Analysis of a smart system of thermal energy generation coupled with a geothermal probe

Caterina Frau*, Enrico Maggio*, Francesca Poggi*, Emanuela Melis, Pier Francesco Orrù****

** Sotacarbo S.p.A. (caterina.frau@sotacarbo.it, enrico.maggio@sotacarbo.it, francesca.poggi@sotacarbo.it)*

*** Department of Mechanical, Chemical and Materials Engineering - University of Cagliari (emymelis@unica.it, pforru@unica.it)*

Abstract: The present paper focuses on using a low enthalpy geothermal system for air conditioning and on its integration into a smart grid, to an efficient self-production and self-consumption of energy. For this purpose, a pilot site was identified in the South-eastern side of the Sardinian Island (Italy). It is a research centre, where different activities are being carried out (office, laboratory and workroom). The study started by analyzing the existing systems (lighting and air conditioning) and the geological and hydrogeological characteristics of the area, as there is a water well potentially usable for geothermal applications. Energetic analyses were performed on electricity consumption, by using bills, quarterly-hour data, as well as those of a consumption monitoring system. In addition, the production of a forthcoming photovoltaic plant was assessed. The technical, economic and environmental feasibility of a water-water heat pump system coupled with a low-enthalpy geothermal probe (using a groundwater well or embedded in the ground) was assessed. Moreover, the possibility of adopting an electric storage system for the amount of electricity generated by the photovoltaic plant and not consumed immediately, was evaluated. Based on the assessed energetic needs, the vertical geothermal probe should have a total length of 2'715 m, corresponding to seven double-U probes of 97 m height. Alternatively, the heat pump can be coupled with a groundwater probe using the primary fluid of the existing water well. The economic evaluations showed the viability of the photovoltaic plant. An opposite result was obtained for the electric storage solution. The replacement of the existing heat pump coupled with a geothermal probe is economically viable only by considering the groundwater solution. Based on environmental impacts and water footprint assessments of the technological scenarios considered in their life cycle, the low enthalpy geothermal energy is less impactful then the current technological solution.

Keywords: electric storage, Life Cycle Assessment, low enthalpy geothermal system, photovoltaic plant, smart grid, Water Footprint Assessment)

1.Introduction

1.1 General framework

The improvement of the energy performance of buildings has an important role to achieve the goals set by the European Union for a climate strategy oriented towards a low carbon economy by 2050. In this regard, the European Union has released various directives, with the aim of implementing harmonized and shared tools, criteria and solutions to increase the energy efficiency of buildings. The Directive 2010/31/EU is the main regulatory instrument at the European level. A key element of that is represented by the NZEB (Nearly Zero-Energy Building). In Italy, this is part of the National Energy Strategy. The national program has been developed to overcome the European targets for 2020, by setting the target of 15,5 Mtoe of final energy saving by 2020 (24% of saving compared to the European reference). The increase in the energy efficiency of buildings and the transition to NZEB is a priority objective for Italy, pursued through a wide range of regulation and incentive measures. Studies aimed at the development of an Energy Management System (in accordance to the international standard "ISO 50001", which Italian version is the UNI CEI EN ISO 50001) should be considered under the above-mentioned framework.

The standard specifies the requirements to create, initiate, maintain and improve an energy management system. The last one allows an organization to pursue a continuous improvement of its energy performance with a systematic approach. In this context, this paper presents a research project related to a micro-grid model for the optimal management of the energy production/storage system of a research centre located in Italy. The potential components are reported in Fig. 1. The thermal generation system for heating and cooling consists of a water-water reversible heat pump, to be coupled with a geothermal probe (vertical -embedded in the ground- or installed into a groundwater well).

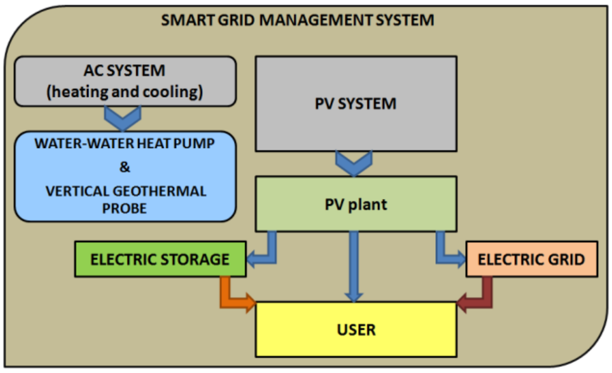

Figure 1: scheme of the smart-grid system

1.2 Brief overview

Two main types of geothermal probes have been developed: horizontal and vertical. A vertical probe has some advantages compared to a horizontal type: it is less dependent on temperature fluctuations, it requires a smaller installation surface, a shorter pipe length, and a lower energy consumption for pumping the heat transfer fluid; its energy efficiency is higher. The advantage of a horizontal probe is a lower installation cost, due to the limited installation depth. In accordance with Ng et al. (2009), geothermal heating/cooling systems can be distinguished into two main types, depending on the fluid circulation arrangement:

