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An urban techno-economic hydrogen penetration scenario analysis for Burdur, Turkey

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ABSTRACT

In this paper, the current energy mix and the power generation infrastructure of Turkey have been analyzed and two different hydrogen based alternative scenarios applied on Burdur TIMES energy model to foresee the economic and environmental results in the 2016−2031 time period.

An improved RES was created to illustrate the current energy network of Burdur city and to determine the relationships between energy carriers and the respective technologies, and then this structure is specified by the relevant data, including fuel cell-powered land vehicle technologies integrated into the land transportation demand side.

This paper analyses the feasibility of hydrogen as an alternative energy carrier in the fuel mix for electricity generation in Burdur City to achieve sustainable economic growth, to improve the energy security by minimizing respective environmental emissions and indicate the possible implications of the introduction of the hydrogen supply chain and respective fuel cell end-use technologies in a city level energy modelling perspective. Burdur is selected as the target city to implement the designated level of land transport passenger demand by hydrogen technologies; and after implementation of hydrogen cars in 2020; it has been evaluated that only 0.09 PJ of hydrogen car activity prevents a total of 43.44 kT CO_2 emission in Burdur, addressing the 8% of the total emission in the base scenario between the analysis time horizon. Finally, hydrogen has been evaluated as a clean, dependable option to diversify the energy mix on the current energy supply system of Burdur.

Introduction

Human activity based energy production and consumption processes caused a significant increase in greenhouse gas (GHG) emissions in the atmosphere, and this has triggered the global mechanisms to take serious measures for a cleaner future. In this concern, 148 nations ratified the Paris Climate Accord in 2015 and agreed on a consensus to cap the GHG emissions as soon as possible [1].

From the energy-development-environment interaction point of view, energy carriers used in both energy generation and consumption processes need to be carefully planned by an engineering approach to support sustainable development by using environmentally friendly technologies.

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Among all the energy carriers, hydrogen offers an environmentally friendly solution, while contributing the energy utilization in higher efficiencies and supporting the combat against climate change. Hydrogen is an element, that can be found easily in nature as the most abundant, odorless and nontoxic option. Additionally; hydrogen is an energy carrier and it has the richest energy content of common fuels by weight, nearly three times that of gasoline. Anyhow, it is not found free in nature and must be obtained from fossil, renewable, nuclear energy or via the electrolysis of water [2].

In terms of the extraction method; hydrogen is mostly obtained from the fossil energy carriers via steam methane reforming (SMR), partial oxidation (POX) and auto-thermal reforming (ATR); as a combination of SMR and POX methods. Hydrogen may be converted to electricity following the production, by the fuel cell technology to operate continuously with hydrogen and oxygen to be utilized in a broad scale of applications: power, industry, transportation and residential sectors. Fuel cells can be designed in different dimensions with the outputs of electricity, heat, and water. Hydrogen has been recognized with its potential to be utilized with mitigation in energy-related CO_2 emissions. Besides, renewable utilization options for hydrogen production are very reasonable from the environmental point of view [2].

Considering the enormous increase in renewables utilization, use of hydrogen to store the renewable-based electricity via water electrolysis seems to create a major shift in energy markets. Hydrogen and electricity are compatible energy carriers, where hydrogen can be converted to electricity, and vice versa, acting as a countable reserve and a supporting the energy supply security. Hydrogen is expected to be integrated into distributed energy systems, taking place in off-the-grid electrolyzers, with low-cost renewables in the long term. As a challenging issue in energy technologies, hydrogen can be used as a substitute to electrify the applications that currently use conventional powering technologies.

The countries like Turkey, surrounded by the seas have an abundant hydrogen source will have a great opportunity to utilize hydrogen and relevant technologies, especially the Black Sea is the largest anoxic basin in the world, where almost 90% of the seawater is anaerobic [3]. However, the hydrogen production and storage technologies stand with huge challenges in terms of the introduction and the penetration of hydrogen into the national electricity infrastructure.

The complete energy infrastructure of a country, or even of a city, may be highly complicated and difficult to analyze. Therefore, energy decision support tools have been used to develop a baseline scenario illustrating the current situation of the energy network of the analyzed system in the first place. Later on, a number of alternative scenarios are to be developed to implement different technology or policy options to foresee the respective consequences on the energy profile of a city.

On a broader scale, national economies have been seeking alternative pathways to implement new energy production methods i.e. solar, wind, geothermal, etc. in order to diversify the options in the energy mix, decrease the additional burdens and the investment costs of renewables, while combating against the climate change. As the selected analysis area, Turkey's energy production is mostly dependent on hydro, coal, natural gas and oil and Turkey has already declared to evaluate its renewable potential in solar, wind and geothermal fields.

Turkey has determined energy-related priorities and targets in "Electric Energy Market and Security of Supply Strategy Paper" under the coordination of "State Planning Organization of Turkey" approved in 2009 [4]. This strategy paper identified the main goal as providing 30% of total electricity production from renewable energy with the actions to be taken for ensuring supply security and electricity generation targets in the long term. "National Renewable Energy Action Plan" has been published in 2014, including a national energy roadmap and the total installed capacity targets have been revised as 5000 MW solar, 1000 MW geothermal, 20000 MW wind and 34000 MW hydraulic power by the end of 2023 [5]. Both the abovementioned strategy paper and the national action plan set the goals with the characteristics of a roadmap for careful planning and efficient development of renewable energy integration until 2023, the centennial of the Turkish Republic.

When we look at the scope of this paper; the hydrogen firstly appeared in the Strategic Plan (2015–2019) of the Ministry of Energy and Natural Resources of Turkey, aimed to establish a fully provided hydrogen technologies laboratory [6]. Following this, the National Energy Efficiency Action Plan (2017–2023) has been published in 2018, with a specific focus on hydrogen integration to transport options will be realized to promote the use of environment-friendly, lightweight, electric or hybrid, hydrogen, natural-gas-fired vehicles with a goal to create a framework to promote public transport systems. This action plan aimed at the implementation to start in 2020 [7].

Keeping all these facts in mind; this paper aims to analyze the respective consequences of the official targets on hydrogen utilization via two alternative scenarios applied on Burdur energy model, developed for the period 2016–2031, as directed by the official action plan. To the best of our knowledge, this analysis is the first attempt to make a long term regional bottom-up modelling implementation on urban energy system analysis based approach in Turkey. This analysis is also the first attempt to propose an integrated optimization model based on an urban energy database including the hydrogen supply chain and respective fuel cell technologies in Turkey.

