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Techno-economic assessment of a high temperature thermal storage integration into a sludge drying process in combination with PV electricity

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Abstract During the ongoing transition towards cleaner energy production to tackle climate change, it is important to identify economically viable solutions. While Renewable Energy Sources (RES) offer clean energy, they cannot consistently meet energy demand. Therefore, energy storage technologies are necessary, particularly for thermal demand where thermal energy storage is the most sustainable, efficient, and cost-effective solution. In this study, a combination of RES, thermal storage, and electrical resistors converting electrical energy into thermal energy is proposed to hypothetically meet the energy requirements of a sludge drying facility. The implementation feasibility of such a setup is assessed, by using commercially available software tools but also developing a new methodology. This methodology calculates the efficient dimensioning of the initial setup (RES and storage technology), based on the hourly energy demand and RES production. Two main technical scenarios were identified. At the end, the most energy efficient scenario was chosen. The economic benefits were extracted, using the setup and the dimensioning proposed from this scenario. The future step of this assessment is to evaluate the environmental profitability of this setup, under the third sustainability development pillar.

Keywords: thermal storage; power-to-heat; decarbonization; Green Heat Module; heat supply

1. Introduction

One of the most pressing issues in global politics is the mitigation and containment of climate change. A significant aspect of addressing climate change is decarbonizing economic activity, thus reducing levels of pollution and emission of greenhouse gases. This issue has driven organizations and countries into committing to carbon neutrality. Some remarkable examples of these commitments are the Paris Agreement, along with the European Green Deal and the EU's Fit for 55. These agreements have been an important asset on setting the future timeframe for the carbon neutral goals. Some additional actions also include the financing of green and sustainable projects and actions, aiming towards decarbonization. A significant example is the European Union Just Transition Fund program.

The motives behind the aforementioned actions have been mainly environmental and social (Sustainability Management and Circular Economy, 2022). However, the decarbonization of the energy (both electrical and thermal) production sector could bring out some economic benefits as well (The Value of Storage, 2016). Specifically, the way the energy market model works (AUTh Energy Source Management notes, 2022), the costs of conventional sources dictate and direct the final price of the market. Therefore, due to the current circumstances where there has been an increase in the price of natural gas, an increase in the share of RES is expected, as it is now more economically viable to produce energy through these sources. This shift in the energy mix could help mitigate the effects of climate change, as well as provide more stable and secure prices for consumers in the long run.

The purpose of this study is to investigate the possible decarbonization of a large portion of the required energy in Thessaloniki's wastewater treatment plant, owned by Thessaloniki's Water and Sewage Company (EYATH). Specifically, the total decarbonization of the sludge drying process heat demand is studied, with the possible use of surplus renewable energy generated to cover part of the plant electrical demand. The RES used are, biogas and the installation of photovoltaics in combination with a thermal storage unit (Green Heat Module). A secondary goal is to present the technology of thermal storage along with the Power-to-Heat technology (Conversion of Electricity to Heat). The final desired outcome of this study was the technical feasibility of the setup, along with a calculation for the investment cost and its payback period.

2. Description of the application and setup

2.1. Presentation of the energy demands

The initial goal of this study was to decarbonize a sludge drying process at a wastewater treatment plant in Thessaloniki. The plant in owned by EYATH, Thessaloniki's Water and Sewage Company. The company is committed with its future actions to sustainable development, taking into consideration the effects its actions have towards the environmental pillar (EYATH Sustainability Report, 2021). The drying process has a heat load demand, covered by natural gas burning up until now. The initial concept was to only decarbonize this heat load. However, the main setup chosen to decarbonize the heat demand was a RES used as an energy production, with a combination of a Power-to-Heat and thermal storage technology (Thermal Energy Storage Systems, 2011). Therefore, it was found that the most efficient scenario was the one that covered part of the electricity demand of the plant, from the excess electricity produced from the RE production. The final target of this assessment was to create a scenario that resulted in a complete decarbonization of the sludge drying heat demand and the electricity demand of the plant.

Table 1. Annual Technical Properties of the Plant (GWh)

Drying thermal demand	14
Electricity demand	20
Biogas production	18
Current total natural gas used	50

Both biogas and natural gas energy numbers represent the heating values of the two fuels. The natural gas value presented, is the necessary fuel quantity to cover the drying heat demand and the electricity demand of the plant. The elimination of this natural gas value would be the final target.