- Open loop – This solution extracts groundwater from a well and uses it as a heat source or sink, according to the season. The water used by the heat pump is discharged in another water body or drainage channel. As an alternative, the configuration "open to reinjection" can be adopted, by re-introducing the process water into the aquifer.
- Closed loop – This configuration makes use of a heat exchanger made of a continuous loop of pipes. It is a closed circuit.

Currently, the most simplified configuration of a heat exchanger is the single U, made of two plastic tubes (delivery/outlet) installed into a well and connected to each other at their terminal parts, to form a U-shape. Another configuration is the double-U: the probe is made of two couples of tubes, connected to the ends to form two U-shaped pipes. It allows the circulation of the fluid also in the case of an occluded tube and the heat pump will continue to work. A third configuration is that of the coaxial exchangers. Coaxial probes consist of an external tube of delivery and in an internal tube of return.

2.Material and methods

2.1 Pilot building

The pilot building is the "Sotacarbo" Research Centre. It is in the former "Serbariu" mine (Carbonia, Sardinia – Italy). From a geologic point of view, the area is characterised by coherent lithotypes formed by recent sandy deposits, recent alluvial deposits and/or pyroclastic flows. From a geomorphological point of view, these are mainly sandy rocks. Aquifers have limited extension and are of low productivity; it affects the potential of using an existing groundwater well for geothermal purposes. The Sotacarbo's service facilities are lighting (indoor; outdoor); air conditioning (AC); laboratories intake; water; Domestic Hot Water (DHW); water discharge (whitewater and sewage). The AC consists of two reversible heat pumps (Table 1, see Appendix A). The operating logic involves a single heat pump operation and the second one is used when the first one is not able to supply the energy demand. As an assumption, only the most energy-intensive plants (lighting, AC) have been taken into consideration. The terminals of the hydronic circuit served by the heat pumps are fan coils (offices and laboratories) and primary air counterflows (four to laboratories and offices, one to the auditorium). The distribution system of the primary air consists of channels and diffusers to supply and return the air of outdoor spaces. A monitoring system of electricity consumption has been installed in the building since October 2016. It measures the energy consumption of different sections: electric cabin (overall consumption); Laboratories; Offices (comprising the auditorium); Standard office (an office chosen as representative); Heat pumps. The energy performance improvement pursued by the company policy includes an in grid-parallel photovoltaic (PV) plant, to be installed for electricity generation. The PV plant has been designed in the recent past, by the appointment of the research centre to professionals. It will be made of 324 polycrystalline silicon modules (with a nominal output of 270 kW_p each and a total extension of 518 m^2) and four inverters. The total power is equal to 87.48 kW, which determines an energy production of about 116'000 kWh per year. The system will be grid-connected, with a three-phase connection in low voltage multi-section, thanks to the arrangement of the surface used for the PV plant installation.

2.2 Energetic analysis

The energetic analysis helps the company to define the best actions to improve the energy performance. It has been carried out by assessing the energy consumption of the building and the energy production of the future PV plant.

<u>Electricity consumption</u>

The electricity consumption has been evaluated by considering:

- Electricity consumption bills
- Quarterly-hour data of electricity consumption (derived from bills)
- Consumption data detected by the monitoring system (collected on a quarterly-hour basis)

The monthly consumption of the period 2013-2016 has been analysed, on the basis of the available electricity bills. Total consumption, consumptions divided into the time slots F1, F2 and F3 (see Note 1, Appendix A), total costs, as well as fixed and variable costs, have been assessed. Quarterly-hour data (provided by the energy provider from July 2016 to June 2017) of electric consumption have been used to perform an hourly consumption analysis on a daily basis. Quarterly-hour data have been added up together to obtain the hourly value and build the consumption profiles of average working days and non-working days. Hourly values have been obtained as the arithmetic average of the hourly consumption of each working day or non-working day of a month. Then, the hourly consumption on the annual scale has been created. Monitoring data have been used to analyse different sections separately. The consumption of the workshop can be obtained by subtracting the values of the other sections (Offices, Laboratories, and Heat pumps) from the overall value (electric cabin). Since the monitoring system of the cabin has started its detections in April 2017, only a few months have been considered for comparisons. The monitoring data have been used to create the hourly consumption profiles on a daily basis, for average working days and non-working days of each available month and each section monitored. In addition, a comparison has been made between bills and monitored data from November 2016 to June 2017, and between the monthly values of the cabin and of the bills.

