Simulation of Integrated Ground Source Heat Pump and Solar Photovoltaic-Thermal System and Feasibility Study in Europe

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Abstract*—Renewable energy systems have received significant attention in the building sector for their potential for reductions in greenhouse gas (GHG) emissions and reduced purchased energy consumption. This paper investigated the integration of ground source heat pumps and photovoltaic-thermal systems by modeling Matlab/Simulink to predict the systems' dynamic, electrical, and thermal behaviors. Two sites in Europe have been selected for the feasibility study, case 1 is in Rome (warm temperature climate), and case 2 is in Helsinki (snow climate). Building heating, cooling, and domestic hot water loads were estimated using models developed in EnergyPlus. The PV/T system was sized at 7kW with 22 panels installed on the roof area in both case studies. The GSHP system was sized at 4kW, determined by the square footage of the single house. A techno-economic-environmental study was performed to evaluate the potential benefits of this integrated renewable energy system, like energy-saving and environmental impact. The system's total energy for Rome was 7082.0 kWh/year and 5687.4 kWh/year for Helsinki. The results demonstrated that the integrated systems could supply 76.8% of Rome's single house energy demands and 43.0% of the energy demands for Helsinki.

***Keywords*—Ground source heat pump; Photovoltaic-thermal system; simulation; renewable energy system, smart grid**

I. INTRODUCTION

Rising energy demands lead to worrying levels of greenhouse gas (GHG) emissions and cause global warming issues. These emissions are contributed by abusing fossil fuels to provide electricity, heating, and cooling for buildings [1, 2]. Renewable energy systems have received significant attention in the building sector for their potential for greenhouse gas (GHG) emissions reductions and reduced purchased energy consumption.

This paper investigates an integrated photovoltaic thermal collector (PV/T) and ground source heat pump (GSHP) system to meet building energy demand. GSHP is a promising technology for reducing GHG emissions for space heating and cooling in buildings [3]. Utilizing geothermal energy, GSHP is approximately 45% more efficient than conventional heat pumps [4]. Camdali et al. studied the Bolu case with numerical modeling techniques for a GSHP [5]. Healy and Ugursal investigated the performance and economic feasibility of GSHPs for the location of Nova Scotia [6].

PV cells and thermal collectors combined into a single device is a PV/T system. Assembling these two solar technologies enables simultaneous conversion of solar energy into electricity and heat. The solar collector absorbs the solar energy and, in return, heats the fluid flowing through the pipes. The heated fluid from the solar collector transfers the thermal energy to water stored in the storage tank to feed the primary water heating system if necessary [7]. Solar thermal technologies are used for domestic hot water (DHW), space heating, swimming pools, etc. The working conditions of the solar collector are often between 60°C and 80°C, with a conversion efficiency level of around 40 – 60%, which can be achieved with a flat-plate collector for domestic use [8]. Charalambous et al. showed that when the PV cell operates at a low temperature, the probability of increasing the electricity efficiency becomes higher [9].

Research methods into numerical models can predict system behaviors at complex levels. Balushi and Yousuf discovered that the behaviors of the PV/T panels are heavily influenced by the quick variation of the conditions of external factors during the daytime, mainly due to solar irradiation [10]. Models produced to demonstrate the outcome of the dynamic behaviors of the PV/T panels represent a flexible tool for developing such systems with a global optimization perspective [11]. According to Al-Waeli, Sopian, and Kazem, there is an evident lack of economic and environmental evaluations, where most articles on PV/T are dominated by the thermal study of the system [12].

The main advantage of integrating PV/T and GSHPs is that they are designed to complement one another. Combining these technologies benefits buildings by independently producing heating, cooling, and hot water. The initial cost of a GSHP is relatively high due to digging boreholes and installing the GHE, although when combined to work with a PV/T system, the solar system could offset the cost by partially meeting the heating load demands. GSHP systems can stabilize heating and cooling energy supply even though the PV/T system performance depends heavily on weather conditions.

