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Photovoltaic-Thermal System Performance Analysis for a Smart Energy Building in Different Climate Conditions

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Abstract. Photovoltaic-thermal (PVT) panels combine solar thermal and photovoltaic technologies and generate simultaneously both heat and electricity. They can be a good variant for small domestic households to reduce their energy costs. This paper looks at the potential of these systems into the climates of Vladivostok, Russia, and Tehran, Iran. In the article, some brief background information on PVT systems and the concept of prosumers is introduced. Next, a similar PVT system is proposed for a given household consumer in Vladivostok and Tehran with the variable weather conditions corresponding to the two locations. The PVT system is modeled in TRNSYS (v18, Thermal Energy System Specialists, Madison, USA). A performance analysis is carried out in order to establish the daily instantaneous energy output and the annual energy production. The results indicate a 15–20 % better performance in Tehran compared to Vladivostok due to slightly better weather conditions, though the total efficiency of system has a better performance in Vladivostok. The system efficiency was assessed through two different methods. This study concludes that both the Russian and Iranian PVT market has a good potential for adopting the technology, especially since it is currently less mature than other leader countries in renewable energies.

Keywords: Renewable energy, solar energy, smart building, efficiency, photovoltaic-thermal (PVT).

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Анализ эффективности работы фотоэлектрической тепловой системы здания в различных климатических условиях

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Аннотация. Фотогальванические тепловые системы (PVT) сочетают в себе функциональные возможности солнечных коллекторов и солнечных батарей в одной панели. Устройство позволяет одновременно получать электро- и теплоэнергию. Такую гибридную установку удобно использовать в частных домах, что позволяет снизить затраты на покупку электроэнергии. В статье приводится краткая справочная информация о системах PVT и концепции просьюмеров. В публикации рассматривается система PVT применительно к бытовому потребителю во Владивостоке и Тегеране с учётом погодных условий в соответствующих местоположениях. Произведено моделирование системы PVT в программе TRNSYS. Представлен анализ выработки энергии системой ежедневно и в течение года. Результаты матмоделирования показывают, что максимальная и годовая производительность системы PVT в климатических условиях Тегерана на 15–20 % больше, чем во Владивостоке, но при этом эффективность преобразования падающей солнечной энергии в тепловую и электрическую выше в климатических условиях Владивостока. Произведена оценка эффективности работы системы двумя методами. Экспериментальные исследования с помощью математического моделирования работы системы PVT показали, что российский и иранский климат имеет хороший потенциал для внедрения PVT технологии, тем более что в настоящее время она менее развита, чем в других странах, являющихся лидерами в области возобновляемой энергетики.

Ключевые слова: возобновляемая энергия, солнечная энергия, умное здание, эффективность, фотогальваническая тепловая система (PVT).

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Introduction

The increasing use of energy resources in recent years and the shortage of fossil fuel resources on the one hand and efforts to reduce greenhouse gas emissions on the other hand, has led to a significant increase in demand for renewable energy sources in recent years. Solar energy is the most wide-spread type of renewable energy, due to its multiple benefits: It is easily available in many locations, has low operational costs and can be adapted to small, decentralized systems. In theory, there is sufficient solar radiation reaching the Earth to meet 10,000 times the current energy needs of the world [1]. The established solar technologies currently available on the market can be broadly classified into photovoltaic (PV) panels and passive solar-thermal panels (ST). Hybrid photovoltaic-thermal systems (PVT) combine these two technologies and maximize their benefits into one single piece of equipment, producing both electricity and useful heat. PVT systems are a type of micro-cogeneration technology that can be very efficiently integrated into individual households. This can achieve decentralized production of clean heat and energy, maximizing the South facing available space and obtaining an overall better payback of the investment, compared to separate side-by-side PV and ST systems.

As presented in IRENA 2021 reports, the capacity of solar PV increased from 40334 MW in 2010 to 773200 MW in 2020. The most important reasons are 85 % decreasing in their price and increasing in their efficiency in last decade from 10.5 % to 22.5 %. The building sector is responsible for 37 % of energy consumption and carbon emissions globally [2]. Also, about 65 % to 85 % of this energy consumption is for heating and cooling [3]. Consequently, many countries have already begun to develop energy conservation plans in their constructions like a policy called 20–20–20, which leads to a 20 % increase in the energy efficiency of buildings [4]. Another critical aspect of these reviews in the energy sectors is to increase the share of renewable energy and move practically towards the true definition of smart energy systems [5]. To achieve these, the electricity grids should be reconfigured into smart grids, and other energy distribution networks (e.g., district cooling and heating, if any) should be compatible with the new buildings and energy trading policies [6]. Low and ultra-low temperature district heating systems are samples of the proposed solutions for the future district heating systems, for instance [6, 7].