PV plant: energy production

The hourly production of the forthcoming construction of a grid-connected PV plant has been assessed. It has been determined through a dedicated commercial software that, according to the site's characteristics (temperature, solar irradiation, etc.) and those of the different sections of the plant (orientation, panels power, production yield, etc.), is able to provide the hourly production values of the plant during the calendar year.

2.3 Technical feasibility of a heat pump coupled with a geothermal probe

To replace the current heat pump, a preliminary assessment has been carried out on the technical and performance characteristics of the water-water heat pumps available on the national market. More specifically, the water flow rate and some performance parameters such as the COP (coefficient of performance) and EER (energy efficiency ratio) of different models and sizes have been compared. The heat pump model to be used in the proposed system has been selected also by considering the energy demand and the operating conditions required by the building. Subsequently, the sizing of the geothermal probe to be coupled with the selected heat pump has been carried out. For this purpose, a preliminary analysis of the most common methods has been made, to identify the best for the specific application. Three methods have been considered:

- German regulations VDI 4640 (Association of German Engineers, 2010)
- IGSHPA (International Ground Source Heat Pump Association) (1991)
- ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) (1999)

The method IGSHPA has been used for the dimensioning because of some limitations of the other methods.

Data used for the probe's sizing are:

- Electricity consumption recorded by the monitoring system for the AC section
- Outdoor temperature data (hourly values), recorded by a monitoring station in the proximity of the building.

COP and EER have been calculated as a function of the outdoor temperature, by assuming the outlet water temperature equal to 7 °C for cooling and equal to 45 °C for heating. The COP has been used to obtain the hourly values of thermal energy exchanged with the building (heating conditions):

$$\text{Useful Energy} = \text{COP} \cdot \text{Electricity Absorbed} \quad (10)$$

A similar calculation has been made to determine the thermal energy exchanged with the building (cooling conditions), by using the EER. It has been assumed a geothermal probe field using double U probes made of polyurethane, which dimensions are 40 mm of external diameter and 3.7 mm of thickness. Values used to determine the total length are reported in Table 2 (see Appendix A).

2.4 Technical feasibility of the electric storage

Most of the energy produced by the PV plant will satisfy the energy demand of the building. Since it will be a grid-connected plant, any temporary excess of production will be introduced into the grid. An electric storage (batteries/electric vehicles) has been evaluated, by overlapping the annual graphs of the hourly production of the PV plant and of the electricity consumption. The size of the electric storage necessary to self-consume the total amount of the energy produced by the plant has been calculated, and the technical and economic feasibilities of this storage have been determined. More specifically, to define its size, the Net Present Value referred to 20 years has been considered and the best condition has been used for the subsequent evaluations.

2.5 Micro-grid

The micro-grid for the specific application will consist of: PV plant; heat pump; utilities (lighting, DHW, etc.); electric storage; electric grid. This micro-grid will be supported by a smart management system of its operation from an energetic point of view, to optimize production and consumption, and to give priority to the electricity self-consumption. Specifically, the operating logic will be:

- To privilege the use of the PV energy, and of a battery storage instead of a vehicle charging
- To maximize the energy self-consumption and to minimize the energy purchased from the grid
- The PV energy overproduced should be sent to the electrical storage and can be introduced into the grid only after a storage system saturation (batteries and vehicles)
- In the case of energy consumption higher than production from renewable energy sources, priority will be given to the electric storage with respect to the electricity purchased from the grid
- Management of utilities, to shift the functioning of certain components when it is expected the PV system to overproduce

2.6 Economic feasibility of the system

A preliminary assessment of the economic viability of the proposed system has been performed. It is a simplified

cost-revenue analysis. The types of costs included in this evaluation are:
- Plant costs (construction), which occur at year 0
- Operating costs (operation and maintenance), which occur every year of the plant’s life
- Dismantling (at the end of the plant’s life)

Revenues occur from the first year. The cost-revenue analysis has been carried out before tax, and by analysing the cash flows only. It has considered total costs and total revenues at the end of each year. To compare flows occurring in different years, they have been discounted to the year 0, through a discount rate. This analysis has been carried out both without public incentives and with the best incentive applicable to the specific case. Two economic parameters have been assessed: Net Present Value (NPV) and Pay Back Time (PBT).

