Advancements and Challenges in Solar Hydrogen Generation Systems: A Comprehensive Literature Review

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ABSTRACT : This study presents a comprehensive synthesis of existing literature on solar thermal systems and solar-hydrogen co-generation technologies, highlighting key findings and advancements derived from previously published research. By systematically reviewing various studies, critical parameters influencing the performance of Solar Water Heating (SWH) systems, such as refrigerant selection and thermal efficiency, are identified. Through the analysis of TRNSYS simulation outputs, the work emphasizes the efficacy of ammonia and ethylene as optimal working fluids, revealing significant energy gain rates and peak temperature outputs across different climatic conditions. Furthermore, the study explores the integration of solar-hydrogen systems, drawing from simulations under diverse environmental scenarios in Karachi, Pakistan, and Fargo, North Dakota, to demonstrate potential for sustainable energy production. Findings underscore the importance of thermal conductivity and fluid viscosity in enhancing system performance. This research aims to consolidate existing knowledge, offering valuable insights for future investigations in renewable energy systems rather than presenting new experimental data, thus providing a thorough overview of current advancements in solar thermal and hydrogen generation technologies.

Keywords: Renewable energy, Solar energy, Fossil fuels, Hydrogen energy, Solar water heating (SWH), Energy demand, Sustainability, Greenhouse gases, Photovoltaic (PV), Energy storage

1.1 Introduction

Energy demand is rising continuously worldwide due to technological growth, modern lifestyle, and growing population. To fulfill the exponentially increasing energy demand due to finite sources of fossil fuels, scientists and engineers are working hard on exploring renewable energy sources [1]. Fossil fuels are getting depleted due to their continuous use over the last 50 years, and in turn, emitting CO2 into the atmosphere.

Among renewable energy sources, solar is a very attractive option due to its abundance in nature and being freely available across the globe [2]. Solar energy is the most promising alternate energy source because of its abundance, sustainability, and environmentally benign nature. In the perspective of solar energy, if only 0.1% of this enormous energy ($1.08x10^{14}$ kW) is harnessed into useful energy with the help of a 10% efficient system, four times more than the global installed capacity of the world, which is about 3 TW, could be obtained [3].

Solar power is intended to make an important contribution to the world energy supply due to the finite amount of fossil fuels and increasing environmental awareness [4,5]. The hindrance in the effectiveness of solar energy utilization is the seasonal availability of the sun, which also varies with the time of day and seasons. Clouds may cover the sun at any time, thus direct radiation may not reach the surface of the earth. This occasional nature of solar energy reduces its effectiveness in domestic and commercial applications, specifically in standalone and district water heating. Transformation of solar energy into serviceable heat energy is one of the oldest and most natural techniques known to humans [6].

Renewable energy, a clean environment, and pollution-free culture can be integrated into society through collaborative learning at school and university levels [7-10]. Although fossil fuels are currently fulfilling the energy demands of the world, these resources are depleting, and energy demand cannot be met by them in the future.

1.1.1 Captivation of Hydrogen Energy

Hydrogen energy can be a potential candidate as a substitute for conventional fuels in the coming days due to its numerous benefits [11]. The combustion of hydrogen can produce approximately three times more energy than hydrocarbons, having a value of 39.4 kW h/kg [12]. The only byproduct of combustion is water [13]. The most prominent advantage is that hydrogen can be stored for extended periods with very minor losses, proving it a reliable source for electricity generation [14]. Hydrogen is also widely applicable in the transportation industry, being an efficient fuel for electric vehicles [15].

Hydrogen is the most abundant element in the environment, but it cannot be used as a primary fuel due to its molecular attachment to water and other hydrocarbons. It requires proper techniques for production and storage [17,18]. In recent years, there has been rising attention in the development of methodologies to produce H_2 from renewable and sustainable resources to avoid the greenhouse gas emissions caused by fossil fuel consumption. Though many techniques are available for hydrogen production, hydrogen fuel cells are highly efficient and produce limited emissions [19]. The photo-catalytic process for water splitting, using solar energy to produce hydrogen, offers an encouraging solution [20].