Brischoux and Bernier [13] examined the performance of a coupled PV/T/GSHP system for space heating and domestic hot water (DHW) heating. The results showed that the coupled PV/T/GSHP system could provide 7.7% more electricity annually with a higher seasonal performance than an uncoupled system. Chen and Yang [14] investigated a numerical simulation of a PV/T/GSHP system for space heating and domestic hot water in China. Xia et al. [15] investigated a GSHP system integrated with water-based PV/T collectors to provide cooling, heating, and DHW for residential buildings in Melbourne, Australia.

Global concerns relating to the usage of traditional fossil fuels need addressing immediately. As environmental impacts accelerate, there is a vital need for implementing cleaner energy development in the building sectors alone. PV/T and GSHP technology can be integrated into a property, establishing a suitable method driven by solar power to generate electricity to provide heating, cooling, and direct hot water (DHW) to buildings (residential and commercial). Meeting energy demands in buildings in an eco-friendly manner have been widely studied. Although, maintaining an appropriate balance between supply and demand with combined renewable energy systems is complex.

This research aims to integrate a PV/T and GSHP system using mathematical modeling through MATLAB/SIMULINK platform. A single house in two sites in Europe has been selected for the feasibility study, case 1 is in Rome (warm temperature climate), and case 2 is in Helsinki (snow climate). The single house monthly energy demands and climatic data are used at the two sites to input the integrated PV/T/GSHP model. This aims to assess the system performance for meeting the house heating, cooling, and electricity demand. The techno-economic-environmental assessment of the integrated system in two different climates is performed to understand whether the system is self-sufficient and needs grid integration of energy storage.

II. METHOD

A. Integrated system

This research investigates the integrated PV/T/GSHP system's performance through mathematical modeling, focusing on a feasibility analysis of the system using two different climates. The systems were modeled independently to aid in the understanding of the system's dynamic and thermal behaviors before the system was integrated. The integrated PV/T/GSHP system is presented in Fig. 1. The methodology for modeling the integrated system was described in [16].

B. Photovoltaic-Thermal System

The electrical power Q_{elec} generated by the PV/T panel is shown (1).

$$Q_{elec} = G * \tau\alpha * AP * \eta PV \qquad (1)$$

Where:

G demonstrates the solar radiation incident on the collector surface in W/m^2.

$\tau\alpha$ demonstrates the transmission absorption effectiveness of the collector.

ηPV demonstrates the efficiency of the PV module at the current temperature.

The thermal energy collection Q_{therm} is calculated based on energy balance as shown in (2):

$$S*A_p = Q_{therm}+U_{back}*A_{back}*(T_{plate,ave}-T_{amb,back})+Ap*(T_{plate,ave}-T_{cover,ave})/(R_{plate\text{-}to\text{-}cover}) \qquad (2)$$

Where:

Q_{therm} is the rate of thermal energy collection

S is the net absorbed solar radiation, regarding the radiation absorbed by the PV cells in W/m2

A_{p} and A_{back} demonstrate the gap area of the back of the collector area, respectively, in m2.

U_{back} demonstrates the heat loss coefficient of the absorber plate to the ambient air behind the collector W/(m^2.K).

$R_{\mathrm{plate\text{-}to\text{-}cover}}$ demonstrates the material's thermal resistance between the absorber plate temperature and the bonded glass to the PV cells in (m2.K)/W.

T_{plate}, $T_{\mathrm{amb,back,}}$ and T_{cover} demonstrate the temperature of the absorber plate and ambient temperature behind the collector, and the surface temperature of the glass in Kelvin.

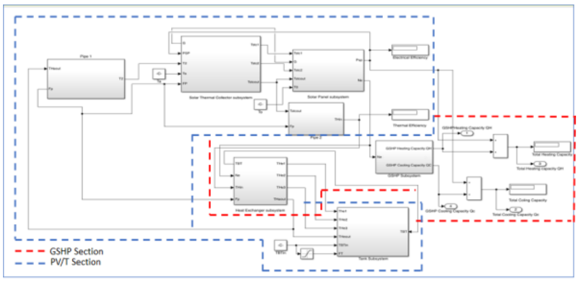

Fig. 1: Integrated Ground Source Heat Pump and Solar Photovoltaic-Thermal System

C. Ground Source Heat Pump

The coefficient of performance is determined by the ratio of heat transferred to the sink (useful heat output) to work done by the compressor (total energy input), as shown in (3).

$$COP=Q/W_{comp} \qquad (3)$$

Where:

COP is the coefficient of performance.

