during summer period.

As stated before, the renewable electricity is very small as compared to the consumption and it is therefore not techno-economically discussed further. Nevertheless, the electrical energy produced from the autonomous photovoltaic is presented in Figure 5. The average yearly energy production is 7,125 kWh and it is considered as relatively low to the installed power of the PV system. Figure 6 presents the electrical energy for charge and discharge of the battery system. The average yearly energy used for battery charge is 5,260.4 kWh and for battery discharge is 3,164.1 kWh. According to the data available to the authors, the autonomous system can increase its electricity generation for at least 80%.

![Electricity generation from autonomous photovoltaic system](image)
Solar thermal energy is the main renewable technology of the site and the solar field installed is considered as one of the largest solar thermal applications in Greece. According to the results of the two years operation, the solar field was able to provide with an average yearly thermal energy of 531.5 MWh. Figure 7 presents the monthly solar thermal energy produced from each solar loop of the field. This is the thermal energy that is delivered to the thermal energy storage system. According the collected data, during summer period, there was significant number of times where the return temperature of the primary loop of the heat exchangers was close to the supply temperature, resulting in stoppage of the energy transfer and consequently resulting in wasted solar energy. The wasted solar energy is due to the limited thermal storage capacity and it is estimated at approximately of 100 MWh/y.

The yearly average biomass pellet consumption during the first two years of operation was 300t. However, as it is stated in section 3.2, during the first two years of operation there were significant issues mainly related to the biomass supply system that resulted in unavailability of the biomass boiler. The biomass pellet consumption that is expected to be consumed by the building complex in normal yearly operation is estimated at 380t.

Biomass boiler is connected in series with the TES and according to heat meter installed after the TES system, the average yearly thermal energy delivered to the biomass boiler is 516.9 MWh. The average yearly thermal energy delivered to the building complex is 1,604.2 MWh as derived from the collected data. Considering the fact that the biomass pellet purchased has an average calorific value of 4.5 kWh/kg, the efficiency of the biomass system is estimated 85.9%, which is relatively low due to the operation issues analytically described in section 3.2.

The estimated total thermal energy consumed by the building complex is 1,913.4 MWh/y and includes an estimation regarding the days of unavailability of the biomass system. The solar fraction is therefore estimated at 27.0%. It has to be mentioned that the heating and domestic hot water system operates according to time schedule decided by the technical manager of the building complex. This
results in unsatisfactory levels of the thermal comfort of the student’s residences, as also shown by the comparison of the thermal energy generated with the thermal energy demand presented in section 2.3.

The operation of the amphitheater during summer period resulted in thermal energy consumption of an average of 45 MWh/y for the operation of the absorption chiller. The thermal energy was delivered at 94% from the solar field.

The geothermal heat pumps system support heating and cooling for the restaurant building. According to the collected data, the thermal energy generated was in average 135 MWh/y. At the same time the average electricity consumption of the geothermal heat pumps was 25.8 MWh/y, resulting in renewable thermal energy generation of 95.2 MWh/y. It has to be mentioned that the geothermal heat pump system was not able to cover the domestic hot water demand of the restaurant mainly due to the increased temperature required for washing activities. The operation of the system in summer resulted in 21.5 MWh/y of renewable energy production and 4.1 MWh/y of electricity consumption. The efficiency of the geothermal heat pumps system is calculated at 5.23 for heating (SCOP) and at 6.24 for cooling (SEER). These values are higher than the expected from the simulation of the system, as presented in [3].

The total renewable energy generated by the integrated systems in DUTH’s campus is calculated at 2,080.9 MWh/y. The installed systems have the capacity to produce more energy in order to fully cover the energy demand of the building complex. The domestic hot water demand is met by the solar thermal system, while the integration of solar system in heating is relatively low, highlighting the need for increased capacity of the thermal energy storage.

3.2. Operation and maintenance issues
The installed RES technologies encountered several issues within the first two years of operation. The origin of the operational issues arises from the integration of new RES technologies into the existing heating and DHW distribution systems. Besides that, the operation of the systems highlighted some installation failures that resulted in inadequate efficiency and malfunctions.

As far as the integration is concerned, the main issue is related to the lack of automation for the operation of the existing heating and DHW system and particularly the absence of thermostats within the students’ residences. The operation of the heating and DHW system follows a time schedule and therefore that limits the integration of RES technologies and usually results in mismatch of the energy generation and demand.