Energy system analysis and modelling efforts have been developed under Energy Technology System Analysis Programme (ETSAP) by International Energy Agency (IEA) with the participation of 20 countries, the official authorities, universities, and private institutions. TIMES (The Integrated MARKAL-EFOM System); is the recent output of ETSAP as an energy-economy-environment model generator to create long-term energy scenarios and in-depth national, multi-regional, and global energy and environmental policy analyses. TIMES can be used to obtain least-cost policy evaluations for sustainable energy systems and is mainly suitable for the preparation of low-emissions development strategies and nationally determined contributions and respective roadmaps.

TIMES is based on a reference energy system (RES) structure, defining the current energy-economy-environment dynamics of the analyzed scope. A detailed technology-rich energy database is created for a long-term, in order to evaluate and foresee the possible interactions and interrelations of the respective energy system over a multi-period time interval. TIMES is the new generation energy system analysis and modelling platform as the successor of MARKAL (an acronym for MARKet ALlocation) model generator [8].

There are various studies conducted in the hydrogen energy field from different perspectives. Karapekmez and Dincer modelled the hydrogen production from hydrogen sulfide in geothermal power plants and employed the AMIS (AMIS®-acronym for "Abatement of Mercury and Hydrogen Sulfide" in the Italian language) technology for the abatement of hydrogen sulphide and mercury emission primarily to produce hydrogen from H_2S [9]. Li et al. aimed to explore the relationship between hydrogen fuel cell vehicle sales and the number of refueling stations and proposed an integrated optimization model [10]. Kougias et al. developed a sustainable energy modelling of non-interconnected Mediterranean islands by analyzing specific island grids of the Aegean Sea over a 20-year period (2016–2036) [11]. Nagasawa et al. analyzed the potential of hydrogen demand and production to estimate the potential hydrogen demand for light-duty vehicles and quantifying temporal renewable hydrogen production from wind energy via a linear programming model [12]. Mah et al. studied the future directions of the hydrogen economy in Malaysia and proposed that renewable hydrogen could penetrate Malaysia market to utilize the hydrogen as feedstock for chemical industries and recommended that hydrogen should be used as fuel for automobiles via using fuel cells [13]. McDowall offered a hybrid approach to assess hydrogen transitions in the UK, by qualitative socio-technical scenarios with quantitative energy systems modelling [14]. Dincer and Acar analyzed the smart energy solutions with a focus on introducing and highlighting smart hydrogen energy solutions portfolio [15]. Chapman et al. assessed the future potential for hydrogen and provided insight to areas of research to help lower economic barriers for hydrogen adoption [16]. Welder et al. used a spatially and temporally resolved optimization model to investigate and economically evaluate options for using surplus electricity and reconvert hydrogen into electricity [17]. Groppi et al. studied the economic and environmental sustainability related to the integration of hydrogen and batteries storage in small islands, by using HOMER software on different scenarios [18]. Huang et al. studied the design and sizing optimization of PV-hydrogen-REVB hybrid energy system for residential usage [19]. Colbertaldo et al. analyzed future energy scenarios at a country scale and developed a multi-node model representing the integrated energy system focusing on the interaction between power and transport sectors [20]. Parra et al. presented a techno-economic review of hydrogen energy systems including power-to-power, power-to-gas, hydrogen refuelling, and stationary fuel cells [21]. Blazquez-Diaz analyzed the pathways to find the best design of a hydrogen refuelling station [22]. Ismail et al. developed a mathematical model to estimate and predict the global solar radiation intensity in Egypt by running a flowchart in MATLAB to increase the quantity of hydrogen produced [23]. Hanley et al. overviewed the drivers and policy scenarios that lead to the emergence of hydrogen over other low-carbon technologies, then advised to assess the various options to be considered regarding hydrogen for moving towards a decarbonized energy system [24]. Kavadias et al. developed a simulation algorithm to assess the specifications of the optimum sizing of hydrogen production storage systems in the area of the Aegean Sea through water electrolysis and storing the excess energy [25]. Han et al. presented a design scheme and a hierarchical energy management strategy for an island PV/hydrogen/battery hybrid DC microgrid by HOMER pro software [26]. Touili et al. conducted a techno-economic analysis of the capacity as the first study assessing the hydrogen production from solar for Morocco [27]. Siddiqui and Dincer performed a comparative well to pump life cycle assessment on the hydrogen production routes of water electrolysis, biomass gasification, coal gasification, steam methane reforming, hydrogen production from ethanol and methanol. They determined the ethanol based hydrogen production route to have a comparatively

Table 1 – Energy reserves of Turkey [40].

Resources	Proven	Probable	Possible	Total
Hard Coal (Million Tonne)	506.5	425	368.4	1308.50
Lignite (Million Tonne)				
Elbistan	4845.50			4845.50
Other	9146.00	768.9	4.5	9919.40
Total	13991.50	768.9	4.5	14764.90
Asphaltite (Million tonne)	82			82
Bituminous (Million tonne)	1641.40			1641.40
Crude Oil (Million barrel)	7167			7167
Natural Gas (Million m^3)	23.2			23.2
Nuclear Resources (Tonne)				
Uranium	9129			9129
Thorium	380.000			380.000

Table 2 – Electricity production of Turkey [42].

Year	Total (GWh)	Coal (%)	Liquid fuels (%)	Natural Gas (%)	Hydro (%)	Renewable Energy and Wastes (%)
2010	211208	26.1	1.0	46.5	24.5	1.9
2011	229395	28.8	0.4	45.4	22.8	2.6
2012	239497	28.4	0.7	43.6	24.2	3.1
2013	240154	26.6	0.7	43.8	24.7	4.2
2014	251963	30.2	0.9	47.9	16.1	4.9
2015	261783	29.1	0.9	37.9	25.6	6.5
2016	274408	33.7	0.7	32.5	24.5	8.6

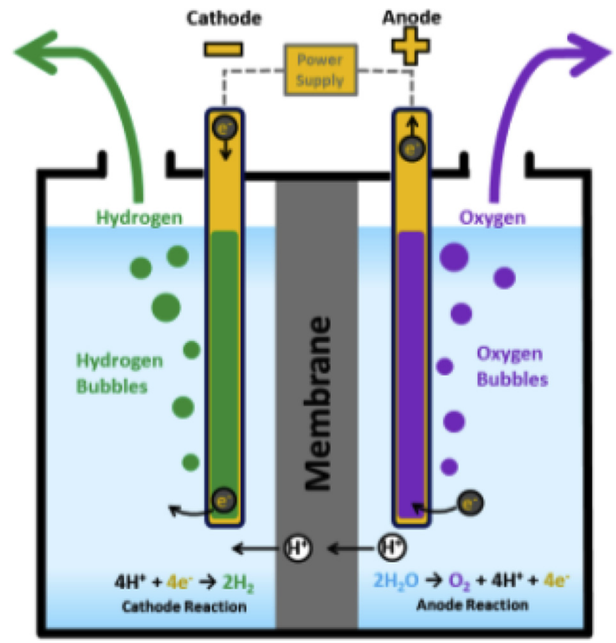

Fig. 1 – Electrolysis process in PEM [52].