Q is the heat supplied to or removed from the reservoir.

W_{comp} is the work done by the heat pump.

D. Case studies

As shown in Fig. 2, a single house is chosen for the case study. The dimensions of the single house are the length of 8.5 m, width of 8.5 m, height of 6 m, the area is 72.25 $m^{2,}$ and the building orientation is South to North. The total conditioned area for the single house is 140 m^2. The integrated system will provide building heating, cooling, and electricity. The building loads for single houses in case study 1 Rome and case study 2 Helsinki was estimated using EnergyPlus. Rome has a Mediterranean climate characteristic with a warm summer and medium climatic cooling potential. Helsinki has a humid continental climate with extreme winter conditions. The single house is shown in Fig. 2; more details about the single house and the case study results for each month, and annual heating, cooling, and DHW demands for Rome and Helsinki are summarised in [17].

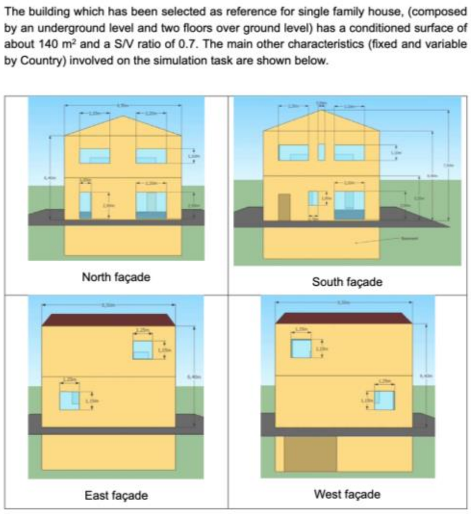
The building which has been selected as reference for single family house, (composed by an underground level and two floors over ground level) has a conditioned surface of about 140 m^2 and a S/V ratio of 0.7. The main other characteristics (fixed and variable by Country) involved on the simulation task are shown below.

Fig. 2: Single house mode [17]

The calculated building loads are used as inputs to the PV/T/GSHP system model to assess the integrated system performance. The simulation outputs will be further investigated with a feasibility study assessing the system's initial cost, total energy savings, extra energy purchased from the grid, simple payback period, and analyze GHG emissions assessing the reduction of CO2 emissions compared to a conventional system. All these factors in this study can be used on similar climates and property sizes to determine if this system is feasible.

III. RESULTS AND DISCUSSION

Climates vary depending on geographical locations. For this study, Rome and Helsinki weather averages for each month in the year 2020 were recorded to predict the performance of the PV/T/GSHP system based on the case study single house size and solar irradiance.

A. *System Energy Production and House Energy Demand*

The results below are produced from the mathematical simulation of the PV/T side of the PV/T/GSHP system model. The predicted electricity production is generated using the average temperatures constant for each month. Fig. 3 shows that based on the climate conditions each month for Rome, the PV/T system meets the demands of the household for April, May, June, September, and October throughout the year. The annual household usage was 9226.33 kWh/year, and the total annual energy produced by the PV/T system was 7081.9719 kWh/year, resulting in 76.76% of the household energy demands being produced by the PV/T/GSHP system. Fig. 4 shows that based on the climate conditions each month for Helsinki, the PV/T system meets the demands of the household for May, June, July, August, and September throughout the year. The annual household usage was 13,228.98 kWh/year, and the total annual energy produced by the PV/T system was 5687.4091 kWh/year, resulting in 42.99% of the household energy demands being produced by the PV/T/GSHP system.

