Development and assessment of renewable hydrogen production and natural gas blending systems for use in different locations

Fatih Sorgulu¹ | Ibrahim Dincer¹,²

¹Faculty of Mechanical Engineering, Yildiz Technical University, Besiktas, Istanbul, Turkey
²Faculty of Engineering and Applied Science, Ontario Tech University, Oshawa, Ontario, Canada

Abstract
In this study, a thermoeconomic assessment of renewable energy-based hydrogen generation and blending it with natural gas in the existing pipeline system is performed for various locations. Selected locations are compared in energy content, environmental impact, and cost. In this regard, solar photovoltaic panels and wind turbines are integrated with electrolyzers along with the reverse osmosis units. The clean hydrogen produced by the electrolyzers is then blended with natural gas and utilized for residential applications in an environmentally benign way. Also, the heat required for a community consisting of 100 houses is provided by a boiler by hydrogen and natural gas blend as fuel. The costs of capital, fuel, operation and maintenance are calculated and comparatively evaluated. The results show that the total net present costs for the integrated systems are calculated to be between $3.01 million and $4.36 million in the selected five different locations. Furthermore, an environmental impact assessment is conducted in terms of carbon monoxide, carbon dioxide, nitrogen oxides, unburned hydrocarbons, and particulate matter. Finally, the CO₂ emissions are calculated to be varying from 443.2 to 491.9 tons/year.

KEYWORDS
cost, efficiency, emissions, hydrogen, natural gas, solar energy, wind energy

1 | INTRODUCTION
Sustainable solutions in terms of energy, cost, and the environment are required to overcome the increasing energy demand. Providing diversity in energy systems to obtain sustainable electricity, heat, and fresh water is recognized vital than ever before. Energy reliability can also be provided by employing various renewable energy sources, systems, and integrating energy storage options. CO, CO₂, SO₂, NOx emissions, and unburned hydrocarbons are recognized as the primary environmental problems. Many studies are conducted to deal with these problems as environmental awareness increases. Since fossil fuel combustion produces these gases, using them wisely by integrating renewable energy and storage options is critical. Innovative studies are required to develop energy storage options such as salt caves (using power-to-gas and compressed air energy storage).¹ Here, hydrogen blending into existing natural gas pipelines is considered a promising way to store hydrogen.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2022 The Authors. Energy Science & Engineering published by the Society of Chemical Industry and John Wiley & Sons Ltd.
Daily natural gas consumption in Turkey in 2020 is given in Figure 1. In Turkey, total yearly consumption was 47.7 billion Sm³ (with an increase of 6.4% from the previous year). Natural gas is currently used for electricity and heating for residential, commercial, and institutional purposes. Natural gas, coal, and oil are still used to meet a ratio of more than 80% of global energy demands. Last year, in Turkey, while 32.3% of natural gas is utilized for residential use, 28.6% of it was used to produce electricity. 12.74 billion Sm³ of natural gas which is 26.7% of the total consumption is used in industry. The rest of natural gas is used for institutional needs. In Canada, 67% of electricity production is provided by renewable energy sources. Moreover, 15% of the electricity production is supplied by 19 nuclear reactors located in the country. The rest of the electricity, which is corresponding to 18%, comes from greenhouse gas-emitting sources. In the world, total natural gas usage was 38,000 TWh in 2020, which is equal to 3.5 trillion Nm³, even though felling 81 billion cubic meters (by considering the lower heating value of natural gas as 39 MJ/m³). Here, for the natural gas at atmospheric pressure, while the normal cubic meter (Nm³) is used for 0°C, the standard cubic meter (Sm³) is used for 20°C, respectively. As of July 2021, in Turkey, a total installed power of 98 GW has been reached, of which 26 GW is the natural gas power plant. In 2020, 68.07 TWh of electricity was produced with natural gas power plants. Besides, 38.3 TWh electricity which is 13% of the total electricity production is provided by renewables including solar, wind, biomass, geothermal, and excluding hydropower. There are many studies and research for renewable energy and hydrogen-based systems even in countries that have great fossil fuel reserves. Okonkwo et al. prepared a sustainable hydrogen roadmap for the production, utilization, and exportation of hydrogen in Qatar. They evaluated alternative scenarios including hydrogen and natural gas blend by utilizing it for commercial and residential heating.