1.1.2 Solar Water Heating System (SWH)

Solar water heating (SWH) systems are energetically and exegetically the most suitable option for saving electricity. Currently, water heating consumes 20% of all household energy used in the USA. Installing SWH systems can save up to 90% of energy used for heating water [1,2]. As SWH is a green technology with no negative environmental impacts, its use has dramatically increased in recent decades due to its sustainability, low cost, and ease of use. When electricity is produced from fossil fuel combustion, CO2 emissions occur, contributing to environmental problems. These emissions are reduced with the installation of SWH systems instead of electric heaters [3]. According to the Renewable Energy Policy Network, approximately 70 million homes worldwide are now using SWH systems [4]. Solar thermal systems are desirable due to their high heat transfer capabilities and can be applied easily in both industrial and domestic settings [5]. A temperature of 30°C higher than ambient is achievable by an SWH system in Dhaka during the winter season [6]. SWH systems require low maintenance and have minimal operational expenses [7]. A typical SWH system consists of a thermal solar collector, a hot water storage tank, a pump to circulate the working fluid, and a controller to manage the flow. These systems are classified as direct and indirect. Direct systems warm water directly from the Sun's heat, while indirect systems use a refrigerant material [8]. In 2009, China reduced CO2 emissions by 26.36 million tons through the installation of SWH systems [9]. Glass tube collectors are more efficient than other types of solar collectors for high-temperature applications and can work under unpleasant weather conditions [10].

The need for hot water at the domestic level has a significant contribution to energy demand. A dynamic modeling study using TRNSYS software, conducted by Valdiserri, demonstrated the sizing process of the system and analyzed variations in the solar fraction and heat loss fraction for different cases [11]. Many studies have been conducted on heat extraction methods from solar collectors [12,13]. Bailey introduced a heat exchanger in the shape of a coiled tube inside the hot water storage tank, using a blend of water and alcohol to transfer heat from the collector to the tank. Selvakumar et al. studied the heat transfer and fluid flow characteristics of various heat transfer fluids [14]. For highly efficient SWH systems, the fluid must have high specific heat capacity, thermal conductivity, low viscosity, and low thermal expansion coefficients, and be anticorrosive and low-cost [15].

Refrigerants with ozone depletion potential (ODP) and high Global Warming Potential (GWP) are banned under the Montreal Protocol (1987) and Kyoto Protocol (1997) [16]. Natural refrigerants were in use until the 19th century but were replaced by synthetic refrigerants due to their toxic and flammable nature [17]. These synthetic refrigerants were also later banned due to their high ODP and long atmospheric life [18]. The focus of current research is on using environmentally friendly refrigerants with low ODP and GWP.

Hydrogen-powered systems are gaining attention for standalone systems. Domestic hot water can be produced by both solar thermal systems and hydrogen fuel cell systems. Heat energy produced by hydrogen fuel cells is directed to hot water tanks to provide uninterrupted domestic hot water during cold seasons, especially at night when solar insolation is not available.

This study is unique in employing solar thermal and hydrogen energy for heat generation in a hybrid model, a type of research not yet reported in the literature. Further hot water demand is met by hydrogen energy, used as an auxiliary source to cover peak load demand during the winter season.