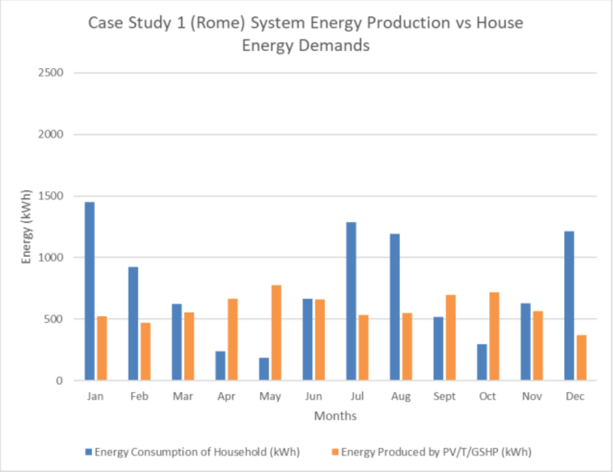

Fig. 3: System energy production vs. house energy demands for Rome

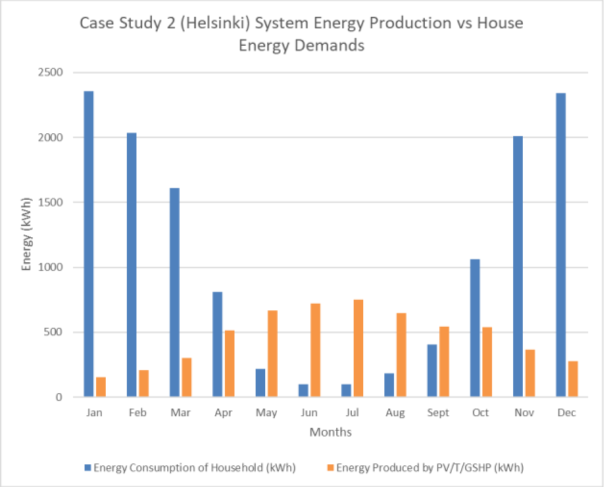

Fig. 4: System energy production vs. house energy demands for Helsinki

B. *Greenhouse Gas Emissions*

Fig. 5 compares GHG emissions between a conventional system, a GSHP system powered by a conventional system, and the proposed PV/T/GSHP system using both case studies' annual energy usage data. The conventional systems method of providing heating and cooling via fossil fuel production produces large quantities of carbon dioxide when burned. Table I presented the greenhouse gas emissions of the conventional system, GSHP, and PV/T/GSHP system.

The GSHP reduces GHG emissions by up to ~20% for both case studies, which benefits the environment. WHEN INTEGRATED, the PV/T/GSHP system can reduce carbon footprint by up to ~ 50% annually compared to conventional heating, cooling, and DHW system. This is due to the PV/T/GSHP system producing and supplying independent electricity generation via a clean, renewable, and emission-free energy production. A PV/T/GSHP system is a more sustainable option to incorporate into both case study houses from an environmental standpoint.

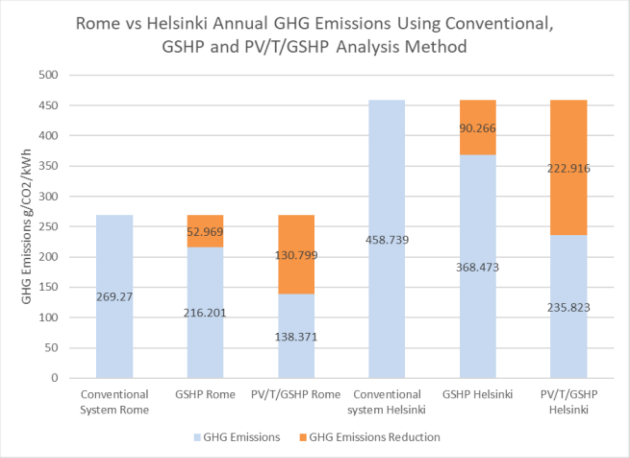

Fig. 5: Rome vs. Helsinki Annual GHG Emissions Using Conventional, GSHP, and PV/T/GSHP system

TABLE I. GREENHOUSE GAS EMISSIONS

System	*GHG Emissions Rome/year, gCO_2/kWh*	*GHG Emissions Helsinki/year, gCO_2/kWh*
Conventional System	269.27	458.74
GSHP	216.20	368.47
PV/T/GSHP	138.37	235.82

C. System Cost and Potential Savings

The average life cycle of PV/T and GSHP systems is predicted to operate for 25 years before requiring renewal [18]. Table II demonstrates the system cost and electricity rate, determining the payback period.