2.2 Energy production sources and thermal storage technology

In order to decarbonize the plant energy demand and thus eliminate the natural gas usage, the strategy used would meet the energy demand by using a combination of RES and thermal storage. At first, the already produced biogas would be used to cover part of the base load heat demand text. The remaining part would be covered by the combination of photovoltaics, Power-to-Heat technology and a thermal storage. The use of Power-to-Heat technology in combination with a thermal storage can provide an efficient and sustainable solution for meeting the necessary thermal demand. Power-to-Heat technology uses electricity to produce heat, while thermal storage can store and release that heat when needed. Therefore, the excess electricity generated by photovoltaics would be stored to the thermal storage through Power-to-Heat. The stored thermal load would be then given to the drying process, when needed. This can help to take advantage of peak loads from photovoltaic systems and meet the company's thermal demand, while also saving energy. Part of the electricity generated would be directly given to the electricity demand.

The specific setup of the Power-to-Heat technology and high temperature heat storage studied, is a patented innovative technology from Kraftanlagen Energies and Services called Green Heat Module (Green Heat Module, 2006). The Green Heat Module (GHM) is an innovative technological solution that enables the storage of high-temperature heat for a short to medium period during the production of electricity from renewable energy sources (RES). This heat can be provided on demand to operate various thermodynamic processes, including electricity generation (Jülich solar power tower – system behavior during downtime, 2017). The GHM operates as a collector of renewable energy excess peaks, coupling the electricity and thermal energy supply to the demand. In this way, surplus energy production from a RES can be stored and serve as an energy provider when energy from the RES is not available. This can contribute to the sustainable development of the energy system. The storage utilizes a ceramic honeycomb type of material to store the thermal load, while thermal resistors are used as the Power-to-Heat technology.

3. Development of the decarbonization methodology

The methodology of this assessment was separated into two stages. The first stage was the technical assessment, on which the dimensioning of the technologies and the decarbonization percentages were extracted. On the second stage, the economic assessment, the total investment cost was calculated along with the payback period of the investment.

3.1 Technical assessment

Initially for the technical assessment, for the creation of the time-static model of the drying cycle, EBSILON software was used. With this model, the thermal power demand was calculated for the operating hours of the process. Then the model was upgraded by introducing a heat exchanger. The thermal energy the heat exchanger provided would represent the necessary heat load the GHM should deliver. From the extraction of the technical characteristics of the exchanger, the technical characteristics of the thermal storage were derived. Thus, an initial assumption was made for the sizing of the storage (system boundary condition). Subsequently, given the possibility of storing the storage layout and the desired thermal power of the process, the daily electrical energy supply of the photovoltaics to the storage arrangement was calculated. Part of this total energy included electrical energy, which through the Power-to-Heat technology, will directly supply the drying. While the remaining part will be converted to thermal energy (again through Power-to-Heat) and stored in the storage for future supply to the drying. The next step, already knowing the needed photovoltaic electricity supply, was to calculate the hourly generation curve per day by using PVsyst. To find the performance of the photovoltaics, the weather data of their theoretical installation location had to be found. Through

PVsyst, the specific performance of the photovoltaics was calculated, and the electrical energy production curve was estimated. The hourly thermal and electricity demand curves, along with the hourly electricity generation curve could then be used as input values into the methodology development. The basic logic behind the methodology steps were as follows:

1. If the hour of electricity production coincided with the hour of electricity, then the power covered the electricity demand.
2. If the amount of electrical power generated at that time was greater than what was needed to cover the hourly electrical power, then the power went to the resistors to produce heat. In the case that there was a heat demand on the current hour, then the heat load was utilized directly into the drying process.
3. The excess electricity was then converted into heat to be stored into the storage for future heat supply.
4. In the case that there is still excess electricity, after all the demands have been covered for the specific hour, this amount is sold to the grid.

3.2 Economic assessment

The technical data, specifically the dimensioning of the setups applied, were exploited to calculate the final investment cost. In particular, to extract the investment cost, the PV park and GHM dimensioning was considered. To calculate the payback period, then it was essential to define the annual economic profit of the installation. For this calculation two scenarios were taken into consideration:

- The first case assumed that there was no capability of exploiting the excess electricity and selling it back to the grid. In this case, the overall power deficit would be covered by the usage of natural gas.

- The second case assumed the possibility of selling the excess electricity into the grid by signing a Power Purchase Agreement (PPA). A PPA would define a contract on which this excess electricity would then be bought back when a power deficit occurred.

4. Methodology results

4.1 Technical assessment results

The proposed setup resulted in a complete decarbonization of the heat demand for the drying process. This was successful due to the combination of biogas burning and the Power-to-Heat and thermal storage technologies. On the other hand, the scenario that did not exploit the excess electricity generated, did not result in a complete decarbonization of the electricity demand. However, on the second scenario that a PPA was formed and the grid was utilized as an electrical storage, the setup managed to decarbonize the electricity demand as well.