Building emissions of CO_2, one of the most important greenhouse gases, can give rise to global warming. Apart from a building's direct CO_2 emissions, buildings can emit CO_2 indirectly due to their consumption of electricity produced in fossil fuel power plants. Therefore, transforming buildings to zero energy users can reduce CO_2 emissions and their effect on global warming. Furthermore, optimizing building system facets, such as thermal insulation, lighting, cooling, and heating, can reduce energy consumption. Additionally, the sustainable design of energy systems is one of the UN Sustainable Development Goals (UN SDGs). Access to affordable, reliable, sustainable, and modern energy is under scored. Therefore, using renewable energy sources can help meet the SDGs [8]. Solar energy systems, such as solar thermal collectors and PV modules, and wind energy have been developed with the aim of clean and sustainable energy production worldwide.

Due to the increase in energy consumption and demand for electricity and heat in households, residential and commercial buildings are considered as a significant source of greenhouse gas emissions.

Smart energy buildings are of the essential elements of future smart energy systems. Smart energy buildings have a highly efficient energy performance and own their individual renewable energy systems while also being connected to the local energy distribution grids.

Smart buildings are supposed to have two-way interactions with the energy distribution grids as well. Two-way interaction means buying energy from the grids whenever the building's energy systems are not sufficiently producing and selling the overproduction of the building energy system to the grids, for peak-shaving, etc. [9]. Among renewable-based energy resources for buildings, solar-driven systems are the most popular choices and available in a variety of designs. Solar-based energy systems create clean, renewable electricity/heat from the sun and benefit the environment due to net-zero greenhouse gas emissions, particularly carbon dioxide (CO_2). PV panels with a battery unit for two-way electricity supply for forming net-zero electricity buildings, solar thermal panels coupled to a thermal storage unit for providing the heat demand and domestic hot water of the buildings, and more recently PVT panels with a battery and a thermal storage unit (with and without heat pumps) are of the common types of building solar energy systems [10].

Due to the vast availability of fossil fuel resources (oil, natural gas and coal) in Iran and Russia, renewable energy plants are less welcomed. However, in recent years, the installed capacity of these power plants in both countries has improved significantly. In Iran, by the end of 2020, the installation capacity of photovoltaic power plants was equal to 455 MW, which has experienced a 31 % increase in 2019.In Russia, the capacity of installed photovoltaic power plants by the end of 2020 is reported to be 1428 MW, which is an increase of 23 % compared to 2019.However, in neither country has the capacity of the photovoltaic-thermal systems installed in them been reported. [11]

PVT Systems

The electrical efficiency of PV cells decreases with a temperature coefficient of 0.3–0.9 %/°C above the standard test condition (STC) of 25 °C. Thus, the PV cells in hybrid PVT systems show an energy efficiency of 4–12 % higher compared to the same cell in an individual PV panel [12], due to the fact that the cell is cooled through the extraction of the thermal energy.

A significant amount of the Sun's spectral emissivity on a PV panel is lost in the form of heat (either by non-absorption or thermalization). This heat can be recovered and used for domestic hot water (DHW) or heating applications, which leads to increasing the spectrum of operation of the panels and improving the rate of solar energy conversion.

The total efficiency of the system is increased by combining the electrical and thermal components, since the total efficiency can be described as the sum between the electrical and thermal efficiency of the system, as shown in Equation (1).

$$\eta_{tot} = \eta_{el} + \eta_{th} \tag{1}$$

Furthermore, PVT reaches a higher reduction of the non-renewable primary energy as well as a higher production of solar thermal energy compared to the two separate systems (PV and ST). In urban locations, where South facing roof and façade space are limited, this solution is ideal for fulfilling or partially contributing towards the heating and electricity needs of the consumer. In addition, the costs associated with transport, installation, and maintenance are significantly reduced by implementing a single piece of equipment instead of two separate ones.

The PVT system can be configured in multiple ways: Flat or concentrated, with a liquid, air or dual liquid-air working fluid. The geometry of the thermal collector can also take multiple forms (harp, spiral, direct flow, fractal) and can be designed by various manufacturing methods (sheet and tube, roll bond, rectangular channels). Aste et al. [13] carries out a comprehensive review on the various geometrical, thermo-physical, and manufacturing solutions for PVT systems. The configuration investigated in this study is illustrated in Fig. 1.