Environmental concerns that emerged with the understanding of the negative effects of human beings on the environment forced decision-makers to make urgent climate plans to reduce greenhouse gas emissions (GHG). The negative effects of natural gas combustion can be reduced by enriching its content and using it in sustainable systems. The natural gas network has a significant role in terms of both electricity and heat in Turkey as well as all over the world. Much work is being done to improve the use of natural gas, including blending hydrogen into natural gas. Hydrogen, produced by renewable energy sources, injection into the natural gas pipeline is an environmentally benign way and a solution to use natural gas sources wisely. Higher efficiencies and lower emissions can be achieved by hydrogen and natural gas blend. Besides lower toxic CO emissions can also be achieved by hydrogen and natural gas blend-based systems. Duan et al. performed an experimental study to analyze the impact of hydrogen enrichment on a natural gas spark-ignition engine. They determined the decrease of the combustion duration with the increasing hydrogen amount in the blend. Hydrogen does not contain carbon and thus generates carbon-free emissions while combusted.

The role of renewable energies is recognized as a crucial step to improve the relationships with the environment, and as an energy carrier, hydrogen shows a distinct promise for reducing the environmental impact of energy systems. Injecting hydrogen into pipelines is one of the most efficient ways to use hydrogen, given the difficulties in the transmission and storage of hydrogen. Furthermore, the natural gas networks already exist in many developed countries. Hydrogen generation by using excess electricity obtained from wind and solar farms is becoming a more common and promising option as an energy storage way. Existing gas infrastructure is recognized as one of the economical and efficient methods for the efficient use of hydrogen. Hydrogen has the capacity to play a significant role in providing heat, transport, and power system services alongside electricity in a low carbon economy. Hydrogen can be burned directly and without producing CO₂ in engines and boilers, or it can be used to generate electricity in fuel cells. Hydrogen technologies, especially fuel cells, provide a stabilizing, controllable capacity as a solution to the problem of intermittent renewable energy sources. In addition to managing short-term dynamics, converting electricity to hydrogen or other fuels can provide long-term storage. Both capital and O&M costs are getting decreased as the high technology-readiness level is achieved.
Renewable energy-based integrated systems, particularly solar and wind sources, are utilized to produce electricity, heating, cooling, fresh water, and fuel for portable and stationary systems, communities, and industries. While solar energy is converted sunlight into electricity by a solar photovoltaic (PV) panel, wind energy is converted into mechanical energy and finally into electricity by a wind turbine. These abundant and unlimited solar and wind energy sources should be converted to a useful form. Solar PV panels are constructed module by module to meet the energy requirement. PV panel installations in the institutional, commercial, residential, and industrial sectors increased rapidly over the last decade. Developments in technology have caused PV panel usage to become an increasing trend. Solar PV panels and wind turbines have been operated for years with increasing interest. The electricity produced by the wind turbine is distributed for residential, commercial, and industrial use. Mostly at night, when electricity demand is low and wind speed is high, a storage system should be integrated.

Multi-generational systems are preferred to utilize the resources wisely by increasing efficiencies and decreasing costs and emissions. Fresh water may be obtained by integrating distillation, osmosis, freeze-thaw, and electrodialysis membrane subsystems by utilizing electricity and heat. Particularly distillation and reverse osmosis units are widely used to produce fresh water. One may note that fresh water is essential to maintain life to utilize for municipal, domestic, irrigation, public services, and commercial purposes. According to the United Nations, global fresh water usage increased to around 3.9 trillion m³/year. After the 2000s, the increase of fresh water use slowed with developing innovative technologies, mainly on irrigation. Globally, 70% of water is used for agriculture. However, fresh water usage increases with the increasing population. Fresh water usage rates of BRICS countries (with 39.6% of the world population), OECD countries (17.56% of the world population), and the rest of the world (with 42.84% of the world population) are 44%, 31.68%, and 24.32%, respectively. Reverse osmosis units, which are employed to separate pressurized seawater into fresh water and brine or wastes, are widely used to produce fresh water. Innovative studies are required to deal with drinkable water shortage.

Seyam et al. conducted comprehensive analyses for a hybrid combined locomotive powering system for rail transportation. They chose five alternative fuels including hydrogen and natural gas blend (NG—75% and H₂—25%) as the best option in terms of cost and environmental impact. Risk-based scheduling of a renewable energy-based hybrid refueling station is performed by Xu et al. They provided off-grid hybrid hydrogen and natural gas refueling station is proposed. Sorgulu and Dincer performed an analysis on hydrogen and methane production, blending, and utilization for an integrated system. They performed an assessment of the integrated system through energy and exergy efficiencies. They calculated the decrease of emissions and the increase of the efficiencies. Baltacoglu et al. conducted a study on hydrogen and natural gas blend. They fed the blend in a diesel engine as fuel with a volumetric flow rate of 20 liters/min (with a volumetric fraction of 20% hydrogen and 80% natural gas). They calculated both energy efficiency and specific fuel consumption values. Using biodiesel enriched with hydrogen and natural gas blend, the effects on the performance, particularly on the energy efficiency, are examined. A comparison between diesel fuel and hydrogen and natural gas blends is presented.