higher photochemical ozone creation potential as well as eutrophication potential of 0.0043 kg PO_4eq/kg H_2 [28]. Ishaq and Dincer analyzed three different configurations of the CuCl thermochemical cycle, as a promising hydrogen production method by the Aspen plus software tool employed for the modeling and simulation of the cycles, and evaluated that the cycle performance can be enhanced by improving the thermal management and reducing the exergy destructions [29]. Ozturk and Dincer evaluation a comparative life cycle assessment (LCA) of the environmental impacts of different fuels to generate electricity through a combined cycle and reported that the results of the study show that the hydrogen is the best fuel option according to the environmental impacts [30]. Ishaq et al. analyzed a multigeneration system for hydrogen production linked with a glassmaking process via thermal management by the simulation software packages Engineering Equation Solver and Aspen Plus, and they reported that the energy efficiency of the overall system is 36.5% while 38.1% is the exergy efficiency [31]. In another study, Ishaq and Dincer proposed a new integrated energy system employing the cement slag waste heat, to generate clean hydrogen thermochemically and convert it into ammonia. Multiple parametric studies have been performed to investigate the system performance under different operating conditions by using the Aspen Plus simulation software [32]. Ahmed and Dincer reviewed the photoelectrochemical hydrogen production systems and highlighted that modeling and numerical simulation of photoelectrochemical processes based on up-to-date multi-scale analysis. They evaluated that the achievements made in semiconductor photoelectrode materials and the utilized engineering methods needed to improve the solar to hydrogen efficiency [33]. Yuksel et al. performed a thermodynamic investigation of solar power tower assisted multigeneration system with hydrogen production and liquefaction for more environmentally-friendly multigenerational outputs. They calculated the energetic and exergetic efficiencies of the multigeneration system as 65.17% and 62.35%, respectively. They concluded that the solar irradiation intensity has been found to be the most influential parameter among other conditions and factors [34]. Safari and Dincer investigated energy and exergy analyses of an anaerobic digestion (AD) of sewage sludge from wastewater treatment plant (WWTP) for multi-generation, operated by the biogas produced from digestion process, where a proton exchange membrane (PEM) electrolyzer has been used for electrochemical hydrogen production in the case of excess electricity generation [35]. Acar and Dincer, investigated the possibility of hydrogen as the major fuel for transportation systems in hydrogen-fueled internal combustion engines context, by an assessment on the conventional, hybrid, electric, biofuel, fuel cell, and hydrogen fueled ICE vehicles in terms of their CO_2 and SO_2 emissions, social cost of carbon, energy and exergy efficiencies, fuel consumption, fuel price, and driving ranges. They reported that, according to these criteria, fuel cell vehicles have the highest average performance ranking, followed by hydrogen fueled ICEs and biofuel vehicles, while the conventional vehicles have the lowest average performance ranking, followed by electric vehicles and hybrid vehicles [36].

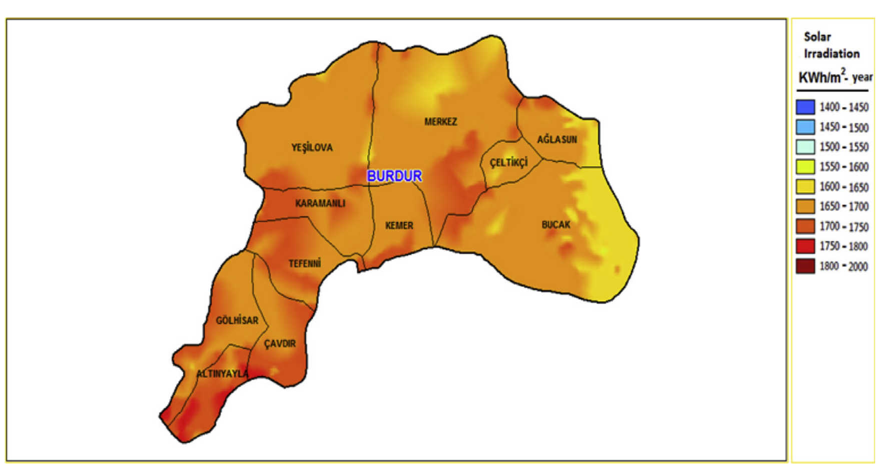

Fig. 2 – Solar irradiation map of Burdur [53].