Methodology

The PVT system modelled in this paper is illustrated in Fig. 2. The system comprises of a PVT collector connected to a water storage tank, a circulation pump, connection to the household water main and an inverter/regulator with a battery bank. The input in the system is the meteorological data: Solar irradiation (G (W/m^2)), ambient temperature (T_{amb} (^oC)) and wind speed (W (m/s)). The temperature at the outlet of the collector is T_{out_coll} and the temperature at the inlet of the collector is T_{in_coll}, the temperature of the tank is $\mathrm{T_{tank}}$ (hot water), the temperature of the water main that feeds

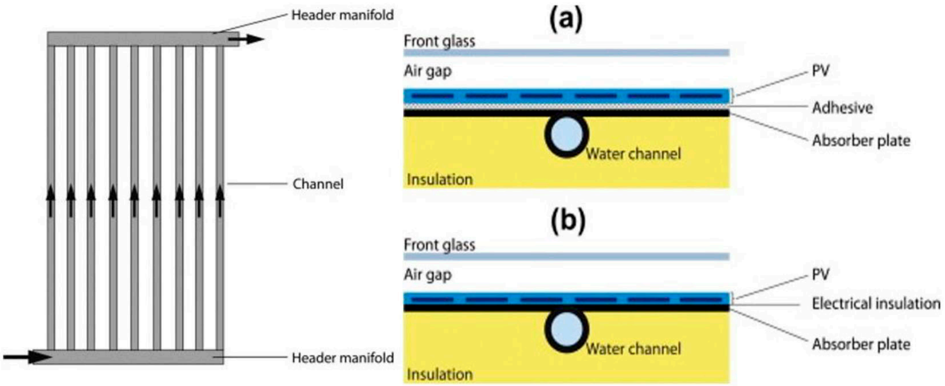

Fig 1. Direct flow collector geometry PVT. Cross section of a PVT collector: (a) with adhesive; (b) with electrical insulation

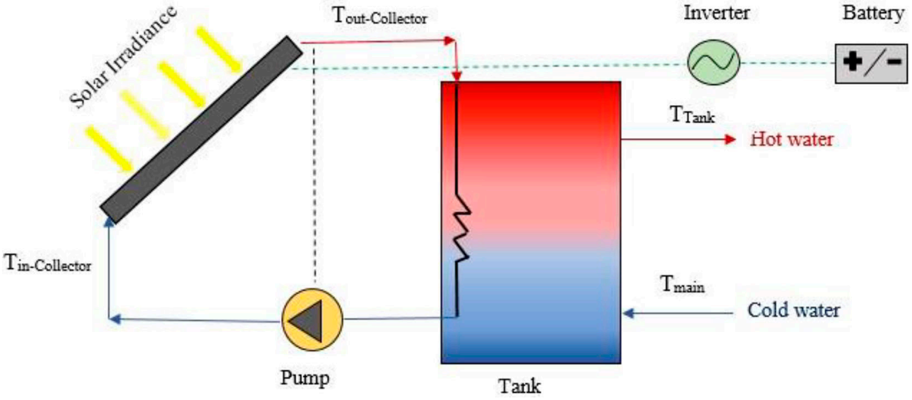

Fig 2. Schematic of a domestic PVT system

the tanks *is* T_{main} (cold water), all in °C. The PVT acts as a pre-heater when the temperature reached by the tank is not sufficient for providing domestic hot water. Schematic of a domestic PVT system is shown in Fig. 2.

Meteorological Conditions

The output of a PVT system is dependent upon three meteorological parameters: Ambient temperature, irradiation, and wind speed. The solar irradiation has the most significant impact on the performance of a PVT system, as it determines the electrical output, but also influences the temperature of the materials through radiative heat transfer. The temperatures in the PVT layers are also dependent on the ambient temperature, through convective and conductive heat transfer processes in the solid and liquid layers of the system, but also on the speed of the wind which determines the convective heat losses at the surface and at the back of the panel. The yearly profile of each parameter is obtained from Solcast Database [14].

The meteorological conditions of both Tehran (Iran) and Vladivostok (Russia) are used in parallel for the simulations. This allows a comparison of the performance of the PVT system in both regions. In Tehran, the summers are hot, arid, and clear and the winters are cold, dry, and mostly clear. Over the course of the year, the temperature typically varies from 1 °C to 36 °C and is rarely below –3 °C or above 38 °C. In Vladivostok, the summers are comfortable, wet, and partly cloudy and the winters are short, freezing, snowy, windy, and mostly clear. Over the course of the year, the temperature typically varies from –15 °C to 22 °C and is rarely below –21 °C or above 27 °C.

The average temperature, rainy days, wind speed and solar radiation are plotted in the Fig. 3, 4, 5, 6 to better compare the weather conditions of the two cities.

The total radiation comprises of three components: Direct beam radiation, diffuse radiation, and reflective radiation. Direct radiation is the direct incident beam radiation that hits the surface of the panel, the diffuse radiation refers to the radiation that has been scattered through the molecules of the atmosphere, and reflective radiation (also referred to as albedo) is the radiation reflected by the surroundings.