de Santoli et al. conducted an experimental study and analysis together on a hydrogen and natural gas blend-based combined heat and power (CHP) system. They described the thermo-physical properties when fuel is burned with enriched air. They fed hydrogen and natural gas blend unconventionally. They calculated electrical and heat recovery efficiencies and emissions. Arsalis et al. performed a study on a gas turbine cycle by utilizing a hydrogen and natural gas blend as fuel. They evaluated the system to define its exergetic efficiency. They calculated the increase of efficiency with the rise in hydrogen rate in the blend. They calculated CO₂ emissions to compare the system in terms of the environment. They defined the decrease of CO₂ emissions as 6.1% with the blend of 10% of hydrogen rate. Finally, they examined parametric studies to the effect of hydrogen rate on system performance.

Although there have been many studies on the combustion of hydrogen and natural gas alone, a limited number of investigations on producing clean hydrogen, blending with natural gas and testing the performance are presented in the open literature. In this particular study, cost and environmental impact analyses on clean hydrogen production and injection into natural gas pipelines for different cities in Turkey are presented. Thermodynamic, environmental impact, and cost assessment studies are undertaken for five different cities, including the location of the laboratory in Konya. In addition, the cities of Istanbul, Antalya, Trabzon and Van are selected for the assessment from the west, south, north and east parts of Turkey, respectively. The data obtained from the studies conducted within the experimental project for improving the performance of natural gas systems with clean
hydrogen injection were used. The data from solar PV panels and wind turbines, which are the main power suppliers in the laboratory, are utilized for calculations. The hydrogen produced by alkaline electrolysers is injected into natural gas and supplied to gas cooktops and combi boilers. In this novel system, the hydrogen and natural gas blend is offered as a promising fuel for a better environment by comparing integrated systems located in various locations.

2 | SYSTEM DESCRIPTION

Wind turbines, solar PV panels, gas engines, boilers and reverse osmosis units are utilized to produce electricity, heat, and fresh water. The data such as heating values (of natural gas and blend), and cost parameters (of electrolyzer, PV panels, wind turbine, reverse osmosis unit) are obtained from our experimental equipment and studies. In this regard, the composition of natural gas used in the residential area is utilized for calculation. The heating value and density of the natural gas are obtained from the natural gas distribution company. In the laboratory, established in the Technical Center of the Natural Gas Distribution Companies Association (GAZBIR-GAZMER) in Konya, Turkey, hydrogen is produced by an alkaline water electrolyzer unit. The electricity required for the electrolyzer is provided by solar PV panels and a wind turbine. The electricity required for the other equipment in the laboratory is also met with PV panels and the wind turbine. With this project, for the first time in Turkey, blending natural gas with hydrogen and feeding it to domestic appliances was implemented.

A schematic illustration of the integrated system including subsystems is given in Figure 2. The electrolyzer is also considered to produce hydrogen. Here, hydrogen is injected into natural gas and utilized in gas engines and boilers. Thermoeconomic assessment of the integrated system is performed utilizing Engineering Equation Solver (EES) software. Environmental impact and cost assessments are conducted by the Hybrid Optimization of Multiple Energy Resources (HOMER Pro) software. The HOMER Pro software simulation scheme considered for the comparison is provided in Figure 3.

The average daily electricity consumption of the community consisting of 100 houses is considered as 838.3 kWh. In addition to the electricity requirement for the community, 89.8 kWh electricity is utilized for the reverse osmosis unit to produce 30 m³ fresh water. Average solar radiations and wind speeds for the selected locations are given in Figures 4 and 5. For five locations daily average solar global horizontal irradiation (GHI) and wind speed are determined as 4.32 kWh/m² and 4.35 m/s. In June and July, Konya, Antalya, and Van have higher solar radiation with a value of over 7.1 kWh/m². In December, January, and February, Istanbul has the highest wind speed with around 7 m/s.

The average daily temperatures and clearness indexes for the selected locations are shown in Figure 6. The yearly average temperatures are listed as 11.3°C, 14.5°C, 18.2°C, 9.0°C and 8.4°C for Konya, Istanbul, Antalya, Trabzon, and Van, respectively. Antalya has the highest temperatures in July and August at over 28°C. Van has the lowest temperature with a value of −6°C in January. The clearness index, which is a measure of the clearness of the atmosphere and defined as the surface radiation...
divided by the extraterrestrial radiation, is also determined. Istanbul and Trabzon have the lowest clearness index due to cloudy weather. Even in the summer season, Trabzon has a clearness index below the average.