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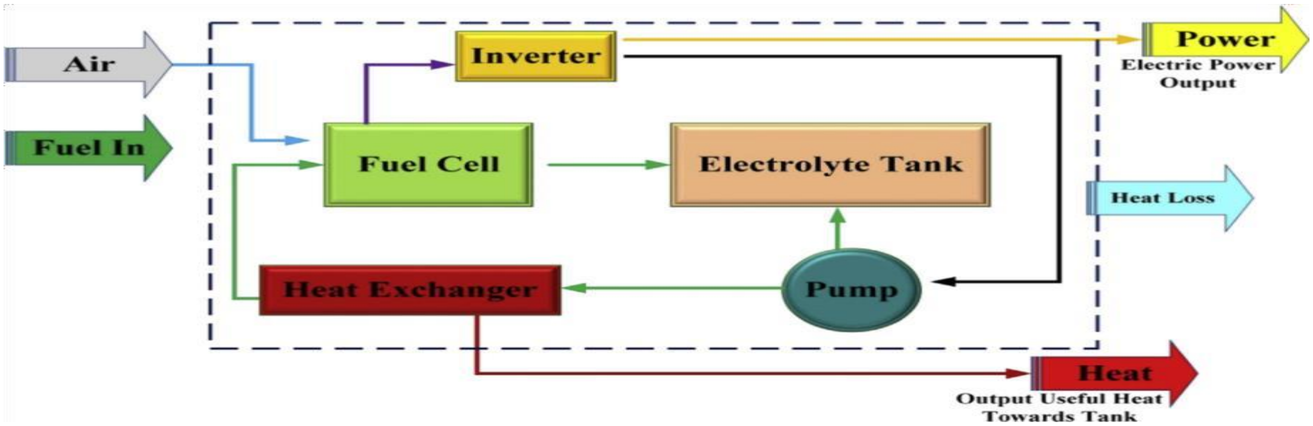

Fig.1: Schematic of energy production from fuel cell.

2.1 Review of Literature on Solar Hydrogen Generation Systems

The production of hydrogen energy promises a future where energy needs can be met with reduced emissions, minimizing environmental impacts. Hydrogen can be generated from sustainable and renewable resources, making it a promising solution to the rising global energy demand. As an energy carrier, hydrogen has the ability to store energy for later use, ensuring availability even when the primary energy source is insufficient or unavailable. This characteristic makes hydrogen an efficient medium for capturing, storing, and transporting solar energy. Moreover, the rate of hydrogen production is influenced by variables such as temperature and light intensity [1]-[3]. Lodhi [4] proposed a hybrid power plant that integrates solar thermal, photovoltaic (PV), and hydrogen energy resources, highlighting hydrogen's dual role as both an energy storage medium and a fuel alternative to conventional fossil fuels. Ulleberg et al. [5] conducted a parametric study using TRNSYS to evaluate a solar-hydrogen system in sub-zero temperatures and low solar radiation conditions. Their study concluded that under such harsh climates, the size of the solarhydrogen system must be significantly large to achieve desired outputs. However, in regions with high solar insolation, the results were more favourable. The researchers recommended reducing thermal and electrical loads within buildings before designing such systems.

Midilli et al. [6] investigated the global stability and sustainability impacts of hydrogen energy, finding that increased use of hydrogen boosts global stability and sustainability ratios. Jose L. et al. [7] suggested using hydrogen storage instead of traditional batteries in renewable energy systems, which enhances reliability and economic performance. Despite these benefits, the high costs associated with electrolyzers and fuel cells, as well as low conversion rates, currently limit their viability. Joshi [8] compared the performance of solar thermal and PV systems for hydrogen production, concluding that the solar thermal method, which generates electricity, is more energy efficient and environmentally friendly. However, PV systems, while having lower energy efficiency due to limited PV performance, benefit from having no moving parts.

Zamfirescu [9] proposed an innovative hybrid system that combines photocatalysis, photovoltaics, thermal engines, and chemical energy storage to improve solar energy harnessing efficiency. An economic analysis suggested that the system is feasible as long as capital investment remains reasonable. Ahmad [10] reviewed the role of reducing agents in water reduction using photoelectrons and highlighted the potential of optimizing photocatalysts to enhance performance under visible light with improved chemical and physical stability.

Bicer et al. [11] developed a hybrid system combining solar and geothermal energy for hydrogen production, power generation, and thermal applications. Their study evaluated the impact of various system parameters on energy and energy performance and found that at a geothermal water temperature of 220°C, maximum efficiencies of 15% and 65% were achieved. Isobutane was identified as the optimal working fluid for the organic Rankine cycle under these conditions. Omar et al. [12] conducted a simulation of a hybrid collector system for hydrogen production, revealing that while pressure has minimal impact on H2 and O2 production, temperature significantly affects both.