DHW and Electricity Demand

In order to carry out an accurate simulation, a realistic daily time dependent profile of the household DHW demand is required. The daily profile of DHW is dependent upon various parameters: The number of inhabitants, appliances, ambient conditions, seasonal variations, the average daily hot water

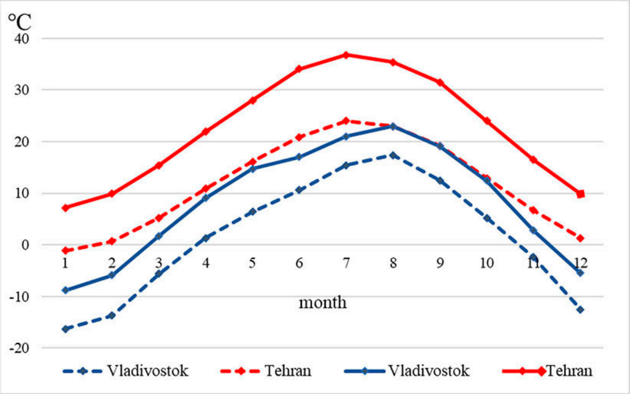

Fig. 3. Average of ambient temperature in different months (°C)

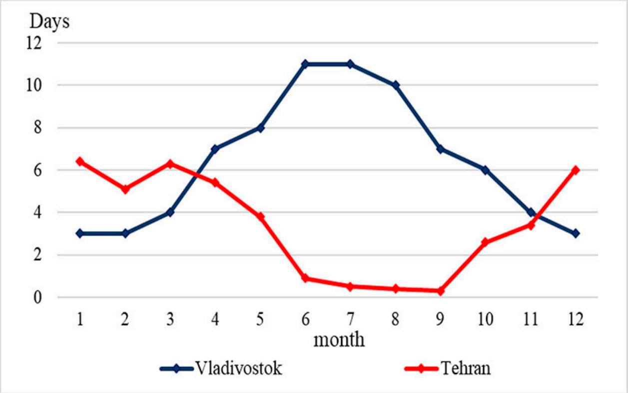

Fig. 4. Average number of rainy days in different months

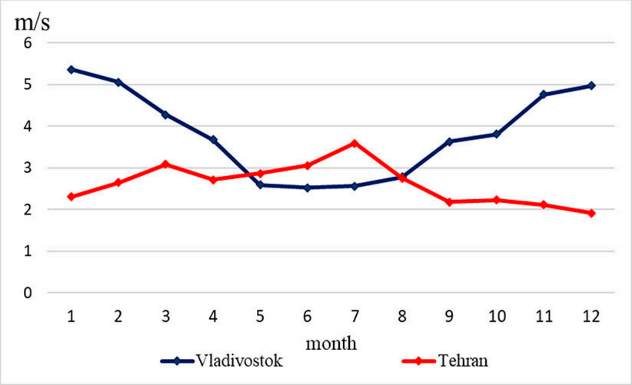

Fig. 5. Average wind speed in different months(m/s)

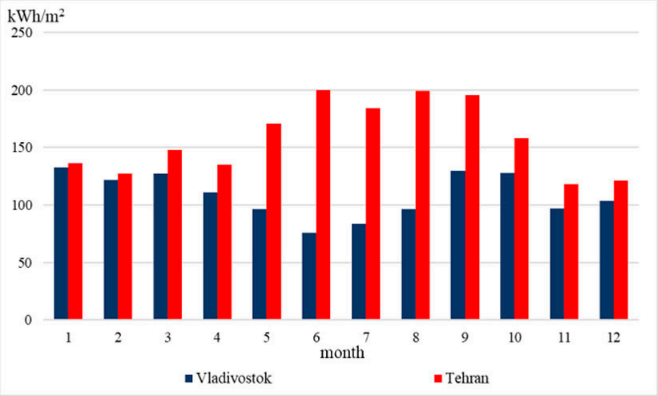

Fig. 6. Average direct normal irradiance in different months

volume, and the yearly demand [15]. The average daily rate of water consumption per 1 resident in the apartments under consideration was 74 liters/day [16]. Statistic data of average water consumption for a three-person family on a weekday shows in Fig. 7. The temperature level for DHW was set to 55 °C, while the cold water from the main is assumed constant across the year at 10 °C.

An electrical demand curve was generated using a forcing function in TRNSYS and considering weekday and weekend variations, as well as holidays, and the system includes a battery bank. The electricity demand also includes the power consumption of the pump for circulating the fluid. The excess of produced electricity is exported to the grid when the battery is full, and when the battery load is less than the demand, electricity is bought back from the grid.

