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Compensating energy demand of public transport and yielding green hydrogen with floating photovoltaic power plant

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ABSTRACT

The last three decades have seen a dramatic increase in the renewable energy sector as a result of increased human energy consumption and environmental concerns about fossil fuels. Offshore renewable energy sources are the most alluring and promising technologies because of more energy potential, less space, and visual restrictions than onshore ones. Among those, floating solar photovoltaic (FPV) has a remarkable reputation. The present study focuses on a viable way to replace energy resources derived from fossil fuels with renewable solar energy. In this regard, electrical energy demand is investigated where a floating photovoltaic system and integrated hydrogen production unit are employed on water surface of Yamula Dam. Energy demand of public trams would be compensated with electricity generated by FPV and rest of energy would be utilized for hydrogen production. Key results illustrated that in various scenarios, the energy generation amounts were around 31×10^6 kW, 32×10^6 kW, and 39×10^6 kW, while the energy consumption amounts were approximately 24×10^6 kW. It was evident that the energy created more than offset the amount consumed. It was also note that the total costs of entire system were \$94.1 M, \$78.5 M and \$71.2 M according to the different cases. It was also observed that in October and November, the remaining energy from the Bozankaya tram produced the most hydrogen with 125 kg, whereas in September and October, the remaining energy from the Sirio tram produced approximately 70 kg.

1. Introduction

In this part, the overview and literature studies will be handled. Also, the novelty of paper and its contribution to the literature will be highlighted in detail. Then, the paper organization will be mentioned to clearly understand at the rest of study.

1.1. Overview and literature studies

The biggest problem facing the 21st century is pollution, energy storage, carbon and greenhouse gas emission for both developed and developing countries (Bashir et al., 2022; Bashir et al., 2023). In this regard, the greenhouse gases (GHG) emissions reduction has been a top goal. As a result, efforts have been performed globally to reduce greenhouse gas emissions and limit the global average temperature increase to 3 °C over pre-industrial levels (Khan et al., 2015). Fossil fuels continue to provide the majority of the world's energy needs, which have risen recently as a result of both the population and the quickly expanding technological innovations. On the other hand, the usage of alternative energy sources is now required due to the world's rising need for energy and the quick depletion of fossil fuel reserves that they contain (Zhao et al., 2019). Research and development of renewable energy technology and strategies to optimize the advantages of renewable energy alternatives should continue to increase despite challenges such as pandemic concerns, recessions, etc. (Koca and Genc, 2020; Hüner and Telli, 2023). Solar, wind, geothermal, and hydropower as well as bioenergy are examples of renewable energy technologies and sources that can help to mitigate environmental pollution and the effects of climate change (Lau et al., 2012; Dalha et al., 2024a, 2024b). Therefore, it is clear that utilizing sustainable energy sources like solar energy is strongly motivated. One of the most practical sources of renewable energy is the solar energy, especially in light of recent improvements (Reichelstein and Yorston, 2013). The renewable energy option that is becoming increasingly competitive with traditional energy sources is photovoltaic systems. On the other hand, due to the erratic nature of solar energy, photovoltaic systems are unable to meet the day's

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energy needs. Hydrogen (H_2) is regarded as a sustainable and ecologically acceptable energy source when looking for an alternative option. To provide a sustainable, the hydrogenization can be introduced as an important smart energy solution. In recent years, hybrid energy systems powered by hydrogen energy have been employed to boost the dependability and continuity of renewable energy sources (Karami et al., 2014).

Related to H_2, it is regarded as an essential energy carrier among alternative energy technologies that can address issues including the depletion of oil and natural resources, climate change, and environmental pollution (Andrews and Shabani, 2012). It is a clean, effective, and eco-friendly source of energy (Veziroğlu and Şahi, 2008). Despite being abundant in nature, it cannot be used as a major energy source since it cannot live freely. Although H_2 is present in a variety of natural compounds, it cannot be utilized directly (Kapdan and Kargi, 2006). The two primary kinds of H_2 production methods are conventional and renewable energies (Holladay et al., 2009). In conventional processes, the fossil fuels such as coal and natural gas, have produce H_2 with hydrocarbon decomposition. Notwithstanding several techniques, water electrolysis is the most feasible method for producing H_2 from renewable energy sources (Daneshpour and Mehrpooya, 2018). In an electrolysis cell, there are three different types of electrolyzers. Alkaline, polymer electrolyte membrane (PEM), and solid oxide electrolyzer, respectively, employ liquid, acidic ionomer and solid oxide electrolyte (Smolinka et al., 2015).