Wei et al. [13] designed a compound parabolic concentrator (CPC) thermal collector for hydrogen generation, achieving an average energy conversion efficiency of 2.98% in laboratory settings, though efficiency dropped to 0.087% in an open environment. Gheorghe et al. [14] analyzed a 100 kg daily capacity hydrogen generation and storage system, powered by solar energy for water electrolysis. They evaluated four technical solutions and three sub-systems for H2 generation and storage,

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concluding that a hybrid solar hydrogen production system can effectively convert solar energy into chemical energy in the form of H2, utilizing both electrical and thermal energy efficiently.

3.1 Methods and Simulation Model

The use of simulation tools is essential in the design and optimization of complex energy systems. Creating a theoretical model often involves numerous iterations and parameter adjustments to ensure accuracy and reliability. Due to the challenges in replicating experimental conditions— such as long durations, financial constraints, and other practical limitations—physical testing is not always feasible. Therefore, simulation software like TRNSYS is employed to model and analyze the system's behaviour, allowing researchers to evaluate performance under various conditions without the need for extensive physical trials [15].

3.2 Simulation model in TRNSYS

Design and optimization of theoretical models is a process of interpolation with a lot of iteration steps. Practical model implementation involves detailed setting of parameters and testing. Sometimes it is hard to create experimental circumstances in the lab due to limitations. Physical experiments are not possible at all due to extreme run duration, trade-offs, and socio-financial implications. So, the designed system is modelled and simulated to check its behaviour in simulation modeling tools [16].

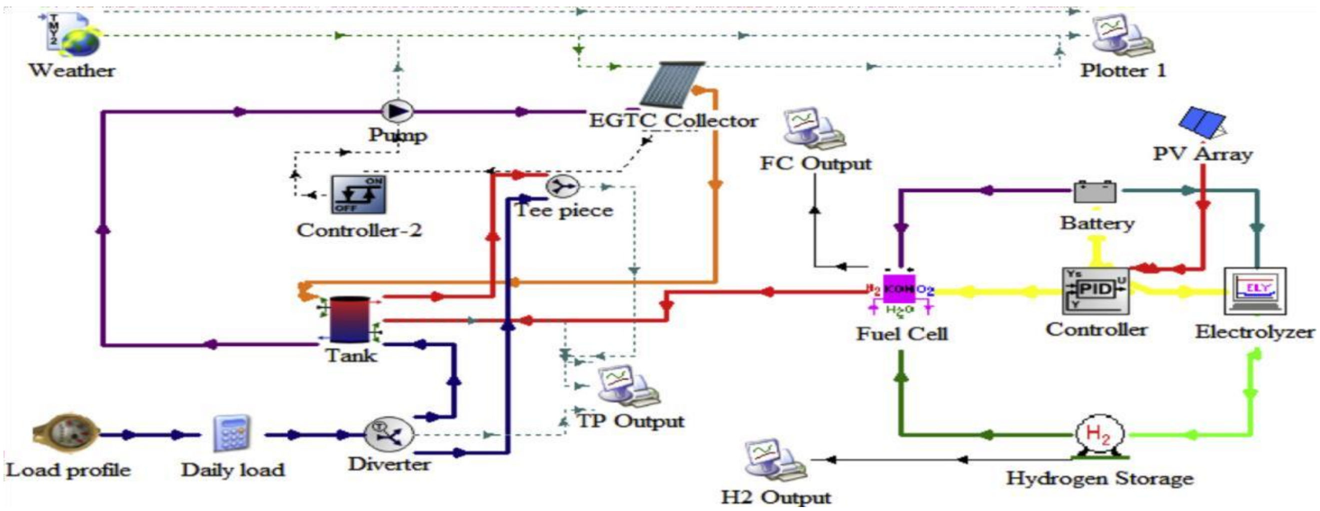

Fig.2: TRNSYS model for Hybrid Solar-Hydrogen System.

Heat energy from both loops is collected at storage tank. Output online plotters are used to draw the graph of the components at monitoring level. System components in TRNSYS environment for H_2 production are shown in Fig. 2.

Schematic for employment of solar thermal and photovoltaic for thermal energy generation is shown in Fig. 3.