The most of the economic parameters and values assumed in this part of the work have been based on market investigations, both for the AC system and the PV system. Those related to the electric storage system have been based on preliminary evaluations.

The operating costs of the PV plant are:
- ordinary maintenance (annual)
- insurance against non-production (annual)
- extraordinary maintenance: at the 10th year, the inverters will be replaced
- dismantling and disposal at the end of its useful life (20th year)

It will also be necessary to calculate revenues coming from the amount of electricity introduced into the grid that has been sold.

For the electric storage, it has been assumed that 1. After the tenth year, batteries will be substituted; 2. Dismantling and disposal at its end of life will be realized at the twentieth year.

The electric storage increases the self-consumption of the energy generated by the PV plant. Thus, a cost reduction will occur, related to the energy purchased from the grid, but also the revenues from the amount of energy self-produced and introduced into the grid will decrease. The price of the energy purchased from the grid is higher than that of the unit price of the energy sold: the total effect is positive.

The assumptions related to the economic analysis of the water-water heat pump to be coupled with a geothermal probe are:
- Plant costs: geothermal probe, pumping system, heat pump (ground drilling costs will be related to a vertical probe embedded in the ground; these are absent in the case of using an existing groundwater well if the probe will work with groundwater. In this case, the cost of the intermediate heat exchanger will be included)
- Operating costs: maintenance costs of the plant, electricity required to the water-glycol circulation into the primary circuit

Two alternatives have been considered: without incentives and with a deduction of 65% for energy efficiency interventions. For the latter, 65% of the plant cost will be returned in 10 annual tranches, equally distributed. Values applied to the economic analysis of the proposed system have been reported in Table 3 (see Appendix A).

2.7 Environmental feasibility of the system

The environmental feasibility of the new AC system (water-water heat pump coupled with a geothermal probe) has been evaluated by applying the Life Cycle Assessment (LCA) (ISO 14040:2006; ISO 14044:2006) and the Water Footprint Assessment (WFA) (ISO 14046:2014; Hoekstra et al. 2003) methodologies. Three scenarios have been considered and compared:
- The current AC system, based on an air-water heat pump
- A water-water heat pump coupled with a geothermal probe embedded in the ground
- A water-water heat pump coupled with a geothermal probe installed into a groundwater well

The system boundaries have involved: production, use, and end of life of the heat pump; production, use, and end of life of the geothermal probe. A cradle to grave LCA has been conducted, by selecting a functional unit of 1 kWh of thermal energy produced by the AC plant. The other parts of the smart-grid have been excluded in this assessment. The main objective is to assess the most important environmental impacts of each solution and to determine the less impactful one. The life cycle inventory has been carried out by using the GEMIS software. The Life Cycle Impact Assessment (LCIA) has been performed using the OpenLCA software. Three LCIA methods have been applied: ReCiPe2008 (Goedkoop et al., 2009), CML baseline (Guinée et al., 2002) and Eco-indicator 99 H (Goedkoop and Spriensma, 1999). The WFA has been carried out on the three scenarios by considering the process water as the blue water footprint (WF), and the grey WF as the water volume necessary to dilute the pollutant load to non-hazardous levels.

3.Results

3.1 Energetic analysis

<u>Electricity consumption</u>

Electricity bills – From 2013 to 2016, the total consumption has increased, due to an increase of laboratory activities and of the number of employees. Most of the increase is related to the time slot F1, instead of the other two (F2, F3). In these time slots, consumption is almost constant. The unit cost has decreased for an increased total consumption of the electricity. The annual consumption on an hourly basis (mean) through years 2013-2016 is reported in Figure 2.

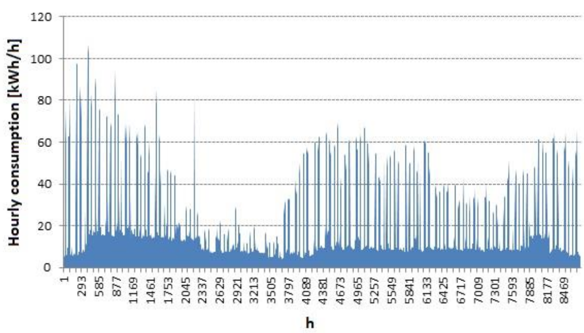

Figure 2: Mean hourly consumption in a year

Monitoring system – Values recorded by the system for the electric cabin are significantly above the monthly data obtained by adding up the quarterly-hour data of the bills. This comparison has been made for two months of contemporary availability of the two datasets. In addition, a comparison made between the cabin values and the sum of the other sections (laboratories, offices, AC system) for the months from May to August 2017 has led to state that the difference cannot be considered as a realistic value of the workshop consumption, because of the high values. Thus, cabin data cannot be used, because of some malfunctioning problems of the monitoring system. The workshop consumption has been estimated by the difference between the bills and the monitored sections of the offices, the laboratories, and the AC system.