In energy community, H_2 is manufactured by hybrid systems based on renewable energy, particularly solar energy, will most probably play a significant role in the future. The excess electricity produced by solar PV powers the electrolyzer and H_2 is produced in conjunction with the electrolysis of water. In recent years, both research on hydrogen and power generation from an intermittent energy such as solar and wind energy has been examined. An optimization investigation for an electricity and hydrogen production based upon wind energy was performed by Safari and Dincer (Safari and Dincer, 2018). In their study, the excessive electricity production was utilized for methane and hydrogen production. Nowotny et al. (Nowotny et al., 2014) study at the economic prediction of solar hydrogen production with a focus on key implementations and educational initiatives. A power management strategy was evolved by Dahbi et al. (Dahbi et al., 2018) so as to arrange for hydrogen production in the grid integrated PV system. The optimal creation of hydrogen is achieved by managing the water's flow. A hybrid system consisting of PV panels, wind turbine as well as a fuel cell (FC) was proposed by Alam and Gao (Alam and Gao, 2007). 80 kW PV array, 10 kW FC, 20 kW converter, 60 kW electrolyzer, 80 kW H2 tank and 20 kW wind turbine were designed by utilizing HOMER software. Their findings clearly pointed out that the sum of electricity production was annually 1.120.819 kWh/year.

1.2. Novelty of paper and study contributions

A floating PV (FPV) configuration was investigated in this study. The system was designed on water surface of Yamula Dam located in Kayseri province. Priority, the electricity production from proposed floating PV was utilized for two tram types working along tram lines as illustrated in Fig. 1. The excessive electricity was then utilized how much hydrogen production could be performed. A detailed glance to the literature, indicates several observational and research gaps, such as the following: (*i*) Researches on renewable energy source via floating PV for electricity and hydrogen production within the Kayseri province context have not been explored. (*ii*) Most of prior studies typically only investigated the design optimization renewable energies via HOMER-Pro, considering single objective such as finding optimum configuration of renewable energy or obtaining hydrogen production.

The present work has made the following significant contributions and its novelty so as to overcome the aforementioned shortcomings:

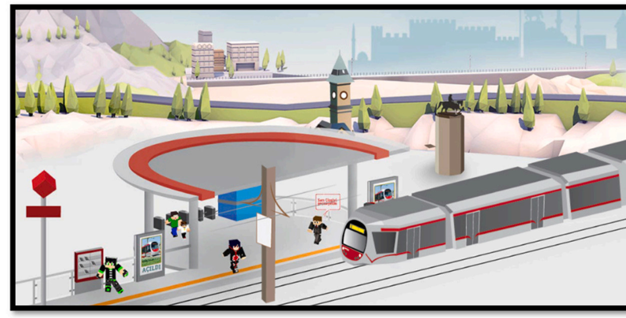

Fig. 1. The sketch of tram and its line in Kayseri province (Kayseri metropolitan municipality, 2023).

- To compensate for energy demands of public transport with electricity production via floating solar PV in Kayseri province.
- To yield green hydrogen with the rest of energy produced for trams and to store them.

1.3. Paper organization

To summarize the structure of the paper: Section 2 describes the methodological framework including study area, system description. the main results and discussions are recorded in Section 3. The most important conclusions, recommendations as well as future works of the study are condensed in Section 4.

2. Methodological framework

2.1. Study region

The proposed FPV plant were designed on the water surface of Yamula Dam located in Kayseri province as shown in Fig. 2. The location of Kayseri province was central of Türkiye and its populations were nearly 1.5 million. The reason of installing a FPV plant on this region can be threefold: (*i*) As mentioned earlier, two tram types as illustrated in Fig. 3 were working in that region (Tramvay – Bozankaya A.Ş., 2023; Vehicle database of AnsaldoBreda Sirio, 2023). The first reason is to compensate electricity consumption of those tram with the electricity production from proposed FPV. In this regard, the necessary data including energy consumption according to the months were provided by Kayseri Transportation Company. (*ii*) The second one is the cooling effects of water bodies for FPVs. According to the study presented by Elminshawy et al. (Elminshawy et al., 2022), the productivity of FPV plants was higher compared to solar PV plant which was installed on land since the FPV plant benefit the water body. (*iii*) The third one is to water saving. As seen in Fig. 4, the evaporation map was presented (Turkish State Meteorological Service, 2021). According to the map, south-east, central, western part of Türkiye as well as Mediterranean coastal exposed the evaporation amount more than another region. The installation of FPV lead to cover of basin partially. Additional advantages of this partial basin covering include a decrease in water evaporation. This is a significant benefit since it prevents more than 80 % of the covered surface evaporation, saving water more than 15,000 m3/year/ha (Rosa-Clot et al., 2017). Apart from those reasons, Kayseri is a developed city and people who live in the rural parts try to move by migrating in Kayseri. This led to energy demand to increase. Hereby, the installation of FPV would compensate for the energy needs.

2.2. System descriptions

In this part, detailed information and descriptions of HOMER-Pro software was provided.