Regarding the installation of the new RE technologies, the main issue faced was the related with the operation of the biomass pellet feed system. In more detail, the underestimated design of the biomass pellet transport screws resulted in several time failures. The transport screws tend to convert the biomass into dust, which has as result the stoppage of the pellet supply. There were some times where the screw axle was broken.

Besides the biomass system, the solar thermal system also encountered operational issues that arise from its initial installation. More specifically, it is concluded that some auxiliary equipment of the solar system, such as the air vents and the expansion tanks were not suitable sized for the operational temperature achieved. The temperature of the heat transfer medium reach temperature of more than 120°C during summer and this was not foreseen in the study and selection of the system components. As far as the geothermal heat pumps system is concerned, it was clear after the first operation period that the system is not capable to provide the hot water required for washing activities due to the high requested temperature. In addition, the geothermal system also faces operation issues that are related to its hydraulic system, requiring the need for improvement interventions.

4. Techno-economic performance analysis

4.1. Objectives
The main objective of the analysis is to highlight the techno-economic efficiency of the integrated RES technologies in DUTH’s student residences utilizing real operation data. The aim of this analysis is to
validate the economic sustainability of the interventions and support their efficient integration in the built environment.

4.2. Cost analysis

The cost breakdown of the installed renewable energy technologies installed that are further discussed in this section is presented in Table 2. Figure 8 graphically presents the cost breakdown highlighting the significant portion of the solar thermal energy system (43%). Considering the fact that the solar thermal system, the biomass system and the cooling system constitute the hybrid heating, cooling and domestic hot water system, the portion of the solar system is more than 57%. The project development costs were 120,000.00 €.

![Figure 8. Cost breakdown of RES technologies installed](image)

**Table 2. Cost breakdown of installed RES technologies**

| Description                                                                 | Cost       |
|----------------------------------------------------------------------------|------------|
| Solar thermal energy system (solar collectors, support system, solar station, piping, etc) | 477,400.00 € |
| Thermal energy storage (water tanks)                                      | 49,600.00 € |
| Biomass heating system (biomass boiler, biomass storage, economiser, piping, etc) | 186,000.00 € |
| Cooling system (absorption chiller, cooling tower, piping, etc)            | 148,800.00 € |
| Geothermal heat pumps system (water to water heat pumps, geo-heat exchanger, piping etc) | 248,000.00 € |
| **Total**                                                                  | **1,109,800.00 €** |

The cost analysis is performed through a cost benefit analysis and through the estimation of the levelised cost of the thermal energy produced by the integrated RES technologies. The calculation of the cost of the thermal energy produced follows the guideline VDI 2067 [6] and is divided to four cost groups: a) cost based on capital (capital and maintenance costs), b) consumption costs, c) operating costs and d) other costs. The capital costs can be calculated by the capital recovery factor (CRF) multiplied by the investment costs. The maintenance costs are calculated as percentage of the investment costs and are equally spread over the years of utilization period. The consumption costs include the cost of the procurement of biomass pellets and the electrical consumption for the operation of the electromechanical equipment. The operating costs include the costs required for the operation of the RES systems, such as the personnel costs. Other costs may include insurance costs, taxes, administration costs, etc.

The discount rate used is 8%, while the implementation period is 20 years. The consumption, maintenance and operation costs are shown in Table 3. The other costs include the insurance costs which are estimated at 980 €/y for the hybrid system and 248 €/y for the geothermal system.
The data used to perform the cost benefit analysis of the RES technologies are presented in Table 3. In order to estimate the cost of heating oil consumption an average price of heating oil is used (1.00 EUR/lt). The cost of heating oil is calculated at 125 EUR/MWh and represents the economic gain from the operation of the installed RES technologies. The cost benefit analysis takes into consideration the electricity consumption for the operation of the integrated RES technologies, as well as the maintenance costs as a percentage of the investment costs (2%). No lending has been included in the cost benefit analysis (100% equity). The study includes depreciation values of 10% for equipment and 20% for studies according to Greek Law 4110/2013. The hybrid solar/biomass heating, cooling and DHW system is assessed separately to the geothermal heat pumps system.