PV plant: energy production

The hourly production of the PV plant during the calendar year is reported in Figure 3.

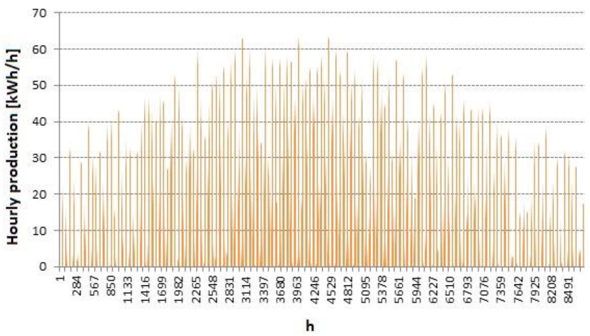

Figure 3: hourly production of the PV plant in a year

By comparing Figure 2 and Figure 3, it can be stated that the two graphs cannot be overlapped in a perfect way. On the annual scale, the electricity consumption of the building is of 191.604 kWh, while the PV production is of 115.777 kWh. By comparing the monthly data, the PV plant production does not match the energy demand, especially during the cold season. In April and May it overproduces, but this energy is not required to the air conditioning. The gross coverage of the electricity demand obtained by the PV plant is about 60.4%. By considering the simultaneity of production and consumption, the coverage without electric storage is reduced to 40.8%. It is due to the overproduction in April and May and during the weekends of the year. The self-consumption is 67.5% (the remaining part will be introduced into the grid). To reach a 100% self-consumption, the energy generated by the PV plant will be too high and not sustainable both from technical and economic points of view (number of panels and space available to install the plant under landscape's constraints). Based on these considerations, a finite-capacity electric storage has been chosen for the subsequent economic assessment of the proposed system. As an assumption of the proposed model, a storage of 100 kWh will increase the net coverage to 49% and the self-consumption to 81%, that can be considered a valid tradeoff.

3.2 Technical feasibility of a heat pump coupled with a geothermal probe

By performing an analysis of the national market of the available water-water heat pumps, a heat pump has been selected. Its main technical specifications are reported in Table 4 (see Appendix A). Since the two current heat pumps are oversized with respect to the thermal energy demand, only a new heat pump will be installed. The remaining part of the system (hydronic network and terminals) will not change. The heat pump needs a direct connection to the primary circuit (closed), in which flows a mixture of water and glycol if the vertical geothermal probe is embedded in the ground. If it is installed into a groundwater well, a stainless-steel heat exchanger should be interposed between the two circuits, to preserve the internal parts of the heat pump from the aggressive action (chemical and physical) of groundwater. The water flows required by the new heat pump are 24'540 $l \cdot h^{-1}$ for heating, 29'130 $l \cdot h^{-1}$ for cooling. The pump to be used in the case of installing the geothermal probe into a groundwater well should supply the maximum water flow (29'130 $l \cdot h^{-1}$). The dimensioning of the geothermal probe field is related to the heating process and it is of 2'715 m. Thus, the characteristics of the geothermal probe field are:

- Total number of the double U probes: 7
- Height of each probe: 97 m

3.3 Economic feasibility of the system

PV plant – The NPV of the investment is 42'000 € and the PBT is between 13 and 14 years (Fig. 4).

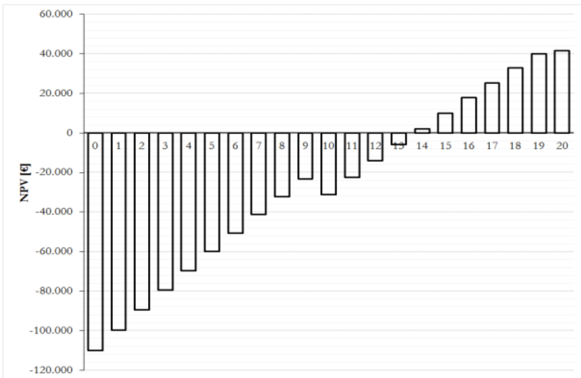

Figure 4: NPV of the PV plant

Electric storage – The economic analysis has been carried out on an electric storage capacity of 100 kWh using batteries (mainly because of a lower economic investment compared to an electric vehicle). The investment of this solution has a negative NPV (Fig. 5).