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b)

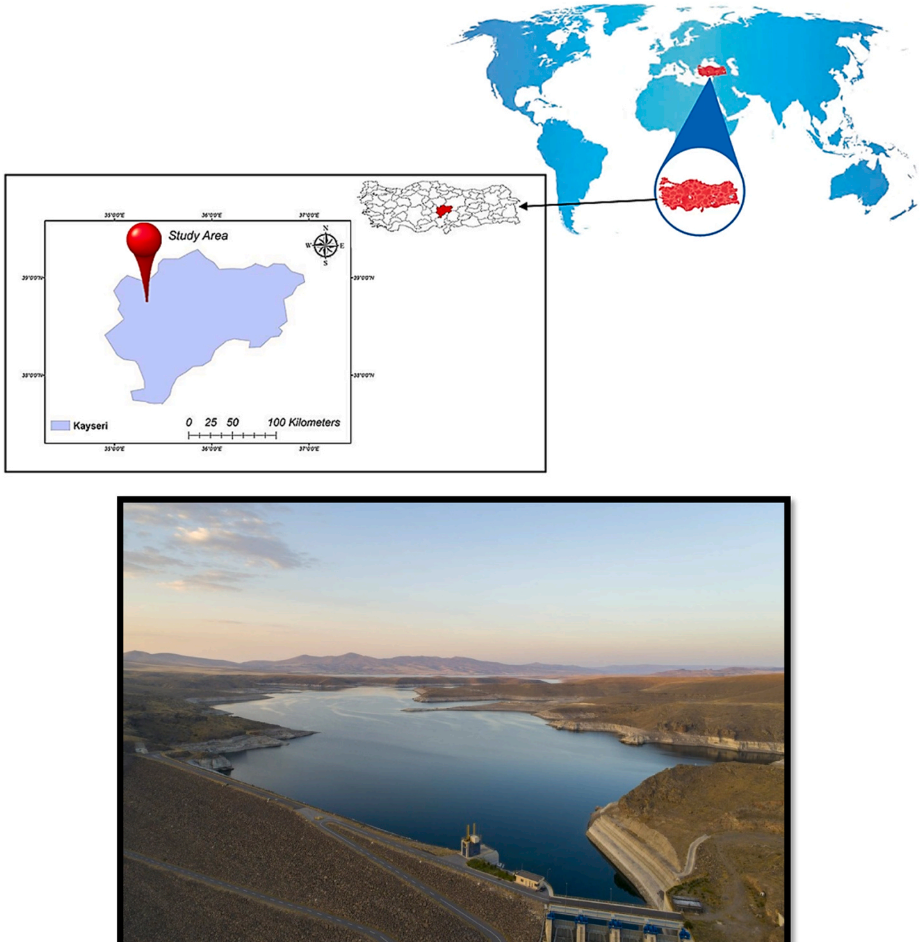

Fig. 2. a) The study region, b) The view of Yamula Dam for the proposed FPV.

a) b)

Fig. 3. The tram types in the line, a) Bozankaya, b) AnsaldoBreda Sirio.

2.2.1. HOMER-Pro configuration

A simulation and modeling program called Hybrid Optimization of Multiple Energy Resources (HOMER) is frequently utilized as a guideline for the best possible planning and evaluation of independent (Elmaadawy et al., 2020) and grid-connected energy systems (Jahangiri et al., 2019). These systems frequently support hourly thermal and electrical loads, encompassing any configuration of different parts such fuel cells (FC), hydrogen storage, wind turbines (WT), generators (GEN), electrolyzers, battery energy storage (BAT), and solar photovoltaic (PV) modules. Thanks to its stability, unified programming formation, and appealing user-interface, HOMER has been utilized in several energy studies as reviewed in (Bahramara et al., 2016; Weinand et al., 2020). A licensed version of HOMER-Pro Software program is available in KOCA Research Group.

The system's primary goals are to generate hydrogen, supply the electrical load for the trams, and slow down Yamula Dam's rate of evaporation. The system comprises, Electric Load, Hydrogen Tank, Electrolyzer, and Floating PV, as depicted in Fig. 5. FPV system generates power when solar energy becomes available. Generated electricity is utilized to power the load directly. If any more energy is available, an electrolyzer uses it in order to produce hydrogen. When solar energy is unavailable (due to cloud day, nights, etc.), produced hydrogen is stored in a hydrogen tank and utilized by a fuel cell to provide the necessary power. Because the FPV structure and modules shade a portion of the water, water evaporation will be reduced during both the charging and discharging phases.