3.2.1 Detail of system components, types and model

System components to design the model are illustrated below: **a. Evacuated Tube Collector**

Evacuated glass tube solar collector (Type71) is selected in this design from standard TESS solar thermal collector library [8]. EGTC offer better performance than other types of solar collectors under severe environmental conditions and provide high heat transport capability [4]. It can be applied for high temperature applications ranging from 70 to 120^{0}C [8].

Thermal efficiency of a EGTC can be find mathematically by following equation [8]:

$$\eta = a_0 - a_1 \frac{(\Delta T)}{I_T} - a_2 \frac{(\Delta T)^2}{I_T}$$

The following three parameters state thermal efficiency of system as a0, a1 and a2.

. **b. Weather Data Processor**

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Weather Data Read and Process Unit (Type 15) loads metrological data file from TRNSYS built in Metronome files with extension.tm2 [8]. Weather data from this external file is read at steady time gaps, incorporates data at time paces below 60 min and provides it to other TRNSYS components.

c. Storage Tank with Internal Heat Exchangers

This element performs the modeling of a stratified fluid storage tank with elective option of internal heaters and optional internal heat exchangers. This model consists of two electric resistance heaters with time control functions of temperature. During peak load times, this control option provides auxiliary heating by incorporating electrical energy.

This model gives provision of up to three internal heat exchangers. Temperature, flow rate and heat exchanger magnitudes are selection parameters defined by user. The Logarithmic Mean Temperature Difference (LMTD) of all heat exchangers is calculated iteratively. The outside natural convection coefficient ho is determined from [2]:

$$h_0 = \frac{Nu_0(k)}{d_0}$$

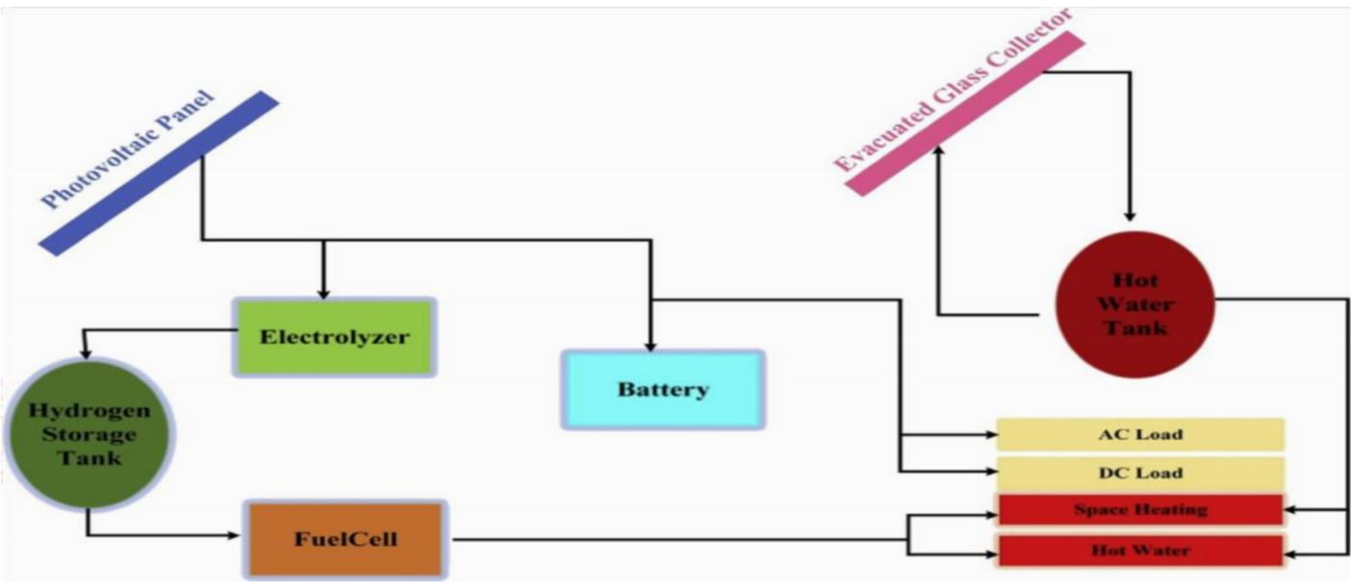

Fig.3: Employment of Solar thermal and PV for heat generation.