TABLE II. SYSTEM COST

Description	*Values*
PV/T 7kW system cost	€8,063.73
GSHP 7kW system cost	€5,556
PV/T/GSHP system cost	€13,619.73
Rome Electricity rate	0.213 €/kWh
Helsinki Electricity rate	0.174 €/kWh

Fig. 6 presents a detailed overview of comparing a conventional system's annual cost and the annual energy costs of the PV/T/GSHP system. There are potential savings in implementing the PV/T/GSHP system in both climates, although there is still a higher volume of energy required from the grid than what the PV/T/GSHP system can produce for Helsinki. Table III compares the potential savings of implementing a PV/T/GSHP renewable energy system onto the property against a conventional system using the energy demands in the case studies. The tables demonstrate the capital of the PV/T/GSHP system, electricity rates in Rome and Helsinki in €/kWh, and potential energy savings the system produces annually. Fig. 6 demonstrates the potential annual savings in € between a conventional system vs. the PV/T/GSHP system (€1508.46 annual savings for Rome and €989.61 annual savings for Helsinki).

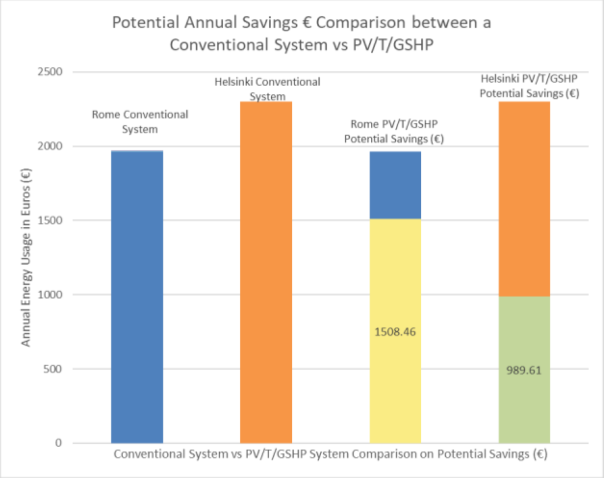

Fig. 6: Potential Annual Savings € Comparison between a Conventional System vs. PV/T/GSHP

TABLE III. PONTENTIAL ANNUAL SAVINGS

Conventional System Total Annual Energy Demands Rome, €	*PV/T/GSHP Rome Savings/year, €*	*Conventional System Helsinki, €*	*PV/T/GSHP Helsinki Savings/year, €*
1,965.21	1,508.46	2,301.21	989.61

The PV/T/GSHP system demonstrated that the typical life cycle is approximately 25 years. Rome's government grant (EcoBonus scheme) reduced the system installation by 50%. Rome's system took 6.7 years to pay for itself. Potential savings of €27,604.82 on Rome's energy bills for the remainder of the 18.3 years of the system's expected life confirm that the system is financially feasible for Rome. The PV/T/GSHP for the Helsinki case study was poor; using the simple payback period (SPP), the system found it would take a staggering 68.3 years to pay off. There are no incentives or government schemes for implementing residential renewable energy systems in Finland (Helsinki). The PV/T/GSHP system in Helsinki's climate is financially not feasible as the system's expected life is around 25 years. Conclusion that emphasis on government schemes for renewable energy systems is constructive.

IV. CONCLUSION

Investigating the PV/T/GSHP systems performance, the study's single house demands were not met in both cases. Grid integration of energy storage is required as it is not a self-sufficient system in both case study climates. The total building heating, cooling, and DHW loads for Rome were 9226.33 kWh/year and 13228.98 kWh/year for Helsinki. The PV/T/GSHP achieved a total energy generation of 7081.97 kWh/year for Rome and 5687.41 kWh/year for Helsinki. Additional energy purchased from the grid resulted in 2144.36 kWh/year for Rome and 7541.57 kWh/year for Helsinki. The PV/T/GSHP system met 76.76% of Rome's single house energy demands and 42.99% for Helsinki.