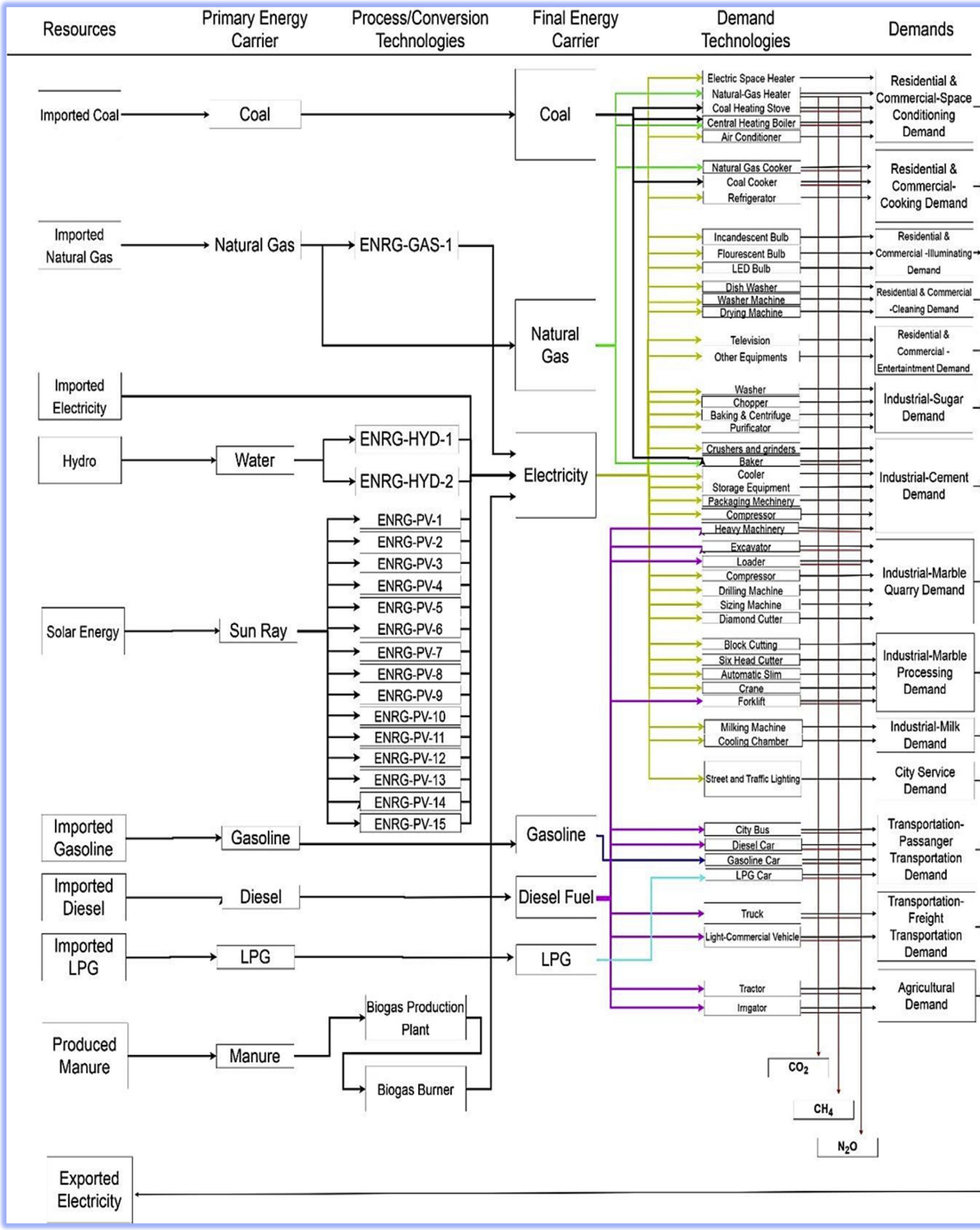

Fig. 3 – Reference energy system of Burdur.

Shah et al. addressed the rural electrification for Pakistan's Balochistan province by assessing the area's potential and economic feasibility of using solar PV for rural electrification [37]. Mirjat et al. focused on the energy and power planning studies conducted in Pakistan integrated energy planning using energy modeling tools e.g. MARKAL/TIMES; LEAP, ENPEP BALANCE, MESSAGE and EnergyPLAN, and highlighted that such tools will be helpful to develop sustainable energy

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Table 3 – Sectoral demands (PJ).

Demand Group	Demand	2016	2021	2026	2031
Residential and commercial	Cleaning	0.130	0.162	0.202	0.252
	Cooking	0.401	0.499	0.622	0.775
	Entertainment	0.130	0.162	0.202	0.252
	Illumination	0.035	0.044	0.055	0.068
	Space conditioning	1.244	1.551	1.933	2.408
Industrial	Cement	0.668	0.832	1.037	1.292
	Marble processing	0.682	0.850	1.059	1.320
	Marble quarry	0.343	0.428	0.533	0.664
	Dairy	0.177	0.221	0.275	0.343
	Sugar	0.041	0.050	0.063	0.078
City services	Street illumination and traffic lights	0.016	0.020	0.025	0.032
Transportation	Freight transportation	3.631	4.525	5.639	7.027
	Passenger transportation	0.911	1.135	1.415	1.763
Agricultural	Agriculture	0.107	0.133	0.166	0.207

policies in country scale [38]. In another remarkable study, Mirjat et al. utilized the Analytical Hierarchy Process (AHP) methodology of Multi-Criteria Decision-Making (MCDM) for the sustainability assessment of energy modeling results for long-term electricity planning by applying four scenario alternatives developed in the energy modeling context [39].

The recent literature denotes that the energy modelling tools have been used in a number of studies within energy-economy-ecology-environment aspects of the energy system with a focus on hydrogen in various approaches.

This paper is divided into four sections. The first section briefly gives the energy overview with the potential of Turkey and Burdur province and some background information on current hydrogen production technologies, and the analysis region respectively; while Section 2 gives an insight about the energy system of Burdur, developed by TIMES methodology with the baseline and alternative scenarios. Section 3 introduces the analysis and results, and the final section concludes with the key findings of the study.

Energy potential and electricity production in Turkey

Turkey is the sixth largest electricity market in Europe and mainly importing 70% of energy requirements from other countries. This proves that Turkey is highly dependent on energy, although its own lignite potential. Table 1 shows the conventional reserves and Table 2 shows the electricity production of Turkey.

Turkey has huge renewable energy potential. Official targets aim to raise total hydraulic capacity by 30%, wind capacity three-fold, and double the solar and biomass capacity. However, geothermal energy national targets have already been achieved in Turkey [41]. Table 2 shows the energy production between 2010 and 2016 in Turkey by the sources. The total production increases simultaneously with an increasing trend in coal and renewables while hydro-based electricity production kept a stable trend.

As an example of lately introduced technology to the domestic energy market, the solar capacity of Turkey was only 6 MW in 2010. The investments in solar power have slightly increased after the legislation held in 2005, by law number 5346. This law regulated the issues of electricity generation by renewable energy sources [43]. Then, this law has been updated in 2010, and then came into force by the law number 6094, and revised the incentives on electricity generated per kWh of 7.3 US dollar cents for hydropower and the wind, 10.5 US dollar cents for geothermal, 13.3 US dollar cents for biomass and solar-based electricity generation. However, hydrogen-based production and the relevant technologies haven't appeared in these official incentive mechanisms in Turkey [44].

Hydrogen-energy process chain

Hydrogen-energy process chain mainly consists of three major steps. The first step is the hydrogen evolution. Tan et al. analyzed the performance and mechanism of hydrogen generation via hydrolysis of ball-milled Mg–Mg2Si composite in deionized water and in MgCl2 solution. They reported that the obtained Mg–Mg2Si composite presented relatively higher hydrogen generation performance than pure magnesium [45]. In another remarkable study, Ma et al. investigated the effect of dielectric barrier discharge plasma-assisted milling (P-milling) on the hydrogen generation properties of Mg-graphite composites. The findings they presented demonstrated that the P-milled Mg-EG composite with high hydrogen density and low cost can be a promising hydrogen generation material [46].

Following the evolution, the second step is the storage of hydrogen. Ouyang et al. reported that, Mg-based materials are promising candidates for high capacity hydrogen storage. However, their poor hydrogenation/dehydrogenation kinetics and high desorption temperature are the main obstacles to these applications. They found that the hydriding/dehydriding process is catalyzed by the combination of in situ formed extremely fine CeH_2/$CeH_{2.73}$ and Ni to Mg/MgH2, and reported that the material can maintain its high performance for more than 500 hydrogenation dehydrogenation cycles [47]. In this direction, Zhu et al. synthesized and investigated composite hydrogen storage alloys in the form of powder and film to improve the hydrogen absorption/desorption kinetic properties of Mg and Mg–Ni alloys. They evaluated that the hydrogen sorption properties of Mg and Mg–Ni-based alloys can be substantially improved by forming composites having proper microstructure features [48]. Cao et al. analyzed the structural characteristics and electrochemical properties of La0.95Sm0.66Mg0.40Ni6.25Al0.42Co0.32 alloy and reported

Table 4 – Limits and freedom in scenarios.