Table 2: Control Parameters of PID controller.

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S/N	Parameter	Description	Unit
1	Gain Constant	This is the gain of the PID controller which acts on three parts of the signal: proportional, integral and derivative.	-
2	Integral Time	Ti is the integral (or reset) time of the controller. User can set Ti to 0 to disable integral control.	hr
3	Derivative Time	Td is the derivative time of the controller. It can be set to 0 to disable the derivative control.	hr

Where do is the outside diameter of heat exchanger tubes and NuD is the Nusselt number for peripheral flow around a tube of diameter D. To Model the tank with internal heat exchanger, program starts iterations from the inlet node of the main coil and ends at the outlet node point of the coil.

d. PID Controller

The PID controller calculates the control signal required to maintain the controlled variable at the set point. It is based on state-of-the-art discrete algorithms for PID controllers and implements anti windup for the integrator. This controller can operate in two modes: mode 0 implements a "real life" (non-iterative) controller, and mode 1 implements an iterative controller. Optimal parameters depend on the algorithm used in the PID, for which different implementations are available. Please check the manual for more in-formation on this component's algorithm. Working mode will provide a faster response at the expense of more iteration and the optimal parameters may be far from real-world values for a similar system. Control parameters are described in Table 2 along unit.

e. Electrolyzer

This subroutine is a combination of a set of control functions for an electrolyzer of a cohesive mini-grid coupled with wind/electrolyzer/H2-storage/fuel cell system. The electrolyzer is designed to work in a constant power mode. The electrolyzers are associated to the mini-grid via power conditioning equipment. Henceforth, the power set point signal should be directed to the output equipment, and not to the electrolyzer itself. Electricity generation from Hydrogen in an Advanced Alkaline Water Electrolyzer is modelled in Type 160 in TRNSYS. The model is based on a combination of fundamental thermodynamics, heat transfer theory, and empirical electrochemical relationships.

f. Alkaline Fuel Cell (AFC)

TYPE173 is a simple mathematical model for an alkaline fuel cell (AFC). The electrochemical model is based on an empirical relationship for the current-voltage characteristic at normal operating temperature. The heat generated by the AFC-stack is calculated. A fuel cell is an electrochemical device that converts the chemical energy of a fuel and an oxidant to electrical current (DC). In the case of a hydrogen-air fuel cell, hydrogen (H2) is the fuel and air (O2) is the oxidant. Below equations show the anode, cathode and over all reactions respectively, which take place in a PEM fuel cell [8].

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$H_2(g) = 2H^+ (aq) + 2e^+$

$2H^+ (aq) + 2e^- + ½ O_2 (g) = H_2O (l)$

$H_2(g) + ½ O_2 (g) = H_2O (l)$

g. Compressed Gas Storage

TYPE164 is a compressed gas storage model. This model is used for the storage of hydrogen gas produced by the system. This instance of the model calculates the pressure in the storage based on the ideal gas law. **h. Photovoltaic Array**

This component models the electrical performance of a photovoltaic array. TYPE 94 may be used in simulations involving electrical storage batteries, direct load coupling, and utility grid connections. It employs equations for an empirical equivalent circuit model to predict the currentvoltage characteristics of a single module. This circuit consists of a DC current source, diode, and either one or two resistors. The strength of the current source is dependent on solar radiation and the IeV characteristics of the diode are temperature-dependent. The results for a single module equivalent circuit are extrapolated to predict the performance of a multi-module array. This model determines PV current as a function of load voltage. Other outputs include current and voltage at the maximum power point along the IV curve, open-circuit voltage, and short circuit current.

3.3 Simulation Process

To measure the dynamic system's performance under super-critical state, two electrical controllers are added in loops of the solar water heating system. Heat exchange material inside the collector absorbs the radiant heat from sun and transmits it to water inside the storage tank through immersed heat exchanger. Forced circulation is used to flow the mediating fluid through the cycle via feed pump. Water draw off load profile is attached to storage tank which defines the demand of water at various times of the day round the clock. PV module absorbs the heat energy of sun and provides electrical units of energy to electrolyzer via battery storage and PID controller. Hydrogen energy produced is stored in the hydrogen storage tank. Fuel cell takes fuel intake of Air/O2 from open environment and H2 from hydrogen storage tank to produce energy. This heat energy works as auxiliary energy to aid EGTC to fulfill demand of hot water as per load profile given in Fig. 4.