TRNSYS Model

TRNSYS (transient system simulation tool) is a flexible software that can simulate the behavior of dynamic transient systems. A TRNSYS model was developed to replicate the system in Fig. 8, and it includes: Weather Data (Type 15), PVT collector (Type 50), Stratified Storage Tank with a capacity of 100 L (Type 4), Single Speed Pump (Type 114), Inverter/Charge controller (Type 48), a Battery Bank (Type 47) and Controllers (Type 2). The Type 15 component is a tool that reads weather data either

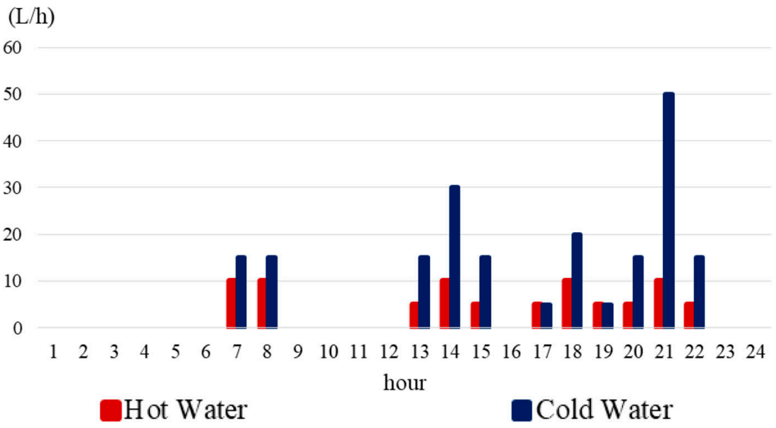

Fig. 7. Average water consumption of a family of three on a weekday

from the built-in database or from a user provided spreadsheet, and processes it to provide the input weather data for the simulation (temperature, radiation, wind speed). The storage tank (Type 4) models a tank that can be subjected to thermal stratification, by establishing the number of thermal nodes N.

If N is equal to one, the tank is modeled as fully-mixed with no stratification, which was assumed for the purpose of this study. Type 114 is the component for a constant speed pump that maintains a constant fluid outlet mass flow rate. The pump control strategy modelled by a Type 2 component is based on the temperature of the liquid in the storage tank and the DHW demand. The collector pump circulates water from the tank when the energy can be collected, and the tank is emptied by the DHW load and refilled when it reaches a low volume. Type 48 models both the regulator of the system, which distributes DC power from the solar cell array to and from a battery, and the inverter converts the DC power to AC. The electrical controller decides whether to use the electrical load for charging the battery or for meeting the demand. Type 47 models the battery bank of the system, which is based on a lead-acid type of battery and can output data on the variation of the state of charge over time and the rate of charge or discharge.

The simulation assumes that no heat losses occur on the pipes, the optical properties of materials are constant and no surroundings partial shading or dust is considered. This model is a simplified version of a complete numerical dynamic analysis that can be performed on a PVT based on the heat transfer in each layer of the panel [17], where a system of ordinary differential equations is solved simultaneously to find the temperatures at any time of the simulation.

The detailed models are used for in-depth layer analysis and geometrical, optical or thermo-physical optimizations and sizing. For the purpose of a quantitative analysis of overall daily, weekly and annual production of energy, the TRNSYS Type 50 model was validated and proved accurate.

The PVT component requires a set of input parameters that depend on the specific PVT that is to be modelled. These can be found in the manufacturer's specifications and refer to: Collector fin efficiency, plate absorbance, number of glasses covers, optical efficiency, collector plate emittance, loss coefficient, temperature coefficient, STC temperature, and packing factor. Thus, the module can be customized to replicate a product available on the market. The detailed models are used for in-depth layer analysis and geometrical, optical or thermo-physical optimizations and sizing. For the purpose