Scenario	Limits	Freedom	Cost
BASE (BAU)	The same trend to 2031	Same trend	Statistical data
HYD-1	10% of passenger transportation demand relocated by hydrogen cars.	Hydrogen car utilization	Low-cost hydrogen production method
HYD-2	10% of passenger transportation demand relocated by hydrogen cars.	Hydrogen car utilization	High-cost hydrogen production method

that it shows high discharge capacity and excellent cyclic property [49]. The regeneration of the hydrogen is considered as the third step in the hydrogen-energy process. Ouyang et al. focused on sodium borohydride (NaBH4) as excellent hydrogen generated material, and they developed a convenient and economical method for NaBH4 regeneration without hydrides used as starting materials for the reduction process [50]. Then, Zhong et al. analyzed the inexpensive Mg–Al alloy to work as a reducing agent transforming the H+ to H in NaBH4. This opens the door to the commercial implementation of simple ball milling processes for the regeneration of spent NaBH4 from $NaB(OH)_4$ by a 20-fold cost reduction compared with the method using metal hydrides [51].

Hydrogen is currently used for hydrocracking and desulfurization in the refining processes. It is used for the production of ammonia in the chemical industry and fertilizer in the agriculture sector. It is also used for production and manufacture of metal, methanol production, applications in food processing and electronics industries.

Syngas containing hydrogen is a product of coal gasification. The coal has been gasified in the late 18th century to produce coal gas for illumination, heating and cooking demands. Nowadays, the most industrial hydrogen product is obtained from methane in fossil energy carriers, e.g. natural gas, and electrolyzing of water via alkaline electrolyzers is another method for hydrogen production.

Electrolysis can occur under different thermal conditions and at varying scales in kilowatt to megawatt. Polymer electrolyte membrane (PEM), as shown in Fig. 1 and alkaline technologies are operated under low-temperatures. PEM electrolysis has higher capital expenditure than alkaline electrolysis, with a more compact structure and suitability to be utilized especially with renewable energy causing no carbon footprint. Fuel cells and electrolyzers mainly based on simple and inverse processes: electrolysis splits water into hydrogen and oxygen, while fuel cells process hydrogen and oxygen to produce electricity. Fuel cells are scalable to be integrated and utilized in comprehensive systems, similar to electrolyzers. Fuel cells are classified into four segments: polymer electrolyte membrane or proton exchange membrane (PEM), direct methanol fuel cell (DMFC), alkaline fuel cells, phosphoric acid fuel cells (PAFC), solid oxide fuel cells (SOFC), molten carbonate fuel cells (MCFC), in terms of operation conditions, catalyst and fuel types, and the purity of hydrogen [43].

Information about Burdur City

The city of Burdur is located in the south-western part of Turkey, with a population of 264776, by the end of 2017. The city is well known for its indigenous marble types, while the marble provides the major income of Burdur. Other than that, agriculture and dairy products are the secondary income source of the city. Burdur has a great advantage in terms of its renewable energy potential due to its location, and specifically, solar energy can be utilized in hydrogen production. Fig. 2 shows the solar irradiation map of Burdur.

Currently, there are eighteen operational power plants in Burdur (two hydraulic, one natural gas based and fifteen solar photovoltaic power plants) as of the end of the year 2017. Hydraulic power plants constitute about 60% of electricity

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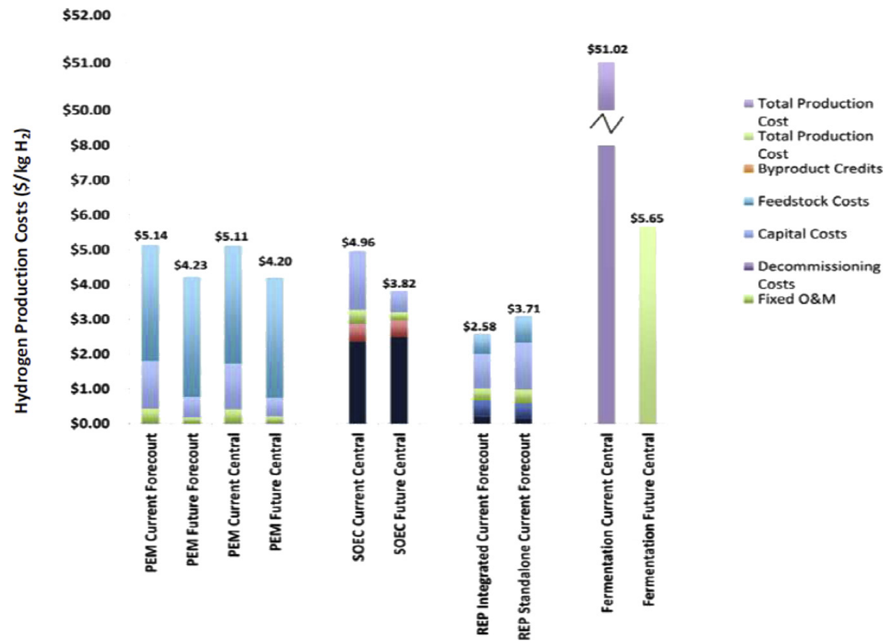

Fig. 4 – Hydrogen production methods and costs [56].

generation. The natural gas power plant of Burdur Sugar Factory constitutes nearly 10% of electricity generation and solar power plants constitute approximately 30% of the annual production, while the solar facilities vary between the installed capacities of 8–260 kW. Additionally, there are two incoming solar PV power plants under construction and one solar PV power plant is under licensing process. According to the Energy Market Regulatory Authority, power plants have produced only one-third of the total consumption in the year 2016. In terms of the operational electricity production infrastructure, it is clear that Burdur is highly dependent on electricity.

Materials and methods

The main structure and the objective function of TIMES

In this study, a MARKAL based Answer-TIMES platform has been used in the analyses. Basically, TIMES is an optimization method used for energy-economy-environment models. A developed model can work in a multi-regional and multi-period level, which means that one can simulate multiple different regions with multiple different time-slices. The model basically calculates and chooses the least-cost method by economic, environmental and technological parameters under given conditions.

TIMES energy model structure is designed by the modeler and then respective energy carriers, technologies, environmental emissions, and demands are specified with relevant qualitative and quantitative data input for each separate region. The specified items characterizes both currently exists in the energy system and the future candidates within the specified time horizon. Specified time-series and time-independent data contain the economic and technology-based policy assumptions over the identified region and time horizon. The reference year is set on a past year and the statistical values are fixed on this year by the modeler.