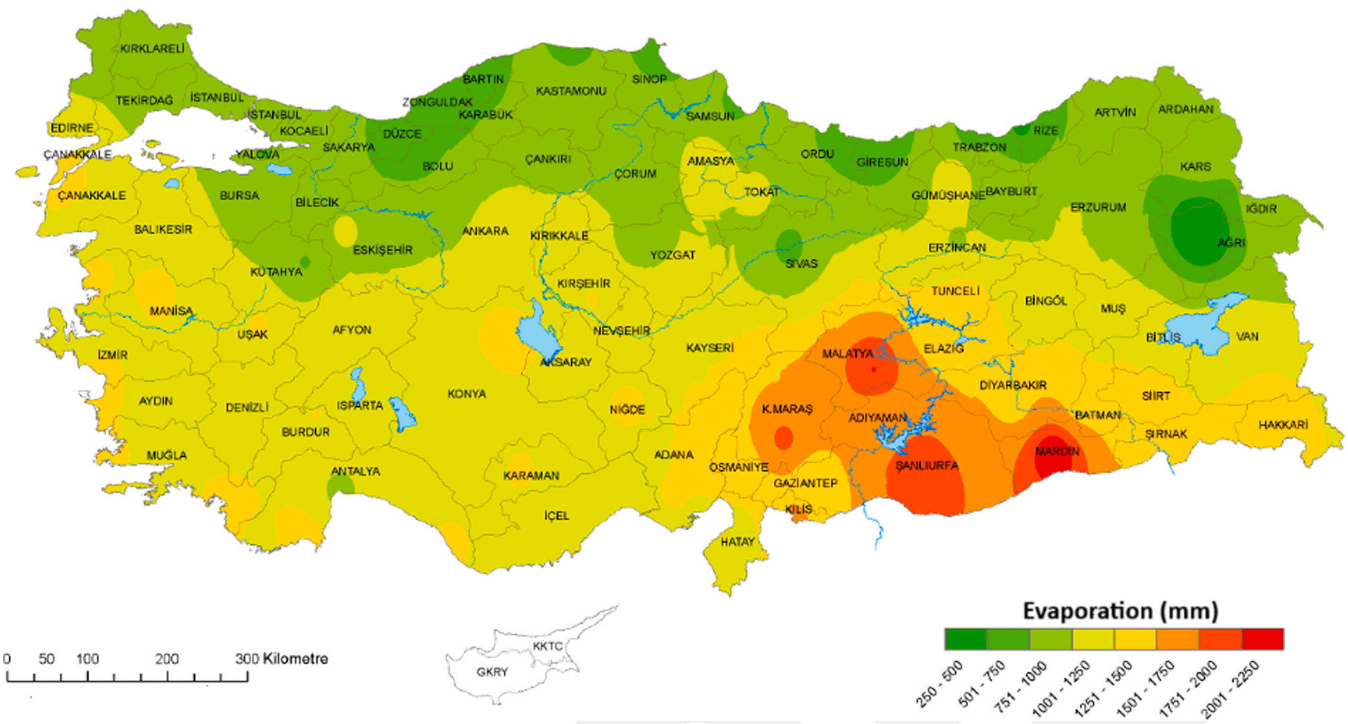

Fig. 4. Evaporation map between May and October.

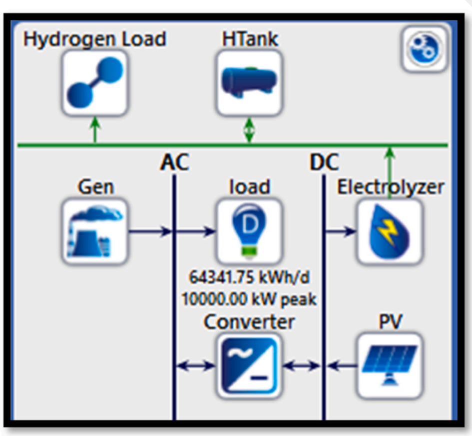

Fig. 5. System configuration.

2.2.2. *Data analysis*

As a data input for resources, Kayseri's sun radiation and monthly average solar data was evaluated. The location's solar energy potential was added to the system using HOMER software, which obtained the data from the NASA database based on the coordinates that were entered. The site's solar radiation and clarity index were illustrated in Fig. 6. After the calculations, the annual average solar radiation was found as 4.54 kw/m^2/day. It was clearly pointed out that December had the lowest sun radiation, whereas July had the highest solar radiation, making it the sunniest month. Further, in the summer, the site's clarity index was high. However, with the daily radiations of 2.18 kw/m^2/day and 1.87 kw/m^2/day, January and December were the months in Kayseri with the fewest daily hours of sunlight, respectively. Furthermore, the amount of energy consumed by trams according to days and months was provided by the Kayseri Metropolitan Municipality and Kayseri Transportation Incorporated Company.

2.2.3. *Research scenarios*

Related to the research scenarios, in system configuration of HOMER Pro, as first step, hydrogen tank with capacity of 1000 kg and electrolyzer with capacity of 300 kW were selected. Furthermore, the PVs with 3 different capacity power of 1 kW, 2 kW and 3 kW were respectively selected in order to investigate effects of generic flat plate PV in detail. It was observed that the sizes of generic flat plate PV and system converters were inherently increased since the capacity power of PVs increased. The detailed system designs belonging to PVs with capacity powers of 1 kW, 2 kW and 3 kW were denoted in Tablo 1. Additionally, the capacity powers of 1 kW, 2 kW and 3 kW were abbreviated and symbolized as C-1 (Case-1), C-2 (Case-2) and C-3 (Case-3), respectively. Table 1

Fig. 7 demonstrated annual trams' electricity usage by months. It was clearly noticed that the highest demand for trams' needs was in December, January and April, whilst the lowest demand was in May. In particular, the demand of fall and spring seasons were higher than summer period. This could be attributed to two reasons. (*i*) People could tend to utilize public transport to reach their work, (*ii*) There are 4 different (three of them are public, one of them is private) universities in Kayseri. Hence, in fall and spring semester, students are coming to Kayseri from different provinces. This naturally causes the population of Kayseri to be higher, making electricity demand of trams more.