4.2 Economic assessment results

An assumption is needed to be made for the natural gas and electricity market prices, in order to calculate the costs and annual profits (EnEx Market Prices Report, 2022).

Table 2. Fuel and electricity market prices during the assessment (€/MWh)

Natural gas buying price	100
Electricity buying price	280
PPA contract price	50

Since currently the prices have altered, and in particular natural gas buying price has dropped to almost half the price, the payback period calculated should be considered double the given value.

Table 3. Economic assessment annual results (€)

Investment cost	18,067,203
Initial cost of natural gas usage (before the installation)	5,463,676
Profit (after the installation)	42,157
Payback period (in years)	3.3

Therefore, since the natural gas market price has dropped, then the initial cost of natural gas calculated would drop,

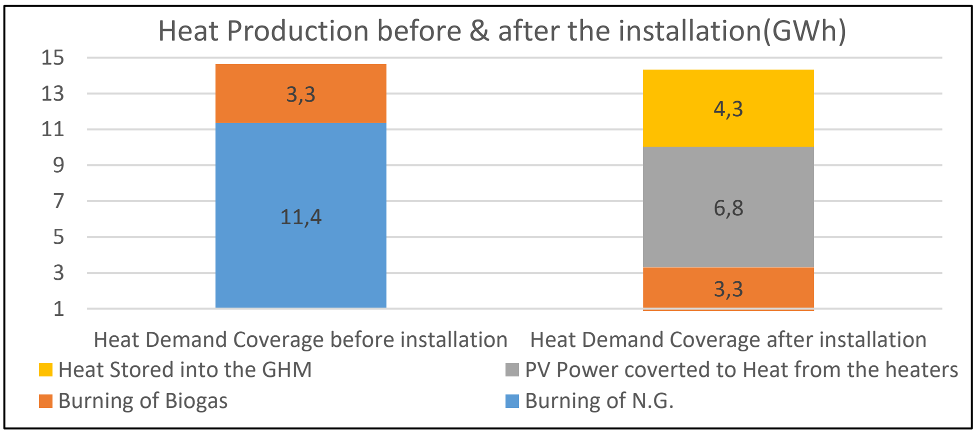

Figure 1. Complete decarbonization of the heat demand

resulting in an increase at the payback period. This happens because the payback period was calculated, dividing the investment cost with the sum of the initial annual natural gas cost and the annual profit after the investment. The annual profit given stands for the PPA scenario, on which the excess electricity can be given and taken back from the grid.

into consideration the environmental pillar on this assessment. The second goal is to convert the methodology, thus making it compatible for as many

technologies and energy storages as possible.
Lastly, for investments that have decarbonization as a goal, it is crucial to further investigate the national and European funding opportunities that have energy transition as their scope.

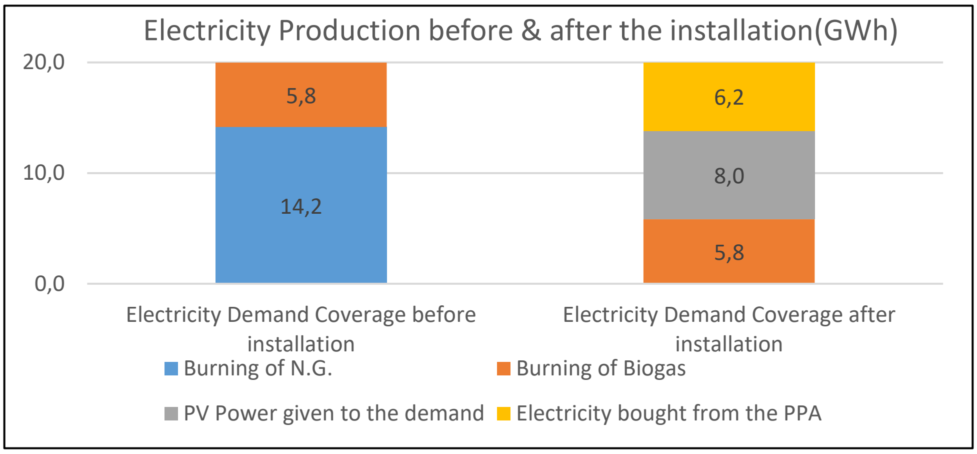

Figure 2. Complete decarbonization of the electricity demand

5. Conclusions and Future steps

In conclusion, the suggested setup can completely decarbonize an industrial process with a heat demand, by mainly using the Power-to-Heat and thermal storage technologies. Moreover, a complete decarbonization of the electricity demand is also succeeded, by forming a PPA contract and storing the excess electricity back to the grid. The future steps of this assessment aim to further develop the methodology developed. The first target is to also take

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