3 | ANALYSIS AND ASSESSMENT

An experimentally set hydrogen injection into the natural gas project is operated in Konya, Turkey. In the laboratory, solar PV panels and wind turbines are utilized to produce electricity for devices, mainly for an electrolyzer. Hydrogen produced by the electrolyzer from the fresh water coming from the reverse osmosis unit is blended with natural gas at the desired volumetric ratios. Hydrogen and natural gas blend is fed into the gas cooktop and the combi boiler unit. The data obtained in the laboratory are utilized in the calculations for this particular study. The composition of natural gas and physical properties used in calculations are given in Table 1. Here, four locations are considered and compared with the laboratory location. Thermoeconomic and environmental impact assessments are conducted by HOMER Pro software.18 A thermodynamic analysis in terms of energy and exergy approaches is performed and solved by utilizing the EES software.17 The total amount of natural gas, blend, and heat power required for the community are given in Figure 7. Here, the calculations are further performed for the same amount of heat power requirements. Moreover, the gas consumption data required for the community are collected from the local natural gas distribution company. For the same amount of power, the difference between the amount of natural gas and the blend are clearly seen in Figure 7.

The financial parameters such as nominal discount rate, real discount rate, expected inflation rate, real interest rate are given in Table 2. The real and nominal discount rates are taken as 5.88% and 8.0%, respectively. Levelized cost of energy (COE), which is defined as the average cost per kWh of usable electrical energy

![HOMER simulation schemes for the hydrogen and natural gas blend-based system](image3)

![The averaged monthly solar radiation values for the selected locations](image4)
produced by the system, can be described by dividing the annualized cost of electricity by the total electric load served, using the following equation:

$$COE = \frac{C_{\text{ann, tot}} - c_{\text{boiler}}H_{\text{served}}}{E_{\text{served}}}.$$  \hspace{1cm} (1)

Here, $C$ refers to cost. ann and tot are subscripts for annualized and total. $H$ and $E$ are the total thermal load and the total electrical load, respectively. The total annualized cost of the system can be described by considering project lifetime ($N$) as follows:

$$C_{\text{ann, tot}} = CRF(i, N)C_{\text{NPV, tot}}.$$  \hspace{1cm} (2)
where \( NPC \) represents the net present cost. \( CRF(i, N) \) is the function of returning the capital recovery factor which is utilized to calculate the current value of an annuity and can be defined as follows:

\[
CRF(i, N) = \frac{i(1 + i)^N}{(1 + i)^N - 1}.
\] (3)

Here, \( i \) is the annual real discount rate which is used to convert between annualized costs and one-time costs to calculate annualized costs and discount factors from net present costs. The annual real discount rate can be described by considering the expected inflation rate \( (f) \) as follows:

\[
i = i' - f \frac{1}{1 + f}.
\] (4)

Here, \( i' \) is the nominal discount rate, which is used to consider the borrowed money. The expected inflation rate is determined as 2.0%. The total net present cost can be calculated as follows:

\[
NPC_{tot} = \sum_{N=1}^{N} f_{d,N} (C_{cap} + C_{rep} + C_{main} - C_s).
\] (5)

TABLE 2 Some financial parameters

| Parameters            | Value |
|-----------------------|-------|
| Nominal discount rate | 8.0%  |
| Real discount rate    | 5.88% |
| Expected inflation rate | 2.0% |
| Real interest rate    | 5.9%  |

A commercially available solar PV panel with a capital cost of 800 $/kW is considered for the integrated system. The clearness index, which is a ratio of the monthly average radiation on the horizontal surface of the earth \( (H_{ave}) \) and the radiation on a horizontal surface.

FIGURE 7 Total amounts and capacities of natural gas, blend and heat power required for the community.

TABLE 3 The technical and economic parameters of the selected horizontal-axis wind turbine

| Parameters          | Unit | Value |
|---------------------|------|-------|
| Rotor diameter      | m    | 2.375 |
| Number of blades    | -    | 3     |
| Hub height          | m    | 12    |
| Nominal speed       | m/s  | 10    |
| Capital cost        | $/kW | 12,500|
| Replacement cost    | $/kW | 10,000|
| Turbine lifespan    | year | 30    |
| O&M cost            | $/year | 20   |

TABLE 3 The technical and economic parameters of the selected horizontal-axis wind turbine