3. Results and discussions

Herein, the findings such as electricity production/consumption, emission values, net present cost and the values of hydrogen production of the FPV design optimization for Kayseri province are shown and discussed.

Electricity production/consumption as well as emission values of different cases were illustrated as in Fig. 8 and Fig. 9, respectively. It was clearly pointed out that electricity production increased when higher capacity of PV was utilized in the system. The production amount of C-1 was approximately 31×10^6 kW, while those values were existed as nearly 32×10^6 kW and 39×10^6 kW for C-2 and C-3, respectively. On the other hand, numerical findings observed that the consumption amounts

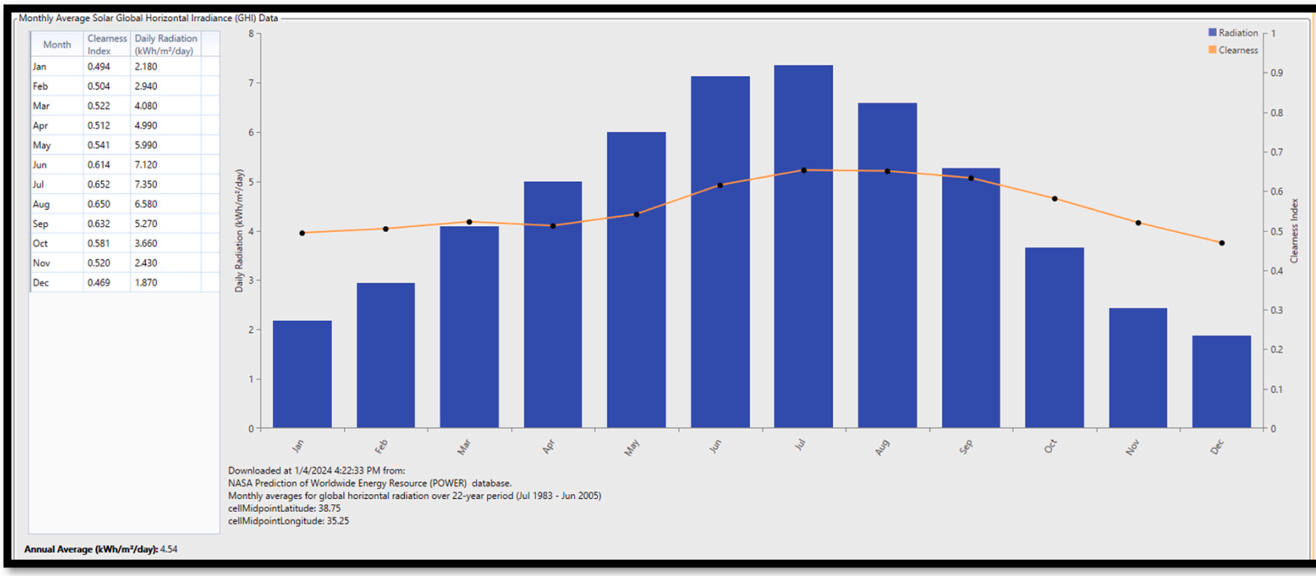

Fig. 6. Monthly average solar data of Kayseri province.

Table 1
System design of various scenarios.

Quantity	C-1	C-2	C-3
Generator (kW)	5000	5000	5000
PV (kW)	10493	15264	17426
System converter (kW)	6880	7379	7500
Electrolyzer (kW)	300	300	300
Hydrogen tank (kg)	1000	1000	1000

Fig. 7. The power demand of all trams by months.

of different versions were close between each other with approximate values of 24×10^6 kW.

The emission values of different cases were explained in Fig. 9 in which the principal portion was CO with the highest values for all cases, followed by NO and SO_2. It was pointed out that the emission values of CO were nearly 6×10^4 kg, 5.3×10^4 kg and 5.1×10^4 kg for C-1, C-2 and C-3, respectively. For NO, it was seen that those values were approximately 5.8×10^4 kg, 5×10^4 kg and 4.8×10^4 kg. With the lowest values, SO_2 was 2.2×10^4 kg, 1.9×10^4 kg and 1.8×10^4 kg. Moreover, those results strongly suggested that raising the generic PV's capacity power allowed all emission levels to progressively decline.

Fig. 10 demonstrated the generic flat plate PV output values and distributions for different capacity power in this study. In first detailed glance, it was noticed that electricity from generic PV was generated between 7:00 am-18:00 pm for all cases. Furthermore, peak generation was obtained when time was approximately 12:00 am since the sun's rays begun to come perpendicular to the earth surface. Also, at the core region of graphs, amounts of fluctuations and their dense were higher than other regions since those dates coincided with the summer periods. On the other hand, the amounts of electricity generated varied when their legends were thoroughly considered. For instance, peak value of C-1 was around 12,000 kW, while those values were nearly 16,000 kW and 20,000 kW for C-2 and C-3, respectively. This clearly denoted that more energy output was inherently obtained when more capacity power of generic PV was utilized.