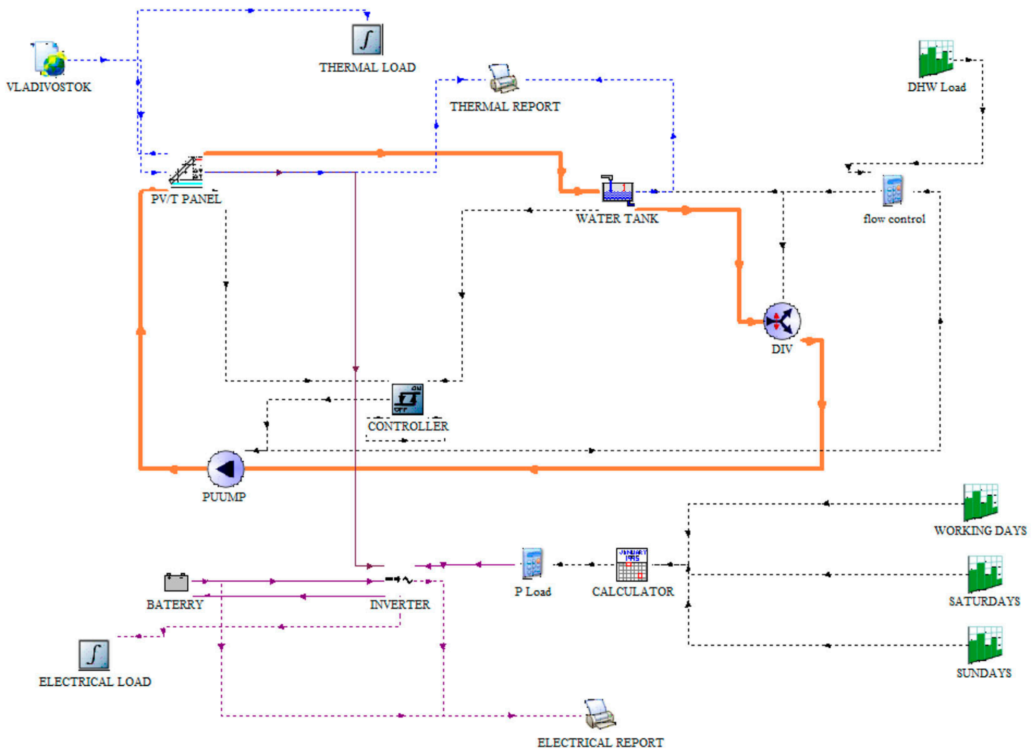

Fig. 8. Components of the transient system simulation tool (TRNSYS) model

of a quantitative analysis of overall daily, weekly and annual production of energy, the TRNSYS Type 50 model was validated and proved accurate. The PVT component requires a set of input parameters that depend on the specific PVT that is to be modelled. These can be found in the manufacturer's specifications and refer to: Collector fin efficiency, plate absorbance, number of glasses covers, optical efficiency, collector plate emittance, loss coefficient, temperature coefficient, STC temperature, and packing factor. Thus, the module can be customized to replicate a product available on the market.

System Performance

The energy performance of the system can be computed in terms of thermal, electrical, and overall efficiencies (η_{th}, η_{eL}, $\eta_{overall}$). The electrical efficiency is calculated as the ratio between the power generated by the system (P_{el}) and the amount of solar radiation incident on the surface of the collector (AG_{irr}):

$$\eta_{el} = \frac{P_{el}}{AG_{irr}} \tag{2}$$

The standard equation for thermal efficiency is represented by the ratio between the amount of thermal energy generated by the system (Q_{th}) and the solar radiation incident on the surface of the collector (AG_{irr}):

$$\eta_{th} = \frac{Q_{th}}{AG_{irr}} = \frac{mC_f\left(T_{out} - T_{in}\right)}{AG_{irr}} \tag{3}$$

where m is the mass flow rate of the fluid (kg/s) and C_f is the specific heat capacity (J/(Kg°K)), which in this case for water is 4186 J/(Kg°K).

Another definition for the thermal efficiency was proposed by Bombarda et al. [18]. Here, a distinction is made between the electrical and thermal power of the system, and thus the electrical power production is subtracted from the total incident irradiation. This definition allows for a more accurate comparison between the thermal performance of a PVT and stand-alone solar thermal system.

$$\eta_{th^*} = \frac{Q_{th}}{AG_{irr} - P_{el}} = \frac{mC_f\left(T_{out} - T_{in}\right)}{AG_{irr} - P_{el}} = \frac{\eta_{th}}{1 - \eta_{el}} \tag{4}$$

From the point of view of the first law of thermodynamics, the global efficiency of the system(η_{GL}) can be calculated as the sum of the thermal and electrical efficiencies. This is also known as the first law efficiency:

$$\eta_{tot} = \eta_{el} + \eta_{th} \tag{5}$$

Another approach is to consider the difference in grade between the two types of energy, i.e., electrical energy is a higher form of energy compared to the thermal. Thus, due to the fact that a kW_{el} cannot be directly compared to a kW_{th}, some authors [19] propose the primary energy saving efficiency (η_{PES}) as a more accurate way of assessing the performance of the system:

$$\eta_{PES} = \eta_{th} + \frac{\eta_{el}}{\eta_{Tpower}} \tag{6}$$

where η_{Tpower} is the average efficiency of producing electrical power, and it depends on the country of reference. On average, it can be assumed to be 0.4 [20].