The objective function of a TIMES run is to minimize the net total cost of the system while meeting a number of defined

Table 5 – H_2 production cost breakdowns for PEM electrolysis [56].

	Projected Current Forecourt (1500 kg/day)	Projected Future Forecourt (1500 kg/day)	Projected Current Central (50000 kg/day)	Projected Future Central (50000 kg/day)
Stack capital cost	$0.42	$0.16	$0.48	$0.17
BOP capital cost	$0.61	$0.25	$0.53	$0.26
Indirect capital cost	$0.32	$0.16	$0.32	$0.10
Decommissioning	$0.02	$0.01	$0.00	$0.00
Fixed O&M	$0.42	$0.18	$0.40	$0.20
Electricity feedstock	$3.34	$3.46	$3.38	$3.46
Variable O&M	$0.01	$0.01	$0.01	$0.01
Total H_2 production cost	$5.14	$4.23	$5.12	$4.20

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Table 6 – Cost breakdown of the reformer-electrolyzer-purifier method [56].

Associated costs	Integrated REP ($/kg)	Standalone REP ($/kg)
Capital costs	$0.99	$1.34
Decommissioning costs	$0.01	$0.01
Fixed O&M	$0.34	$0.41
Feedstock costs	$0.57	$0.76
Raw material costs	$0.00	$0.00
Byproduct credits	$0.00	$0.00
Other variable costs	$0.67	$0.58
Total	$2.58	$3.10

constraints; as the summation of all regions of the reduced present value of annual costs, occurred over a predetermined time horizon. Therefore:

$$NPV = \sum_{r=1}^{R} \sum_{YEARS} (1 + d_{r,y})^{REFYR-y} * ANNCOST(r, y) \quad (1)$$

In Eq. (1), NPV (Net Present Value) of the model shows the total value of the modelled energy system. ANNCOST refers to the annual cost. The general discount rate is shown by "d". REFYR is the reference year for discounting, YEARS is the number of years in each period "t" and the letter "R" stands for the number of regions.

$$VAR\_OBJ_{(z)} = \sum_{r \in REG} REG\_OBJ(z, r) \quad (2)$$

The Eq. (2) represents the overall objective function including all regions, and each regional objective OBJ(z,r) consists of the sum of nine elements as given in Eq. (3) below.

$$REG\_OBJ_{(z,r)} = \sum_{y \in (-\infty,+\infty)} DISC\,(y, z) * \{ INVCOST(y) + INVTAXSUB(y) + INVDEC(y) + FIXCOST(y) + FIXTAX(y) + VARCOST(y) + ELASTCOST(y) - LATEREVENUES(y) - SALVAGE(z) \} \quad (3)$$

where;

O(z): Total system cost, discounted to the beginning of year z,

VAR_O(z): Total cost of all regions, discounted to year z,

REG_O(z, r): Total cost of the region r, discounted to year z.

INVCOST(y): It is the investment cost,

INVTAXSUB(y): The tax and subsidy costs,

INVDEC(y): Decommissioning capital costs, FIXCOST(y): It is the fixed annual cost,

FIXTAX(y): Fixed annual tax and subsidy, VARCOST(y): All variable costs (proportional to some activity),

ELASTCOST(y): Cost incurred when demand is reduced due to price elasticity,

LATEREVENUES(y): Revenue accounts for commodity recycling occurring after the end of horizon,

SALVAGE(z): Salvage value of all capital costs of technologies whole life extends beyond the end of horizon [54].

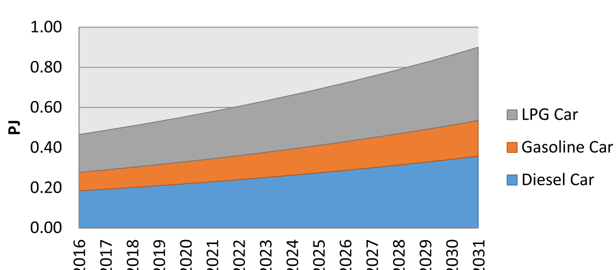

Fig. 5 – Gasoline, LPG and diesel cars total demands in base scenario.

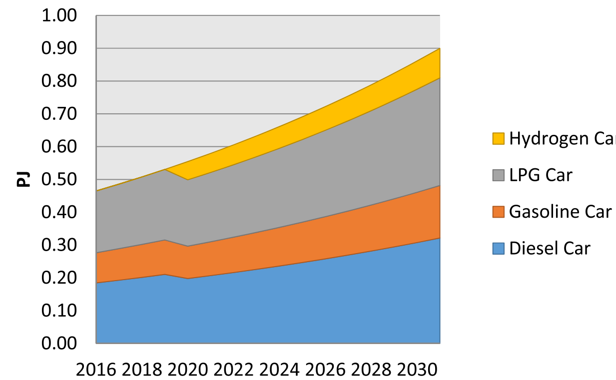

Fig. 6 – Demands of hydrogen, LPG, gasoline and diesel cars in alternative scenario.

The reference energy system of Burdur

A reference energy system (RES) is a detailed schematic of the analyzed energy system, including the conversion or processes and the flows of energy carriers throughout the energy system. The initial phase to develop a comprehensive energy database and model; namely, a detailed RES has been built

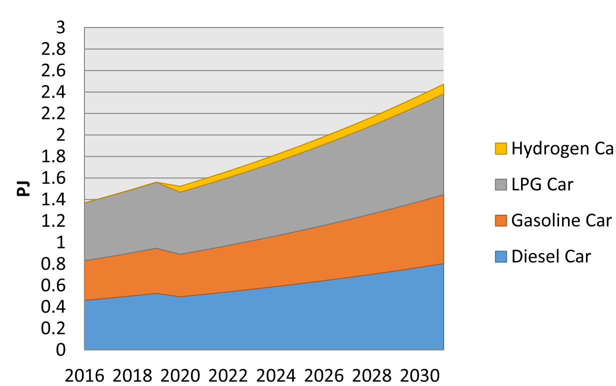

Fig. 7 – Process activity after hydrogen car implemented.