The values of hydrogen tank levels were presented in Fig. 11. These graphs implied how many kg hydrogens could be stored yearly. As focused on graph of C-1, it was seen that hydrogen storage of first 4 months was nearly 600 kg. After 4th month until 10th month, it was observed that the hydrogen storage capacity increased until 1000 kg. For graphs of C-2 and C-3, the hydrogen storage was fulfilled at first 2 months with approximately 600 kg again. However, there was a remarkable result in this time. The optimization findings clearly pointed out that enhancing capacity power of generic PV provided the hydrogen tank to store more hydrogen amount for more days. On the other hand, it was observed that there was not any change on an hourly basis for all cases.

The summary of net present cost for every item of different cases was described in Table 2, Table 3 and Table 4. As a first glance, the principal portion went to the initial capital costs of renewable component such as Generic PV, followed by the operating costs. Further, it was observed that the initial capital costs of renewable component decreased when capacity powers of Generic PV increased, simultaneously. Concerning the system converter, the net cost composed of the initial capital cost with \$2.06 M, followed by the replacement of with \$875,638 for C-1. On the other hand, the essential portion of all systems went to the cost of resource with \$49.9 M, followed by the initial capital, operating and replacements costs, respectively. It was pronouncedly noticed that the total costs of all system were \$94.1 M, \$78.5 M and \$71.2 M for C-1, C-2 and C-3, respectively. This suggested that increasing the renewable component's capacity power progressively reduced the overall cost of the entire system.

As mentioned earlier, the principal objective of present study was to generate electricity from FPV so as to compensate the demand of public transport in Kayseri province. The secondary objective of this study was to produce hydrogen with the remaining energy from compensated energy demand of public transport. In this respect, Fig. 12 and Fig. 13 demonstrated that hydrogen production with the remaining energy generated by FPV for Bozankaya and Sirio types of trams, respectively.

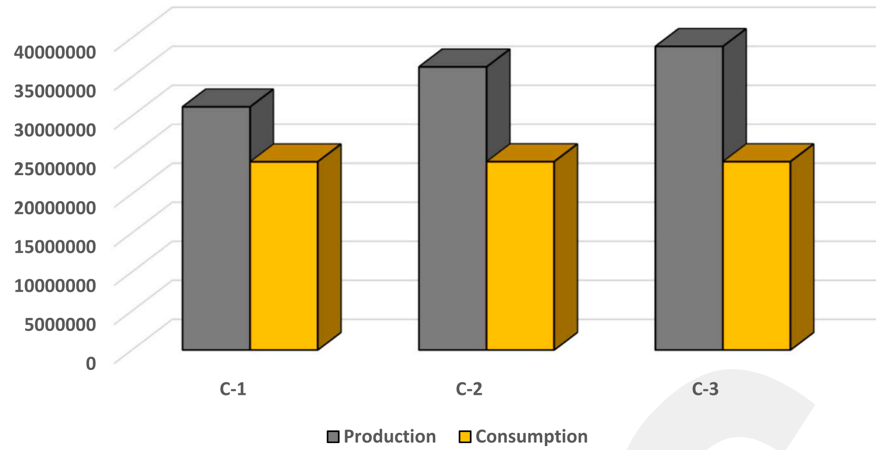

Fig. 8. Electricity production and consumption values of different cases (unit is kW).

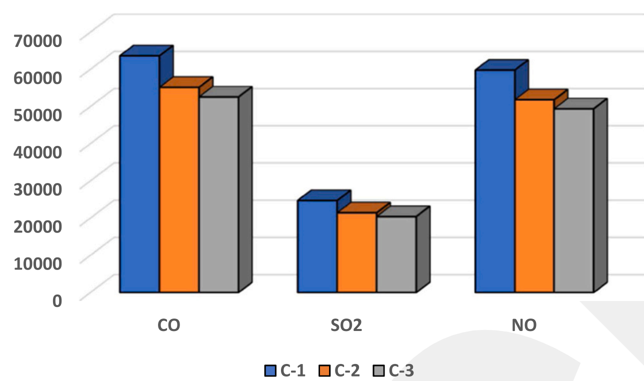

Fig. 9. Emission values of different versions (unit is kg).

For Bozankaya tram, it was seen that hydrogen production started with second month and continued for all months. It was noted that peak generation of hydrogen was October and November with 125 kg. Moreover, production increased gradually first 9 months. In what follows, with regards to Sirio tram, it was observed that there was not any hydrogen generation first 4 months. However, after 4th month, hydrogen production started with approximately 8 kg and reached the maximum value with nearly 70 kg in September and October. Additionally, it was clearly noticed that total hydrogen production for Bozankaya tram was higher than those occurred for Sirio tram. This was most probably due to fact that Sirio tram was using for public transport more than Bozankaya one during year, resulting in less remaining energy from FPV.