Results

Over a year, the weekly average thermal and electrical energy outputs are illustrated in Fig. 9, 10. Overall, the annual energy produced by the system in the two cities is summarized in Table 1. Assuming an annual electrical energy consumption of 3000 kWh and a thermal energy for DHW of 4200 kWh_{th}, the table also shows the percentage of coverage for the household. It can be observed that the system performs better under the meteorological conditions of Tehran, where it is capable of covering more than 50 % of the annual consumption. The results indicate that a 6 m^2 system would operate well in both climates, but with a 10–12 % better performance in Tehran.

Efficiency of system

Another investigated topic is the efficiency of the system in terms of electrical, thermal, and global performance. As discussed, the system performance can be described in multiple ways: First law efficiency and primary energy saving efficiency. The thermal efficiency was computed according to Equation (3), by subtracting the electrical power from the total incident irradiation. The monthly efficiency of the system is calculated by taking into account the total monthly energy production (shown in Fig. 11) and the total energy received from the sun to the surface of the panel during that week. Fig. 11 illustrates the monthly electrical and modified thermal efficiency of the system. It can

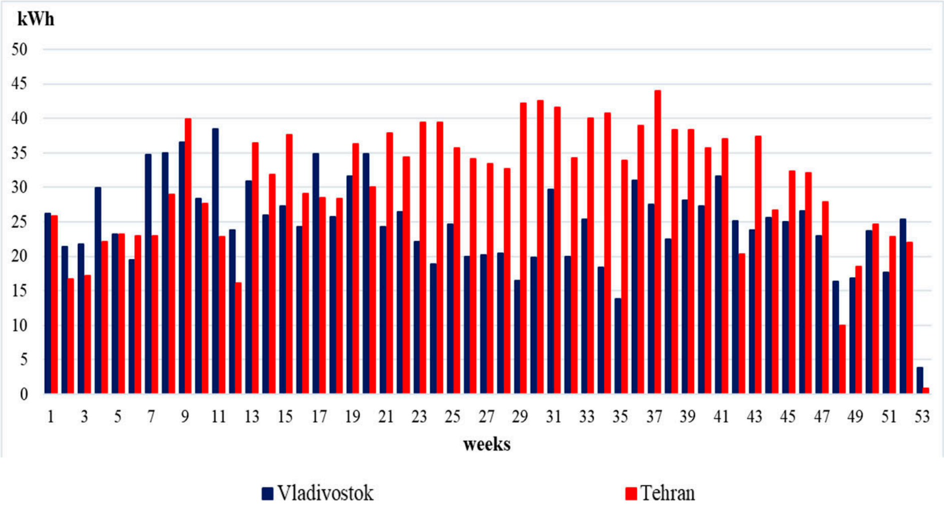

Fig. 9. Weekly thermal energy production of a year (kWh)

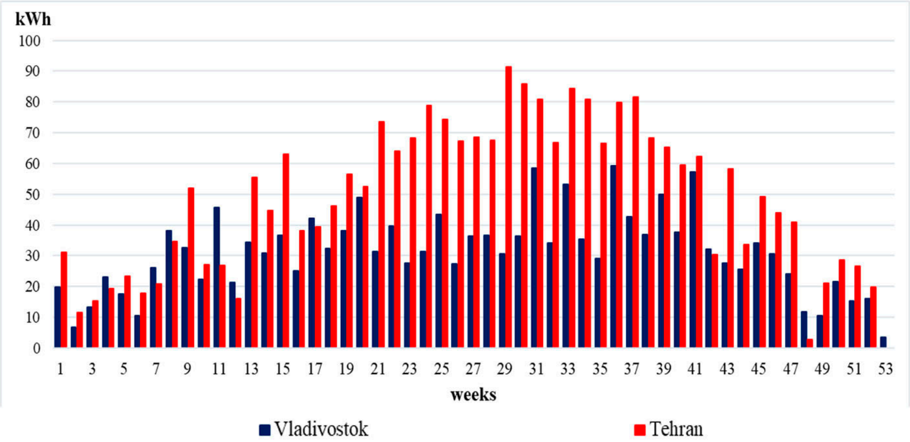

Fig. 10. Weekly electrical energy production of a year (kWh)

Table 1. Total annual energy output for the two different locations

Energy	Total annual output (kWh)	Percentage of consumption (%)
Thermal energy in Tehran	2580.97	61.45 %
Thermal energy in Vladivostok	1652.40	39.34 %
Electrical energy in Tehran	1615.03	50.46 %
Electrical energy in Vladivostok	1316.02	41.12 %