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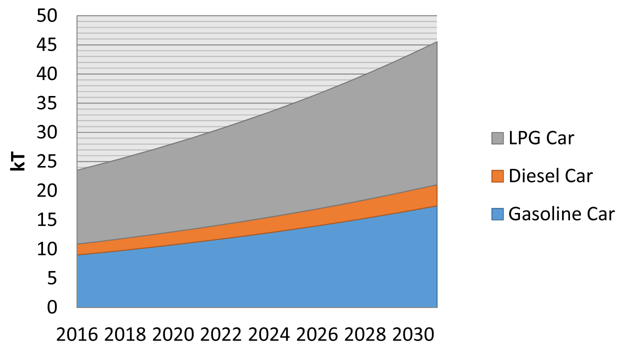

Fig. 8 – Annual CO_2 emission of LPG, gasoline and diesel car in base scenario.

representing the current energy system of Burdur as a detailed scheme of the analyzed energy system representing the input-output interaction of process-conversion technologies, demand devices and demands by energy commodities. It also represents how the commodities enter or leave to/from the region by mining, import, and export. Commodities imported or mined can be processed in the process or conversion technologies or facilities. Burdur city has been modelled as a single region in RES. Processed commodities (coal, crude oil, natural gas, etc.) or commodities already processed at the outside of the region have been utilized by demand devices or end-use technologies as coal, natural gas, diesel fuel, gasoline, LPG, electricity, low-temperature heat or high-temperature heat, etc. In the final part of the RES, end-use technologies have been linked to respective demands. Fig. 3 represents the reference energy system of Burdur province.

Burdur imports coal, gasoline, diesel fuel, LPG and two-thirds of its electricity from the national grid. The last one-third of its electricity is generated by two hydroelectric power plants, a natural gas power plant, and fifteen solar photovoltaic facilities. Natural gas and hydroelectric power plants have been specified to the energy database as ENRG-GAS-1, ENRG-HYD-1, and ENRG-HYD-2, respectively. Solar PV plants have been introduced to RES as ENRG-PV-1 to PV-15, reflecting the current situation of the current electricity generation infrastructure.

The demand side structure of Burdur has been classified into five major sectors. Residential and commercial demand group contains; space conditioning, cooking, illumination, cleaning, and entertainment demands. Main industry sectors are sugar production, cement production, marble quarry, marble process, and dairy products. These demand groups mainly consist of the industrial demand group. Other sector groups are specified as city service, passenger and freight transportation, and agricultural demands. The demand devices or end-use technologies can be seen under “Demand Technologies” pillar in Fig. 3.

Energy database of Burdur

Sectoral parameters and the relevant data has been collected from the meetings with experts from local Directorates of Ministry Offices in Burdur and official reports of Electricity Market Regulatory and Turkish Statistical Institute (TURKSTAT) database in order to establish the RES. The respective emission factors are calculated by using the Intergovernmental Panel on Climate Change (IPCC) methodology and National Greenhouse Gas Inventory Reports [55].

Demand increases, population growth rate and gross domestic product (GDP) forecasting from official statistics have been used for the demand projections. Table 3 shows demand groups and demand amounts in PJ.

Energy demands are clustered in five major components; i.e. residential and commercial, industrial, city service, transportation, and agricultural demands. Residential and commercial demand consists of cleaning, cooking, entertainment, illumination, and space conditioning in the residential and commercial buildings. Cement production, marble processing, and quarries, dairy and sugar have been classified under industrial demands, while the city services include the street illumination and traffic lights, and the transportation demand consists of freight and passenger transportation. Total demands are given in Table 3 and the time horizon of Burdur-TIMES model starts in 2016, extending to 2031.

Description of the alternative scenarios (HYD-1 and HYD-2)

The aim of this paper is to seek economic and environmental effects of hydrogen production and penetration of hydrogen cars into the energy system of Burdur. For this aim, the hydrogen production introduced into the energy system of Burdur in 2020, and then hydrogen cars with fuel cell technologies implemented into the system, as well. Two different alternative scenarios have been developed and applied against the Business as Usual (BAU) scenario. BAU scenario represents the current situation of the energy system by the growth of on-going trends in energy policy, energy carriers, energy technologies, and demands. In HYD-1 scenario, diesel, gasoline and LPG car demands identified into the system with a growing rate in parallel to the trend of population increase in Turkey, associated with the increasing total emissions caused by the passenger transportation demand. HYD-2 scenario is the mid-price level hydrogen production via hydrogen cars. In this scenario, 10% of the passenger transportation demand

Table 7 – Cost comparison of PEM and REP.

	Costs (Mi US $)	2016	2020	2026	2031	Cost increase (%)
Proton Exchange Membrane	Investment cost	0	0,098	0,128	0,159	9,63%
	Fixed O&M costs	0	1,737	2,264	2,823	170,60%
	Variable O&M costs	0	0,005	0,006	0,007	0,45%
Reformer-Electrolyzer-Purifier	Investment cost	0	0,072	0,093	0,116	7,03%
	Fixed O&M costs	0	0,42	0,548	0,683	41,28%
	Variable O&M costs	0	0,309	0,403	0,503	30,38%

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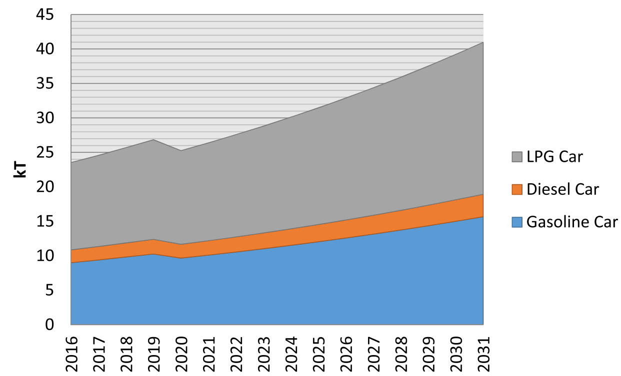

Fig. 9 – Annual CO_2 emission of LPG, gasoline and diesel car in alternative scenario.

has been relocated and calculated for hydrogen cars. To refuel the hydrogen cars, the exact amount of hydrogen production plant has been implemented to the system.

Limits and freedom issues specified in the scenarios have been shown in Table 4. Under the Base Scenario, it is assumed that the share of the fuels and technologies will continue by the same pattern over the modelling period, representing the continuation of the government energy policies and technological trends. Both HYD-1 and HYD-2 Scenarios, the model is supposed to increase the share of hydrogen cars allocating 10% of passenger transportation demand met by the diesel, gasoline, and LPG powered cars; while HYD-1 scenario addresses the low-cost and HYD-2 scenario addresses high-cost hydrogen production methods.

Fig. 4 shows the hydrogen production methods and costs. The proton exchange membrane electrolysis (PEM) technology has been used in the first alternative scenario. Basically, water is split to H^+ and O^{2-} ions by electrical current in the electrolyzer. H^+ cations pass through the cathode and at the cathode H^+ ions reforms into diatomic hydrogen. With this method, hydrogen production cost varies between 4.20 and 5.14 \$/kg-H_2. PEM central can produce 50000 kg/day hydrogen which is higher than annual needs. In this scenario, PEM projected current forecourt selected, with a cost of 5.14 \$/kg-H_2 and specified into the energy model database. Table 5 represents the cost breakdown of PEM production method. The total cost contains stack capital, the balance of plant (BOP) capital, indirect capital, decommissioning, fixed operations and maintenance, electricity feedstock, variable operation and maintenance costs.