4. Conclusion

The current study set out to investigate practical methods of substituting renewable solar energy for energy resources produced from fossil fuels, with the goal of offsetting the energy consumption of public transportation in the province of Kayseri. Thereupon, a floating photovoltaic system and integrated hydrogen production unit were simulated and assessed on water surface of Yamula Dam. Foremost, the power produced by FPV would be used to offset the energy demand of public trams, with the remaining energy being used to produce hydrogen. The key findings were provided as follows:

- The energy generations were almost 31×10^6 kW, 32×10^6 kW and 39×10^6 kW for C-1, C-2 and C-3, whilst the energy consumption amounts of various cases were nearly 24×10^6 kW. It was clearly

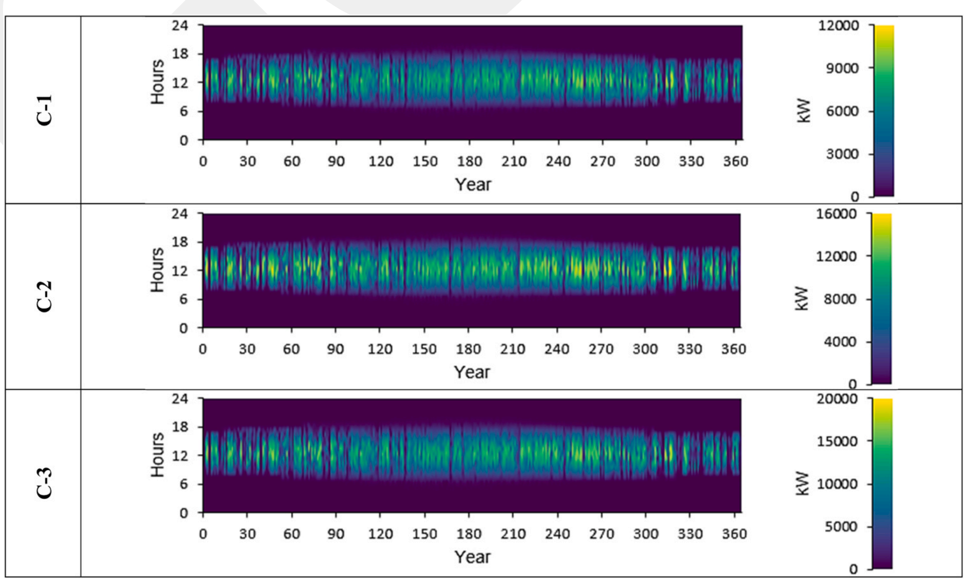

Fig. 10. Generic flat plate PV output values and distributions.

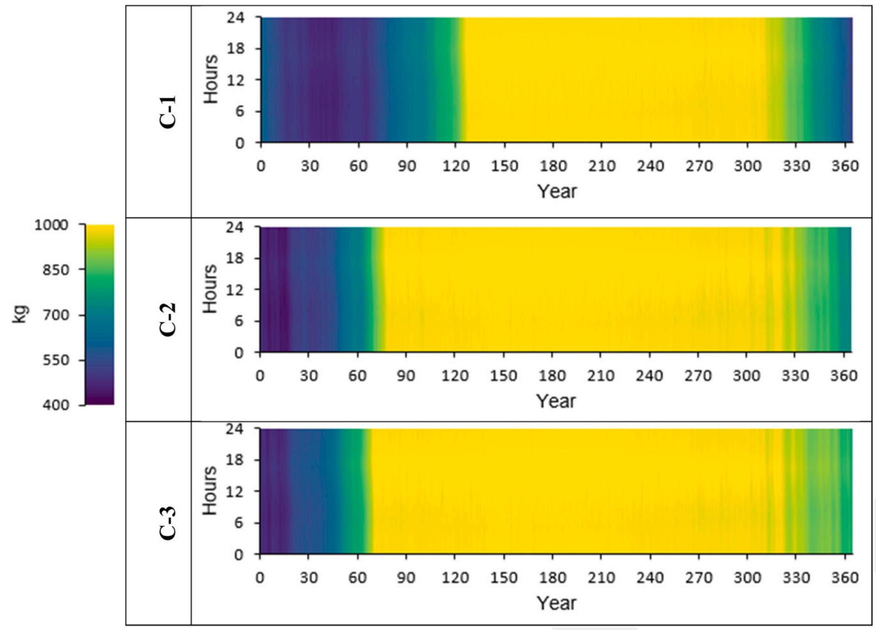

Fig. 11. Values of hydrogen tank levels.