Here, \( A_r \) refers to the swept area of the rotor. The net power generated by the wind turbine can be calculated by considering power coefficient, mechanical efficiency, and the efficiency of the generator as follows:

\[
\hat{W}_{gen} = c_p \eta_{mech} \eta_{gen} \dot{E}_{wind}.
\] (7)

A commercially available solar PV panel with a capital cost of 800 $/kW is considered for the integrated system. The clearness index, which is a ratio of the monthly average radiation on the horizontal surface of the earth \( (H_{ave}) \) and the radiation on a horizontal surface.
at the top of the earth’s atmosphere \( (H_{0,\text{ave}}) \) and can be defined as follows:

\[
K_T = \frac{H_{\text{ave}}}{H_{0,\text{ave}}},
\]

where \( K_T \) refers to the monthly average clearness index.

The specified PV energy conversion efficiency can be defined as follows:

\[
\eta_{\text{PV}} = \frac{W_{\text{E,PV}}}{I_{\text{APV}}},
\]

Here, \( W_{\text{E,PV}} \) is the electrical PV power output for the area of solar PV panels \( (A_{\text{PV}}) \). Moreover, \( I \) is the direct normal irradiation (DNI) of the selected location. The technical and economic properties of the selected flat-plate PV panel are tabulated in Table 4. Residential reverse osmosis systems usually work with grid pressure. Mains water passes through a membrane to obtain fresh water. When the amount of fresh water production is not enough, a particular amount of electricity is supplied to the reverse osmosis unit to meet the energy requirement. The work needed for the pump \( (W_{\text{P,RO}}) \) can be calculated as follows:

\[
W_{\text{P,RO}} = m(h_{\text{out}} - h_{\text{in}}).
\]

The Wobbe Index is utilized to compare the combustion performance of fuels and gas mixtures. It is defined by considering the energy density rate (volumetric), the density of the gas, and the density of air. According to the standards (i.e., DIN 51857), which is a standard method to calculate calorific value and Wobbe index of gaseous mixtures (fuels and other gases), the Wobbe index of the hydrogen and natural gas blend can be calculated as follows:\(^b\):

\[
W_I = \frac{LHV_{\text{vol,l}}}{\sqrt{\rho_l/\rho_{\text{air}}}}.
\]

Here, \( W_I \) and \( LHV_{\text{vol,l}} \) are the Wobbe index \((\text{MJ}/\text{m}^3)\) and volume-based lower heating value \((\text{MJ}/\text{m}^3)\), and \( \rho_l \) is the density \((\text{kg}/\text{m}^3)\) of the gas. While mass-based lower heating value increases, volumetric lower heating value and Wobbe Index decrease with the increase of hydrogen fraction in the blend. An experimentally set electrolyzer unit is assessed to calculate its efficiency, electricity need, and hydrogen production. The electricity obtained from PV panels and wind turbines is used to generate hydrogen. The technical and economic properties of the selected electrolyzer unit are tabulated in Table 5. The energy and exergy efficiencies of the electrolyzer unit can be defined as follows:

\[
\eta_{\text{en,EL}} = \frac{m_{\text{H}_2}\cdot\text{LHV}_{\text{H}_2}}{W_{\text{EL}}},
\]

and

\[
\eta_{\text{ex,EL}} = \frac{m_{\text{H}_2}\cdot\text{ex}_{\text{H}_2}}{W_{\text{EL}}},
\]

The energy \((\eta_{\text{en}})\) and exergy \((\eta_{\text{ex}})\) efficiencies of the integrated system, which consists of solar PV panels, wind turbines, electrolyzers, and hydrogen and natural gas blend-based generators, reverse osmosis units, gas cooktops, and combi boilers, can be defined as follows:

\[
\eta_{\text{en}} = \frac{W_E + Q_H + (m_{\text{fw}}\times h_{\text{fw}})}{Q_{\text{solar}} + E_{\text{wind}} + Q_{\text{fuel}} + (m_w\times h_w)}
\]

and

\[
\eta_{\text{ex}} = \frac{W_E + E_{\text{ex}} Q_H + (m_{\text{fw}}\times\text{ex}_{\text{fw}})}{E_{\text{ex}} Q_{\text{solar}} + E_{\text{wind}} + E_{\text{ex}} Q_{\text{fuel}} + (m_w\times\text{ex}_w)}.
\]
energy and exergy of the power supplied by fuel (here, considered as hydrogen and natural gas blend) for the gas cooktop burner and combi boiler. Finally, \( w \) and \( w' \) are the fresh water obtained and water utilized in the reverse osmosis unit, respectively. In this study, hydrogen is generated by the electrolyzer unit. Since the electricity required for the electrolyzer is provided in the integrated system, it is not considered in the efficiency calculations.