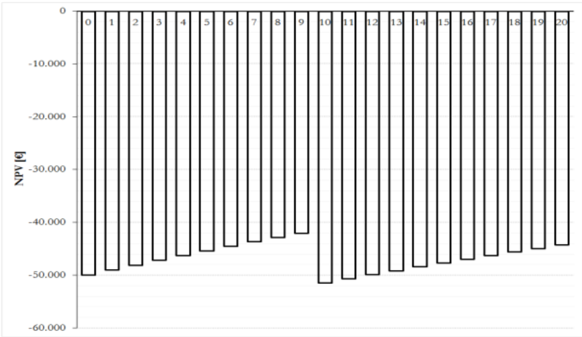

Figure 5: NPV of the electric storage system (100 kWh)

Heat pump coupled with a geothermal probe – The solution embedded in the ground shows a negative NPV, because of the relevance of drilling costs (Fig. 6). The solution with groundwater shows an NPV without the incentive of 33'700 € and a PBT of nine years. With incentives, the NPV increases (55'000 €) and the PBT decreases (six years) (Fig. 7).

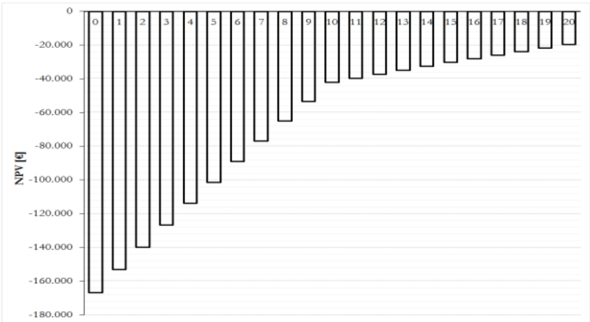

Figure 6: NPV of the geothermal system with the probe embedded into the ground; with the incentive

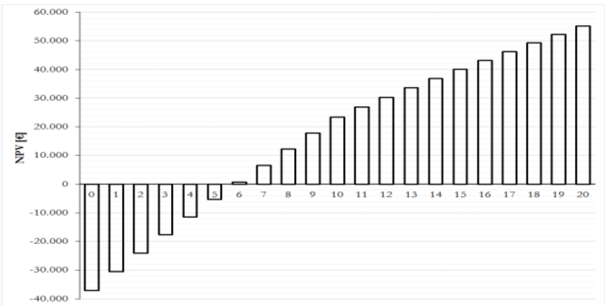

Figure 7: NPV of the geothermal system using groundwater; with the incentive

3.4 Environmental feasibility of the system

LCA

"ReCiPe" – Impact category "Climate Change": the less impactful scenario is that of the heat pump coupled with a geothermal probe using groundwater, which is close to the result of the vertical probe embedded in the ground. With respect to the current AC system, the CO_2 equivalent emissions saving is 74.5% for the geothermal probe installed into the groundwater well. The saving related to the AC scenario with a geothermal probe embedded in the ground is 70.6%. The water-water heat pump coupled with the geothermal probe using groundwater is the most favourable solution also for the impact categories "Fossil depletion", "Freshwater eutrophication", "Marine eutrophication", "Particulate matter formation", "Photochemical oxidant formation", "Terrestrial acidification", "Water depletion", followed by the solution with a vertical probe embedded in the ground. This one is the less impactful with respect to the categories "Freshwater ecotoxicity", "Human toxicity", "Marine ecotoxicity", "Terrestrial ecotoxicity". The current AC scenario is the worst.

"Eco-indicator 99" – The most sustainable scenario is that of the heat pump coupled with a geothermal probe using groundwater. The other geothermal scenario shows impacts similar to the above-mentioned one.

"CML Baseline" – The impacts on the category "Climate Change are the same as the ReCiPe method. For the most part of the impact categories (6), the groundwater scenario is the less impactful, followed by the ground scenario. About the category "Terrestrial ecotoxicity", the current scenario and that using groundwater produce similar impacts and the ground scenario is the most sustainable.

WFA

The results are reported in Table 5.