Tablo 2
Net present cost of C-1.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Autosize Genset	$2.50 M	$6.00 M	$5.87 M	-$506,066	$49.9 M	$63.7 M
Generic PV	$26.2 M	$1.36 M	$0.00	$0.00	$0.00	$27.6 M
System converter	$2.06 M	$0.00	$875,638	-$164,804	$0.00	$2.77 M
System	$30.8 M	$7.35 M	$6.74 M	-$670,870	$49.9 M	**$94.1 M**

Tablo 3
Net present cost of C-2.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Autosize Genset	$2.50 M	$5.23 M	$4.81 M	-$303,440	$43.2 M	$55.4 M
Generic PV	$19.1 M	$986,658	$0.00	$0.00	$0.00	$20.1 M
System converter	$2.21 M	$0.00	$939,266	-$176,779	$0.00	$2.98 M
System	$23.8 M	$6.21 M	$5.75 M	-$480,219	$43.2 M	**$78.5 M**

Tablo 4
Net present cost of C-3.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Autosize Genset	$2.50 M	$4.99 M	$4.66 M	-$424,217	$41.2 M	$52.9 M
Generic PV	$14.5 M	$750,915	$0.00	$0.00	$0.00	$15.3 M
System converter	$2.25 M	$0.00	$954,680	-$179,680	$0.00	$3.03 M
System	$19.3 M	$5.74 M	$5.61 M	-$603,897	$41.2 M	**$71.2 M**

showed that generated energy compensated the consumption amount well.

- Concerning the hydrogen storage, it was seen that it was stored with different amount with changing of hours a day and month. Further, increasing the general PV system's power capacity allowed for the hydrogen tank to hold more hydrogen for longer periods of time.
- About financial analysis, the results of net present cost clearly revealed that, the initial capital expenses of the renewable component fell with a rise in the capacity powers of Generic PV. It was also important note that the total costs of all system were $94.1 M, $78.5 M and $71.2 M for C-1, C-2 and C-3, respectively. The total cost of the entire system was reduced when the capacity power of renewable component increased gradually.
- Hydrogen production with the remaining energy generated via FPV for different types of trams was fulfilled. It was noticed that the maximum hydrogen generation with 125 kg was seen for Bozankaya tram in October and November, while it was nearly 70 kg for Sirio tram in September and October.

Given that the displayed results were in good agreement with certain comparable research in the literature, it can be concluded that the given approach can be employed effectively for the modeling of FPVs. For future works, research may be focused on evaporation of water, ecological impacts of placing solar panels on water bodies, cooling mechanisms, floating structure effects, etc. This research study will elucidate compensating energy demand issue for this local region and

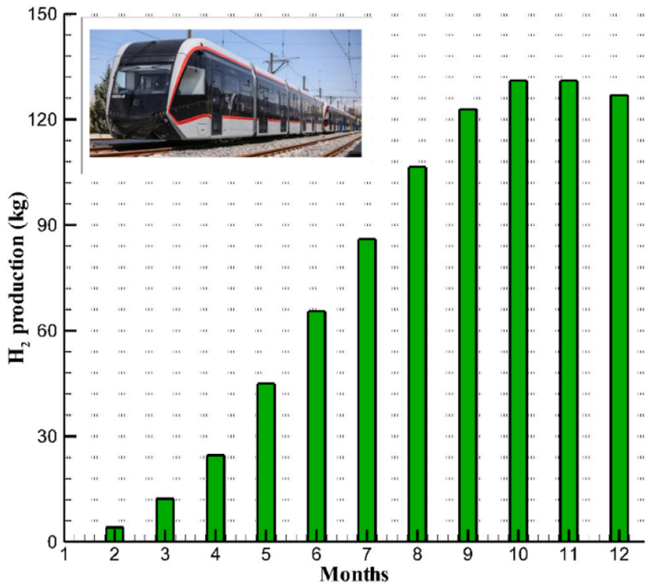

Fig. 12. Hydrogen production with the remaining energy for Bozankaya tram.

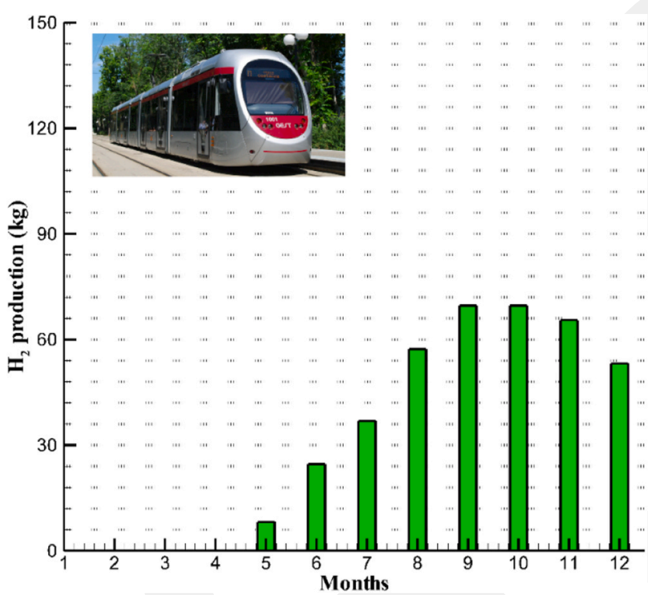

Fig. 13. Hydrogen production with the remaining energy for Sirio tram.

entire of Türkiye by providing an alternative and innovative energy solution.

CRediT authorship contribution statement

Kemal Koca: Conceptualization, Investigation, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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