4 | RESULTS AND DISCUSSION

In this study, five locations with different climate zones are selected to assess the optimal cost-effective and technically feasible configurations. Those locations are Konya (37°55.4' N, 32°33.5' E) (which is the same location with the laboratory), Istanbul (41°0.5' N, 28°58.7' E), Antalya (36°53.8' N, 30°42.8' E), Trabzon (41°0.2' N, 39°43.0' E) and Van (38°30.1' N, 43°22.4' E) in Turkey. The solar irradiation, daily temperature, clearness index, and wind speed data for the five selected locations are obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database included in the HOMER Pro software. For the summer season (June, July, August) the average daily temperature is determined to be between 18°C and 27°C. The capacities and hours of operation of the PV panels, wind turbines, gas engines, boiler, and electrolyzer units for the selected locations are tabulated in Table 6.

The amounts of CO\(_2\), CO, NO\(_x\) emissions, unburned hydrocarbons, and particulate matter in the selected locations are tabulated in Table 7. Here, the hydrogen and natural gas blend is utilized as fuel for the boiler and gas engine. Natural gas is relatively cleaner than other fossil fuels due to its low or zero sulfur content. However, CO and CO\(_2\) are produced with natural gas combustion. Note that the carbon content can be reduced to 53.6% by adding 20% hydrogen into natural gas. Furthermore, the amounts of hydrogen produced by the electrolyzer for the hydrogen and natural gas blend-based cases are given in Figure 8. Here, the electricity, heating, and fresh water requirements are considered the same for five locations. For the same electricity, heat power and fresh water requirements, the amounts of hydrogen required for the communities in Konya, Istanbul, Antalya, Trabzon, and Van are calculated as 4798, 4810, 8078, 8074, and 9050 kg/year, respectively.

The changes in hydrogen and natural gas requirements as to hydrogen fraction in the blend are shown in Figure 9. In this parametric study, the gas required for the same amount of power is calculated. Also, the volumetric-based blend gas requirements are more than natural gas due to the low density of hydrogen. In this particular study, the hydrogen with a ratio of 20% (which is also performed in the experimental study) is injected into natural gas and supplied to the community. With the increase of hydrogen fraction in the blend, while hydrogen requirements increase, natural gas requirements decrease. Here, the existing pipeline is used to distribute hydrogen. In the experimental studies, hydrogen is injected into the natural gas pipeline up to 40% safely. The heating values of the blend and emissions such as CO\(_2\), CO, and NO\(_x\) are then calculated. A homogeneous blend is obtained and burned both in the gas cooktop and combi boiler.

| TABLE 6 | The main components and their utilization in the integrated system |
|----------|------------------|------------|----------|----------|----------|
| Konya (37°55.4’ N, 32°33.5’ E) | Capacity (kW) | 475 | 320 | 130 | 198 | 200 |
| | Hours of operation (h/year) | 4352 | 8466 | 4268 | 7052 | 8134 |
| Istanbul (41°0.5’ N, 28°58.7’ E) | Capacity (kW) | 248 | 270 | 150 | 198 | 150 |
| | Hours of operation (h/year) | 4389 | 8499 | 3872 | 7191 | 8391 |
| Antalya (36°53.8’ N, 30°42.8’ E) | Capacity (kW) | 474 | 350 | 150 | 192 | 180 |
| | Hours of operation (h/year) | 4387 | 8333 | 4970 | 6571 | 8078 |
| Trabzon (41°0.2’ N, 39°43.0’ E) | Capacity (kW) | 606 | 365 | 150 | 189 | 210 |
| | Hours of operation (h/year) | 4384 | 8247 | 5306 | 6383 | 8043 |
| Van (38°30.1’ N, 43°22.4’ E) | Capacity (kW) | 991 | 15 | 150 | 186 | 250 |
| | Hours of operation (h/year) | 4386 | 8349 | 5328 | 6408 | 7871 |
The changes of lower heating values and Wobbe Indexes for the hydrogen fractions considered in the blend from 0% to 100% are calculated and given in Figure 10. Here, mass-based lower heating values are considered as 119.96 and 47.78 MJ/kg for hydrogen and natural gas. Lower heating values of the blend with a hydrogen rate of 20% and natural gas rate of 80% are calculated as 49.8 MJ/kg and 33.62 MJ/m³. For the same fraction, the Wobbe index of the blend is calculated as 47.7 MJ/m³. Furthermore, the Wobbe indexes of the hydrogen and natural gas are determined as 43.0 and 50.4 MJ/m³, respectively.