HYD-2 scenario is based on the introduction of reformer-electrolyzer-purifier (REP) hydrogen production method to the current energy system. REP method is based on a fuel cell that operates reverse to produce hydrogen. In this method, electrolyte passes carbon ions; water, electricity and natural gas feed are the inputs and REP give the hydrogen output with a purity of 95%. Costs of REP method vary between 2.58 and 3.71 \$/kg H_2 [47]. Electrolyzer stack has to be replaced in every five years. In this scenario, integrated REP system used in calculations and capital cost, decommissioning, fixed operation and maintenance, feedstock and variable costs have been identified into the energy database of Burdur, as shown in Table 6.

Results analysis

Fig. 5 represents the base scenario results of the passenger transportation demand met by diesel, gasoline and LPG car process activities. According to the demand side of base scenario results, these three passenger transport technologies consume 0.45 PJ in 2016 and 0.9 PJ in 2031 BAU trends. At the process activity side, three technologies utilize 1.4 PJ in 2016 and 2.7 PJ in 2031 BAU trends.

10% of gasoline, diesel and LPG demand have been relocated by the hydrogen-based technologies. Fig. 6 shows that hydrogen car entered the market in 2020, by 0.0554 PJ and the total demand increases to 0.9 PJ in 2031.

10% of demand relocation of conventional car technologies impacted the system drastically. In BAU scenario, 2.7 PJ process activity occurred by conventional technologies. After implementing the high-efficiency hydrogen cars starting from the year 2020, total process activity decreased to 2.5 PJ in 2031. This means that 0.09 PJ of hydrogen car utilization decreased the total activity by 0.2 PJ in 2031, as can be seen in Fig. 7. To make more understandable of 0.2 PJ decrease, one can think that 6.3 MW power plant has to operate 8760 h (1 year) constantly to cover 0.2 PJ of energy.

Burdur-TIMES model gives economical results as another outcome of this study. Two different hydrogen production technologies have been evaluated in this analysis. HYD-1 scenario utilizes the PEM technology, and if the hydrogen would be produced by this technology, 0.005 mi \$ variable O&M, 1.737 mi \$ fixed O&M and 0.098 mi \$ investment cost occurs in 2020, mainly caused by the incremental hydrogen requirements. 0.007 mi \$ variable O&M, 2.823 mi \$ fixed O&M and 0.159 mi \$ investment cost addresses in 2031. HYD-2 scenario uses REP technology to produce hydrogen. In this method, 0.309 mi \$ variable O&M, 0.42 mi \$ fixed O&M and 0.072 mi \$ investment cost occurs in 2020. This costs increases to 0.503 mi \$ variable, 0.683 mi \$ fixed and 0.116 mi \$ investment in 2031. Despite the high cost of PEM, this technology requires natural gas feedstock. If construction location is far from to natural gas pipeline, REP method loses the advantage over PEM method. Proton exchange membrane method only needs electricity and water to feed the system Table 7.

Emissions are the third results of this analysis, as illustrated in Fig. 8. In the base scenario results, three conventional technologies cause 23.52 kT total CO_2 emission in 2016 and 46 kT in 2031, drawing an increasing trend.

After the implementation of hydrogen cars in 2020, total emissions decreased. Total equivalent CO_2 of the system is 23.5 kT in 2016, and 26.83 kT in 2019. After the hydrogen car enters the system, total CO_2 emission decreases to 25.26 kT in 2020 and with the usual trend, 41 kT CO_2 being emitted in 2031.

The annual CO_2 emission production differences between alternative and base scenarios are shown in Fig. 9. Between 2020 and 2031, only 0.09 PJ of hydrogen car activity prevents a total of 43.44 kT CO_2 emission in Burdur, addressing the 8% of the total emission in the base scenario.

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Conclusion

Base Scenario for Burdur City in Turkey has been developed using AnswerTIMES energy modelling framework to provide the energy mix and electricity generation technologies during the modelling period 2016–2031 under existing government policies, which has been calibrated for 2016 in the modelling period. This scenario satisfies the initial condition of meeting electricity demand and serves as a reference scenario for developing two alternative scenarios developed under the hydrogen technology scenarios, HYD-1 and HYD-2 based on the same modelling framework.

According to the demand projection in base scenario results, three of passenger transport technologies consume 0.45 PJ in 2016 and 0.9 PJ in 2031 BAU trends; where two different hydrogen production technologies have been evaluated in this analysis. HYD-1 scenario utilizes the PEM technology, and if the hydrogen would be produced by this technology, 0.005 mi $ variable O&M, 1.737 mi $ fixed O&M and 0.098 mi $ investment cost occur in 2020, mainly caused by the incremental hydrogen requirements. 0.007 mi $ variable O&M, 2.823 mi $ fixed O&M and 0.16 mi $ investment cost addresses in 2031. HYD-2 scenario uses REP technology to produce hydrogen. In this method, 0.3 mi $ variable O&M, 0.42 mi $ fixed O&M and 0.072 mi $ investment cost occurs in 2020. This costs increases to 0.5 mi $ variable O&M, 0.7 mi $ fixed and 0.116 mi $ investment costs in 2031.

In the base scenario results, three conventional transportation technologies create 23.52 kT total CO_2 emission in 2016 and 46 kT in 2031, by an increasing trend. In an environmental point of view; total equivalent of CO_2 emission in the analyzed energy system addresses 23.5 kT in 2016, and 41 kT CO_2 in 2031, after implementation of hydrogen cars in 2020. Only 0.09 PJ of hydrogen car activity prevents a total of 43.44 kT CO_2 emission in Burdur, corresponding 8% of the total emissions in the base scenario between the analysis period.

In conclusion, PEM technology results with an advantageous investment and variable O&M costs over REP technology, while PEM brings relatively higher fixed O&M costs, when compared to overall energy system profile. Although there is no formal policy for the dissemination of the use of hydrogen energy in the provinces, it is obvious that a strict regulation is required to deploy hydrogen as a clean, dependable option to diversify the energy mix on the current energy supply system of Burdur City.

Additionally, utilization of energy modelling tools should be applied both in universities and governmental level for decision-support in energy system analyses to support the policy makers. In the light of the above recommendations, efforts to include hydrogen as an energy carrier in the city energy system are expected to contribute positively to energy security and climate change in Burdur province.

Disclaimer

The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied of Turkish Armed Forces, Turkish Naval Forces, National Defense University, Marmara University, and any affiliated organization or government.

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