Investigating GHG emissions assessed a GSHP and PV/T/GSHP against a conventional system incorporating the case study energy demands to conduct a comparative study amongst the system's GHG emissions. The conventional system released 269.17 gCO2/kWh GHG emissions for

Rome and 458.74 gCO2/kWh for Helsinki. The conventional system used to power the GSHP reduced CO2 emissions in Rome by 19.77% and in Helsinki by 19.68%. The PV/T/GSHP can reduce GHG emissions by up to ~50% against the conventional system for both cases.

The PV/T/GSHP system demonstrated that the typical life cycle is approximately 25 years. Rome's government grant (EcoBonus scheme) reduced the system installation by 50%. Rome's system took 6.7 years to pay for itself, with potential savings of €27,604.82 on Rome's energy bills for the remainder of the 18.3 years of the system's expected life, confirming the system is financially feasible for Rome. Helsinki's system took 68.3 years to pay for itself; the system is barely feasible for the single studied house located in this snow climate.

REFERENCES

[1] D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, R. Gorini, The Role of Renewable Energy in the Global Energy Transformation, April 2019.

[2] C. D. T. Abergel, Tracking Buildings, June 2020. Accessed on: November. 25, 2020.

[3] D. L. Cao, Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade, September. 15, 2016.

[4] H. Qian, Y. Wang, Modelling the Interactions between the Performance of Ground Source Heat Pumps and Soil Temperature Variations, December 2014.

[5] U. Camdali, M. Bulit, N. Sozbir, Numerical Modelling of a Ground Source Heat Pump: The Bolu Case, May, 14, 2015. Accessed on: February. 21, 2021.

[6] P. Healy, V. I. Ugursal, Performance and Economic Feasibility of Ground Source Heat Pumps in Cold Climate, August 1997.

[7] The Renewable Energy Hub, Solar Thermal System Components, 2018. Accessed on: February. 1, 2021.

[8] A. G. Lupu et al,. A Review of Solar Photovoltaic Systems Cooling Technologies, 2018.

[9] P. G. Charlambous, G.G. Maidment, S. A. Kalogirou, K. Yiakoumetti, Photovoltaic thermal (PV/T) collectors: A review, February 2007.

[10] A. Balushi, A. Yousuf, Feasibility Study of Solar Photovoltaic Thermal (PV/T) Water Collector in the Local Environment (Perth), 2018. Accessed on: January. 4, 2021.

[11] D. R. Mattia, R. Giorgio, R. Cellia, S. Federico, A. T. Luca, Dynamic Thermal Model for Hybrid Photovoltaic Panels, December 2015. Accessed on: February. 15, 2021.

[12] A. H. Al-Waeli, K. B. Sopian, H. Kazem, Photovoltaic Thermal PV/T Systems: A Review, April 2017.

[13] N. Sommerfeldt, Review of Solar PV/Thermal Plus Ground-Source, October. 14, 2016. Accessed on: February. 12, 2021.

[14] X. Chen, H. Yang, Performance Analysis of a Proposed Solar assisted Ground Coupled Heat Pump System, 2012. Accessed on: March. 14, 2021.

[15] L. Xia, Z. Ma, G. Kokogiannakis, Performance of a Ground-Source Heat Pump System integrated with Solar Photovoltaics Thermal Collectors for Residential Applications, September 2017.

[16] L.M. Orr. Simulation and operational characteristics of solar photovoltaic integrated with ground source heat pump systems. 2021. Northumbria University.

[17] ENTRA NZE, Heating and Cooling Energy Demand and Loads for Building Types in Different Countries of the EU. March 2014.

[18] C. Good, Environmental impact assessment of hybrid photovoltaic-thermal (PV/T) systems- A review, March 2016. Accessed on: April. 5, 2021.