The effects of ambient temperature on exergy efficiencies for the selected locations are shown in Figure 11.

|                     | Unit | Konya        | Istanbul     | Antalya     | Trabzon     | Van         |
|---------------------|------|--------------|--------------|-------------|-------------|-------------|
| Carbon dioxide (CO₂)| kg/year | 443,151      | 442,314      | 469,961     | 481,056     | 491,845     |
| Carbon monoxide (CO)| kg/year | 1541         | 1521         | 1997        | 2187        | 2394        |
| Unburned hydrocarbons| kg/year | 67.9         | 67           | 88          | 96.4        | 105         |
| Particulate matter| kg/year | 9.25         | 9.12         | 12          | 13.1        | 14.4        |
| Sulfur dioxide (SO₂)| kg/year | 0            | 0            | 0           | 0           | 0           |
| Nitrogen oxides (NOₓ)| kg/year | 1449         | 1430         | 1877        | 2055        | 2250        |
At 20°C, the exergy efficiencies are calculated as 36.2%, 40.2%, 38%, 35.3%, and 36% for Konya, Istanbul, Antalya, Trabzon, and Van, respectively. Besides, the energy efficiencies of the integrated systems located in Konya, Istanbul, Antalya, Trabzon, and Van are determined as 26.5%, 31.7%, 27.9%, 25.7%, and 26.4%. Finally, the total net present costs (NPC) and levelized costs of electricity (COE) of the selected locations are provided in Figure 12. The integrated systems potentially located in Istanbul and Konya have the lowest prices due to high solar GHI and wind speed. The operating costs ($/year), which are the annualized value of all costs and revenues other than initial capital costs, are also provided in the same figure (i.e., Figure 12).
5 | CONCLUSIONS

In the present study, an integrated system is developed to produce clean hydrogen which is the utilized in blending with natural gas for domestic appliances in residential buildings, and five locations are identified in Turkey as a case study where thermodynamic, thermoeconomic, and environmental impact analyses and assessments are performed for. Hydrogen and natural gas blend-based integrated system is further analyzed in terms of energy, cost and environment impact through emissions. The power requirements are mainly provided by solar PV panels and wind turbines. Hydrogen is produced in sunny and windy hours. Hydrogen produced by electrolyzer is utilized in gas engines to provide sustainable electricity and heating for the community. The main findings obtained in this study are listed as follows:

- The levelized costs of electricity of the integrated system are calculated to be between 0.556 and 0.863 $/kWh for five locations.
- The total net present costs for the overall system are calculated to be between $3.01 million and $4.36 million for the selected locations.
- The carbon dioxide emissions are calculated to be between 443.2 tons and 491.9 tons/year for five locations.
- While the energy efficiencies are calculated as 26.5%, 31.7%, 27.9%, 25.7%, and 26.4%, exergy efficiencies are calculated to be 36.2%, 40.2%, 38%, 35.3%, and 36% for the selected cities of Konya, Istanbul, Antalya, Trabzon, and Van, respectively.

NOMENCLATURE

- \( E_{\text{served}} \) total electrical load served (kWh/year)
- EES Engineering Equation Solver
- \( f \) expected inflation rate (%)
- GAZBIR Natural Gas Distribution Companies Association of Turkey
- GHI global horizontal irradiation (kWh/m² × day)
- \( h \) specific enthalpy (kJ/kg)
- \( H_{\text{served}} \) total thermal load served (kWh/year)
- HOMER Hybrid Optimization of Multiple Energy Resources
- \( I \) average solar radiation (direct normal irradiation) (kWh/m² × day)
- IEA International Energy Agency
- \( i \) annual real discount rate (%)
- \( i' \) nominal discount rate (%)
- \( K_r \) clearness index
- \( LHV \) lower heating value (kJ/kg)
- \( m \) mass flow rate (kg/s)
- \( N \) the project lifetime (year)
- NG natural gas
- \( Nm^3 \) normal cubic meter (at 0°C and 1 atm)
- NOx nitrogen oxides
- NPC total net present cost ($) 
- O&M operating and maintenance
- \( P \) pump
- PV photovoltaic
- RO reverse osmosis
- \( Sm^3 \) standard cubic meter (at 20°C and 1 atm)
- UK United Kingdom
- US United States
- \( V \) velocity (m/s)
- \( W \) work rate (kW)
- WT wind turbine

GREEK LETTERS

- \( \rho \) density (kg/m³)
- \( \eta \) efficiency

SUBSCRIPTS AND SUPERSCRIPTS

- ann annual
- ave average
- \( E \) electricity
- EL electrolyzer
- en energy
- ex exergy
- FC fuel cell
- fw fresh water
- gen generator
- H heating
- mech mechanical
- r rotor
- tot total
- w water
ACKNOWLEDGMENTS
The authors would like to thank the GAZBIR-GAZMER (Technical Center of Natural Gas Distribution Companies Association of Turkey) for providing data and the EPDK (Energy Market Regulatory Authority of Turkey) for financial support for the project.