Table 5: Water Footprints of the three scenarios ($m^3 \cdot kWh^{-1}$)

	Current AC scenario	Geothermal Heat Pump-Groundwater	Geothermal Heat Pump-Ground
Blue WF	0.00114	0.000473	0.000574
Grey WF	150	102	82.2

By comparing the water footprints of the three scenarios, the component related to the pollution is considerably higher than that related to the freshwater volume required by the processes. The current scenario is the worst for both the grey and the blue water footprints; the two geothermal solutions have similar blue water footprints. The scenario with the lowest grey water footprint is that of the probe embedded in the ground.

4.Conclusions

This paper has presented a research project to the development of a smart grid model for an efficient energetic self-production and self-consumption, by including the use of a low enthalpy geothermal system for AC. A pilot building in the South of Italy has been selected. A preliminary assessment of the technical, economic and environmental feasibilities of that system has been carried out. Through an energetic analysis of the pilot building, it has been found that the most relevant electricity consumption is related to the AC system, the lighting plant, and the laboratory activities. The highest consumption occurs during the central part of the working hours (from Monday to Friday). During the remaining part of the working days and holidays, the consumption values are negligible. Three different scenarios have been evaluated:

- Current AC system: air-water heat pump
- Alternative scenarios: water-water heat pump coupled with a vertical geothermal probe a) embedded in the ground; b) installed into a groundwater well.

In addition, the feasibility of an electric storage to be coupled with a PV system (which will be installed in the near future) has been carried out, to maximize the energy self-consumption. Then, the substitution of the current AC system has been proposed. A water-water heat pump coupled with a vertical geothermal probe has been selected and its dimensioning has been performed, based on the thermal energy demand of the building.

The preliminary economic analysis has led to state that the PV plant is viable, but not the electric storage. Indeed, energy production and consumption cannot be overlapped, and an electric storage will produce an increase of the energy self-produced not sufficient to balance the plant costs. The substitution of the current AC system is economically viable only if the geothermal probe is installed into the existing groundwater well because the drilling costs are considerably high and affect the return on investment. The environmental assessment carried out by applying the LCA and the WFA has highlighted the most sustainable AC scenario between the three under study in their life cycle: the water-water heat pump coupled with a geothermal probe installed into the existing groundwater well. Because of the potentially limited availability of groundwater in the considered area, future studies will address the real conditions by carrying out a flow test on the existing well, to know if it can supply the water flow rate required by the selected heat pump. In addition, further developments will focus on a sensitivity analysis on the most influencing parameters of the economic assessment. In this work, only the case of electric storage based on batteries has been evaluated; a more in-depth analysis will consider both battery storage and recharge of an electric vehicle.

To provide more robust results of the chosen economic indicators, a sensitivity analysis of the most important parameters and a risk analysis will be carried out. Outcomes will be compared to the current results obtained through the preliminary economic evaluations reported by this paper. Finally, the environmental impact assessment can be extended, by including the PV and the storage system, in order to identify possible enhancements of the proposed micro-grid model.

The approach presented in this paper can be applied to other buildings located in similar climatic conditions; these can be found in the regions and territories of the South of the Mediterranean sea basin. Moreover, the proposed micro-grid model can be extended and modified, by adding other types of data and information or energetic inputs derived from other renewable sources, depending on the building's characteristics and purposes.

References

ASHRAE (1999). *ASHRAE Handbook: HVAC Applications*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta.

Association of German Engineers (2010). VDI 4640. Thermal use of the underground.

European Union (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.

European Union (2012). Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency.

GEMIS model and database, iinas.org/gemis.html.

Goedkoop, M.J., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., van Zelm, R. (2009). ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition, Report I: Characterisation.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Sleeswijk, A.W., Sangwon, S., Udo de Haes, H.A., de Bruijn, J.A., van Duin, R., Huijbregts, M.A.J. (2002). *Handbook on life cycle assessment: operational guide to the ISO standards*. Dordrecht: Kluwer Academic Publishers.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M. (2011). *The Water Footprint Assessment Manual*. Setting the Global Standard. Earthscan, London-Washington, 228 pp.

IGSHPA (1991). *Design and installation standards*., International Ground Source Heat Pump Association, Oklahoma.

ISO (2006). ISO 14040 - Environmental management - Life cycle assessment - Principles and framework.

ISO (2006). ISO 14044 - Environmental management - Life cycle assessment -Requirements and guidelines.

ISO (2011). ISO 50001 – Energy Management System.

ISO (2014). ISO 14046 - Environmental management – Water footprint – Principles, requirements and guidelines.