### Table 3. Entry data for the cost benefit analysis

| Description                               | Unit       | Value       |
|-------------------------------------------|------------|-------------|
| Solar thermal energy                      | MWh/y      | 516.9       |
| Biomass thermal energy                    | MWh/y      | 1,396.5     |
| Thermal energy from geothermal heat pumps | MWh/y      | 135         |
| Lifespan                                  | Years      | 20          |
| Equipment costs hybrid system             | €          | 861,800     |
| Equipment costs geo system                | €          | 248,000     |
| Project development costs hybrid system/geo system | € | 120,000/20,000 |
| Consumption and maintenance costs hybrid system/geo system | €/y | 120,650/5,750 |
| Inflation                                 | %          | 1.0         |
| Operating costs hybrid system/geo system  | €/y        | 12,000/2,000 |
| Lending                                   | %          | 0           |
| Equity                                    | %          | 100         |
| Profit                                    | €/MWh      | 125         |
| Average increase rate of diesel price     | %          | 0.5         |

#### 4.3. Results and discussion

As far as the hybrid system is concerned, the cost of the thermal energy produced is 122.10 €/MWh and it considered as relatively high as compared to the gas cost of thermal energy (75€/MWh [8]). The cost of the thermal energy generated from the geothermal heat pumps system is 19.31 €/MWh, that is to say significantly lower than the hybrid system and it within the limits presented by IPCC in [7]. The above results indicate that there is still necessity for economic support of such RES technologies in order to compete with the fossil fuel heating and cooling technologies, mainly due to the increased capital costs that RES technologies have. It has to be mentioned that the cost of thermal energy of the hybrid system, neglecting the capital cost, is 69.84 €/MWh, significantly lower than the heating oil cost of thermal energy (125 €/MWh).

The Internal Rate of Return (IRR) of the investment for the hybrid system in 20 years period is 8.54%. The Net Present Value (NPV) for reporting period of 20 years is estimated at 415,432 EUR and the simple payback period at 9.5 years. The results of the cost benefit analysis validate the techno-economic efficiency of the installed RES technologies and highlight the need for subsidy in order to increase their bankability.

The geothermal heat pumps system is examined separately, since its operation is solely for the restaurant of the building complex. In this case, the Internal Rate of Return (IRR) of the investment in 20 years period is 0.34%, while the Net Present Value (NPV) is negative. The high investment cost of the geothermal system in relation with the lower energy generation and the low efficiency in heating
operation result in poor techno-economic performance. As stated before, it is important to subsidize of the technology, in order to increase its techno-economic efficiency.

If a grant of 50% is taken into consideration, the cost of thermal energy decreases to 96 €/MWh for the hybrid solar/biomass system and to 68.5 €/MWh for the geothermal heat pumps system. In addition, the IRR for the hybrid system increases to 20.87% and the IRR for the geothermal system to 8.13%.

As shown, the techno-economic performance of the RE technologies is highly related to the thermal energy demand. Moreover, the consumption costs are mainly related to the cost of the biomass pellet procurement, which depicts the importance of the price of biomass pellets. The energy production data presented in this work highlight the need to increase the thermal storage capacity in order to increase the share of solar thermal energy in the energy consumption mixture. The increased solar fraction result in decrease of biomass pellet consumption and therefore enhances the techno-economic performance of the interventions.

5. Conclusion
The analysis of the two years’ operational data supports the efficient integration and the technical sustainability of the renewable energy technologies installed in DUTH’s student residences in Kimmeria, Xanthi, Greece. The renewable energy technologies installed have the capacity to efficiently replace the conventional fossil fuel based thermal energy systems and the scale of installation in the present work highlight the potential development of decentralised cooperative thermal energy generation and consumption systems.

During the first two years of operation, included the adjustment period, the RE systems presented issues that limited their availability and reduced their efficiency. The operational and maintenance issues resulted in decreased renewable energy generation, focused on the hybrid biomass/solar system. Nevertheless, these issues are not considered as fundamental and their solution is relatively straightforward.

The techno-economic performance analysis strongly captures the necessity of subsidization of the specific RES technologies in order to decrease the capital costs and directly compete with the conventional technologies. As highlighted, there is potential for increased operational efficiency that will result in improved techno-economic performance of the RE technologies. The experience from the operation of such RE systems is valuable for the promotion of renewable energy in the building sector supporting the development of thermal microgrids.

Taking into consideration the outcomes of the present work, the authors are investigating the efficient adaptation of the installed RES technologies in order to overcome the operational and maintenance issues encountered, to increase the techno-economic performance and to further exploit the solar thermal energy produced. As highlighted the further investigation of thermal energy storage, as well as the efficient utilisation of thermal energy for electricity generation (e.g. ORC turbines) is within the scope of future work. One of the objectives is the development of a smart local energy (thermal and electrical) microgrid fully supported by renewable energy sources.

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