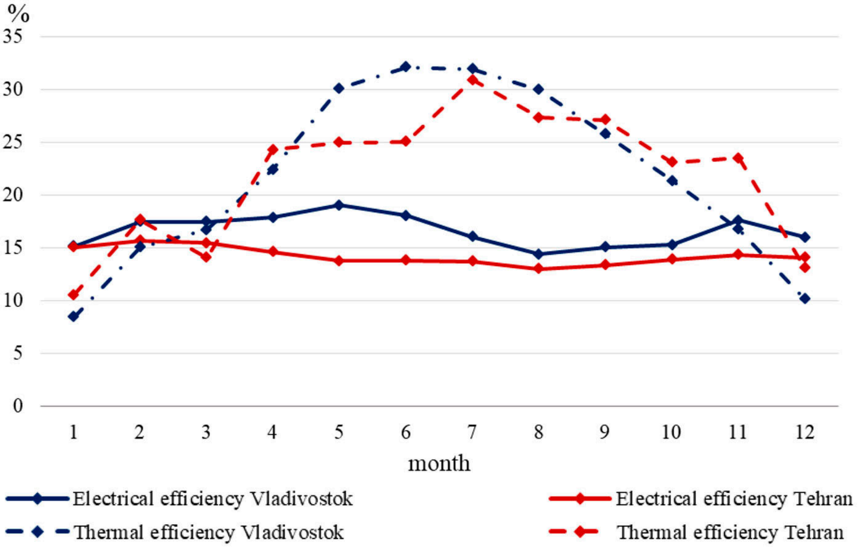

Fig. 11. Thermal and Electrical efficiency of system for different cities

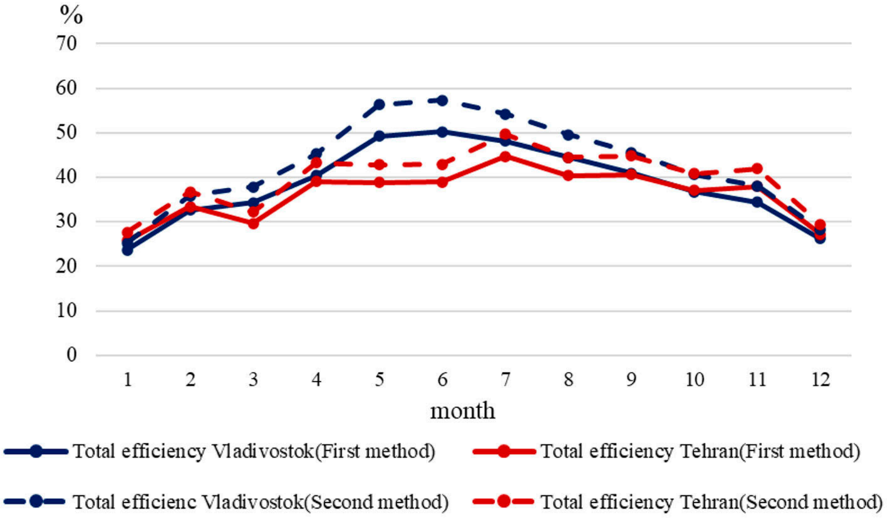

Fig. 12. Total efficiency of system for different cities in two methods

be observed that the electrical efficiency in both cases slightly drops during the summer, due to the increase in the operating temperature of the cells, while the thermal efficiency is at its maximum during the summer weeks.

The overall efficiency of the system is obtained as the sum of the electrical efficiency and the thermal efficiency of the system in both methods described in this article and is shown in Fig. 12. As shown in the diagram, the overall efficiency of the system in both cities increases in the hot seasons due to the increase in thermal efficiency.

The efficiency conversion of the incident solar energy into thermal and electrical energy, according to (Equation 3), is higher in the climatic conditions of Vladivostok.

Conclusion

This paper has performed a dynamic simulation of a PVT system for a small size domestic household using the software TRNSYS. The system includes both thermal and electrical storage, and is coupled to the simulated electrical and DHW demand of the household.

The results show that, with a battery storage system, the household demand can be 50.46 % covered in Tehran and 41.12 % in Vladivostok. Since the simulation is considered using H_2O as coolant, due to the climatic conditions in Vladivostok, 5 months of the year (from November to April), the PVT system produces only electrical energy. For year-round operation of the PVT system in Vladivostok, it is advisable to have an anti-freeze coolant. The PVT cooling system will provide 61.45 % hot water supply to an individual consumer in Iran throughout the year, and 39.34 % in Vladivostok.

Overall, it appears that PVT is a promising solution for maximal harvesting of the solar energy. Residential prosumers are the target market of this technology, which is quickly developing in the Western European countries, but is lagging behind in other countries. More public awareness and demonstrative projects providing proof of concept are required to further push this technology on the mainstream market, next to conventional PV and solar thermal. The system would be an interesting direction for further research about consideration of the CO_2 emission savings.

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