Ng, B.M., Underwood, C., Walker, S. (2009). Numerical modelling of multiple standing column wells for heating and cooling buildings. In the Proceedings of Eleventh International IBPSA Conference, Glasgow (UK), July 27-30, 2009, pp. 49-55.

OpenLCA, www.openlca.org

UNI (2011). UNI CEI EN ISO 50001 – Energy management systems – Requirements and guidelines for the use.

UNI (2014). UNI/TS 11300-1:2014 - Energy performance of buildings - Part 1: Determination of the building's thermal energy requirements for summer and winter air conditioning.

Appendix A. FIRST APPENDIX

Table 1: Main technical specifications of the current AC system

	Thermal power [kW]	Electric power [kW]	EER or COP
Cooling (1)	169.3	33.5	5.05
Heating (2)	187.1	40.2	4.65

(1) T_{inlet} = 7 °C – T_{outlet} = 35 °C (2) T_{inlet} = 45 °C – T_{outlet} = 7 °C

Table 2: Geothermal probe dimensioning – Values applied

Parameters	Heating	Cooling
$Capacity_{heating, cooling}$ [W]	$187.4 \cdot 10^3$	$203.25 \cdot 10^3$
COP	5.9	6.7
r_0 [m]	0.02	0.02
r_i [m]	0.0326	0.0326
k_p [$W \cdot (m \cdot K)^{-1}$]	0.4	0.4
$T_{S.min}$ [°C]	-5	-
T_{min} [°C]	1	-
$T_{S.max}$ [°C]	-	43
T_{max} [°C]	-	36
$PLF_{h,c}$	0.34	0.34
Other parameters		
α_s [$m^2 \cdot h^{-1}$]		$2.33 \cdot 10^{-3}$
Time of plant functioning, t [h]		11
k_s [$W \cdot (m \cdot K)^{-1}$]		1.5

Table 3: Values used for the economic assessment

General parameters	
Energy cost (3) [€/kWh]	0.18
Cost of the energy introduced into the grid [€/kWh]	0.12
Discount rate [%]	2
PV system	
Unit cost of the energy self-consumed [€/kWh]	0.18
Energy saving – Self-consumption [€/yr]	14'069
Unit price of the energy introduced into the grid [€/kWh]	0.12
Revenue from the energy introduced into the grid [€/yr]	4'426
Cost of the purchased energy introduced into the grid [€/yr]	6'771
Plant cost [€]	110'000
Cost of the ordinary maintenance [€/yr]	550
Cost of the extraordinary maintenance (10th year) [€/yr]	20'000
Insurance cost [€/yr]	550
Dismantling cost [€]	8'250
Electric storage	
Energy cost – Self-consumption [€/kWh]	0.18
Revenue from the energy introduced into the grid (without storage) [€/yr]	4'426
Revenue from the energy introduced into the grid (with storage) [€/yr]	2'578
Cost of the energy purchased from the grid (without storage) [€/yr]	20'420
Cost of the energy purchased from the grid (with storage) [€/yr]	17'595

Cost of intervention [€]	50'000	
Cost of the extraordinary maintenance [€/yr]	12'500	
Water-water heat pump & geothermal probe		
	Ground	Groundwater well
Energy cost (without probe) [€/yr]	10'291	10'291
Energy cost (with probe) [€/yr]	6'872	5'908
Drilling cost [€/m]	50	-
Plant cost [€]	166'750	37'000
Operating cost [€/yr]	417	93
Incentive [%]	65	65
Years of incentive [yr]	10	10
Annual tranche [€/yr]	10'839	2'405
(3) mean value derived from the bills		

Table 4 Main technical specifications of the water-water heat pump

Heating (values referred to an outlet temperature of the evaporator of 5 °C and to an outlet temperature of the condenser of 45 °C)	
Nominal thermal power [kW]	179.02
Absorbed power [kW]	40.04
COP	4.43
Water flow [$l \cdot h^{-1}$]	24'540
Cooling (values referred to an outlet temperature of the evaporator of 7 °C and to an outlet temperature of the condenser of 35 °C)	
Nominal thermal power [kW]	169.34
Absorbed power [kW]	33.5
EER	5.05
Water flow [$l \cdot h^{-1}$]	29'130

Note 1

- Time slot F1: from 8 A.M. to 7 P.M., from Monday to Friday
- Time slot F2: from 7 A.M. to 8 A.M. and from 7 P.M. to 11 P.M., from Monday to Friday; from 7 A.M. to 11 P.M. on Saturday
- Time slot F3: From midnight to 7 A.M. and from 11 P.M. to midnight, from Monday to Saturday; all day on Sunday and holidays