ORCID
Fatih Sorgulu  http://orcid.org/0000-0003-2734-106X
Ibrahim Dincer  http://orcid.org/0000-0002-7092-2102

REFERENCES
1. Câmara RJB, Carneiro JF, Câmara GAB, de Araújo PSR, Rocha PSDM, Andrade JCS. Methodology for sub-commercial calculation of the potential energy storage capacity of hydrogen, natural gas, and compressed air in salt caves. J Energy Resour Technol. 2020;142(4):042007.
2. EXIST (EPIAS). Transparency platform, Real-time generation. Accessed August 20, 2021. https://seffaflik.epias.com.tr/transparency
3. Karaca AE, Dincer I. Overview of Canada’s energy storage related research activities: a perspective. Int J Energy Res. 2021;45:17450-17460.
4. BP. Statistical Review of World Energy (70th ed.); 2021.
5. Okonkwo EC, Al-Breiki M, Bicer Y, Al-Ansari T. Sustainable hydrogen roadmap: a holistic review and decision-making methodology for production, utilisation and exportation using Qatar as a case study. Int J Hydrogen Energy. 2021;46(72):35525-35549.
6. Quarton CJ, Samsatli S. How to incentivise hydrogen energy technologies for net zero: whole-system value chain optimisation of policy scenarios. Sustain Prod Consum. 2021;27:1215-1238.
7. Duan X, Deng B, Liu Y, Zou S, Liu J, Feng R. An experimental study the impact of the hydrogen enrichment on cycle-to-cycle variations of the large bore and lean burn natural gas spark-ignition engine. Fuel. 2020;282:118868.
8. Boretti A. Concentrated solar energy with thermal energy storage for hydrogen production by three-step thermo-chemical water-splitting cycles. Energy Fuels. 2021;35(13):10832-10840.
9. The Food and Agriculture Organization (FAO) of the United Nations. Annual freshwater withdrawals, total (billion cubic meters). 2021.
10. Gill EZ, Ratlamwala TAH, Hussain G, Alkahtani M. Energy, exergy, exergo-economic and exergo-environmental analyses of solar based hydrogen generation system. Int J Hydrogen Energy. 2021;46(57):29049-29064.
11. Seyam S, Dincer I, Agelin-Chaab M. Exergetic, exergoeconomic, and exergoenvironmental analyses of a hybrid combined locomotive powering system for rail transportation. Energy Comms Manage. 2021;245:114619.
12. Xu X, Hu W, Liu W, et al. Risk-based scheduling of an off-grid hybrid electricity/hydrogen/gas/refueling station powered by renewable energy. J Clean Prod. 2021;315:128155.
13. Sorgulu F, Dincer I. Development of a hythane based cogeneration system integrated with gasification and landfill subsystems. Energy. 2021;215:119109.
14. Baltacıoğlu MK, Arat HT, Kenanoğlu R. Exergy and performance analysis of a CI engine fuelled with HCNG gaseous fuel enriched biodiesel. Int J Exergy. 2017;24(1):39-56.
15. de Santoli L, Paiolo R, Basso GL. Energy-environmental experimental campaign on a commercial CHP fueled with H2NG blends and oxygen-enriched air hailing from on-site electrolysis. Energy. 2020;195:116820.
16. Arsalis A. Thermodynamic modeling and parametric study of a small-scale natural gas/hydrogen-fueled gas turbine system for decentralized applications. Sustain Energy Technol Assess. 2019;36:100560.
17. EES. Engineering Equation Solver Software. Accessed September 24, 2021. www.fchart.com
18. HOMER Pro. Accessed August 8, 2021. https://www.homerenergy.com
19. Mepas Energy. Accessed August 2, 2021. https://www.mepasenerji.com
20. Santoli L, Basso GL, Bruschi D. Energy characterization of CHP (combined heat and power) fuelled with hydrogen-enriched natural gas blends. Energy. 2013;60:13-22.
21. NASA. The Prediction of Worldwide Energy Resources. Accessed May 9, 2021. https://power.larc.nasa.gov

How to cite this article: Sorgulu F, Dincer I. Development and assessment of renewable hydrogen production and natural gas blending systems for use in different locations. Energy Sci Eng. 2022;10:1739-1751. doi:10.1002/ese3.1114