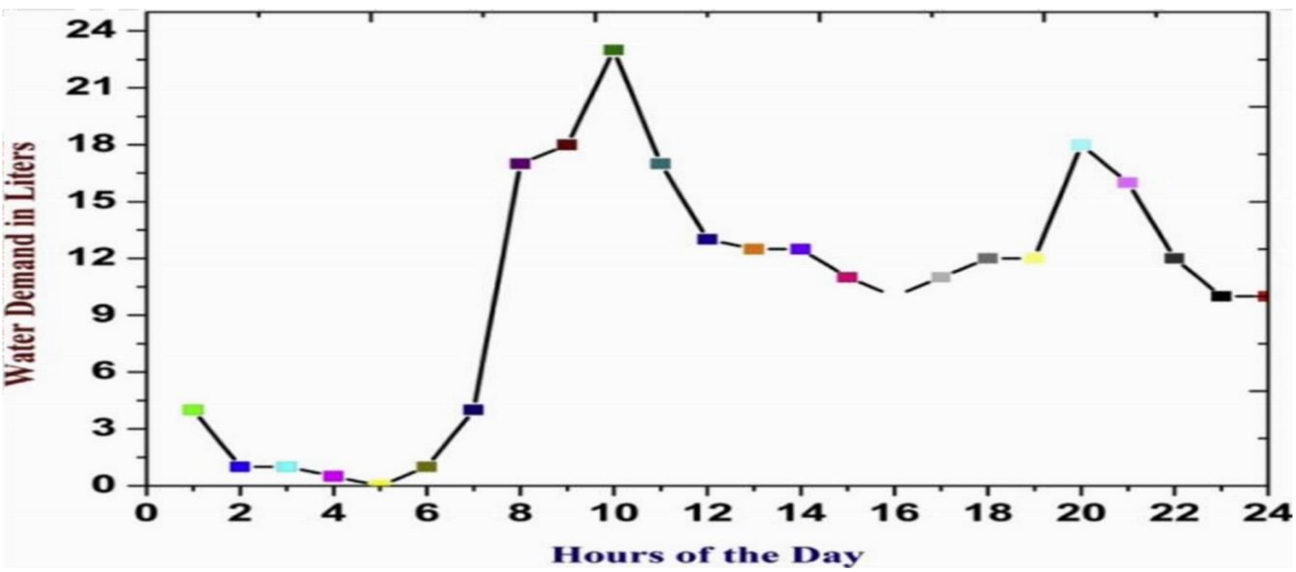

Fig. 4: Daily domestic hot water (DHW) consumption profile [8].

Steps of the system simulation and working are as follows:

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i. As the temperature of working fluid at the outlet of thermal collector crosses the dead band limit of 30^0C, the controller will divert it towards water tank to exchange heat with utility cold water. At this stage the flow rate of cooling water is assumed 300 kg/h.

ii. When the temperature of refrigerant at collector outlet falls below 30^0C, the controller will sidestep the water tank and direct the flow towards heat exchanger through t-piece. During this mode the flow rate through heat exchanger will be 150 kg/h.

iii. When the temperature of mediating fluid is less than 15^0C the controller will turn off the pump and wait until temperature rises up to 15^0C.

iv. A daily hot water demand profiles for a single family of 2-3 members is also presented.

v. Photovoltaic system powers the electrolyzer for the generation of hydrogen gas. A SOC parameter H_2-storage 'state of charge' which depends upon normalized pressure level is used for normal operation of electrolyzer.

vi. Generated hydrogen is stored in hydrogen storage tank and volume of gas stored in tank is1Nm^3 at 0^0Cand1bar initially.

vii. An alkaline fuel cell takes air and hydrogen as input and outputs heat generated by stack at 8700 W and electrical power output from FC unit at default value of 6700 W.

Flow diagram of the model developed in TRNSYS is shown in Fig. 5.

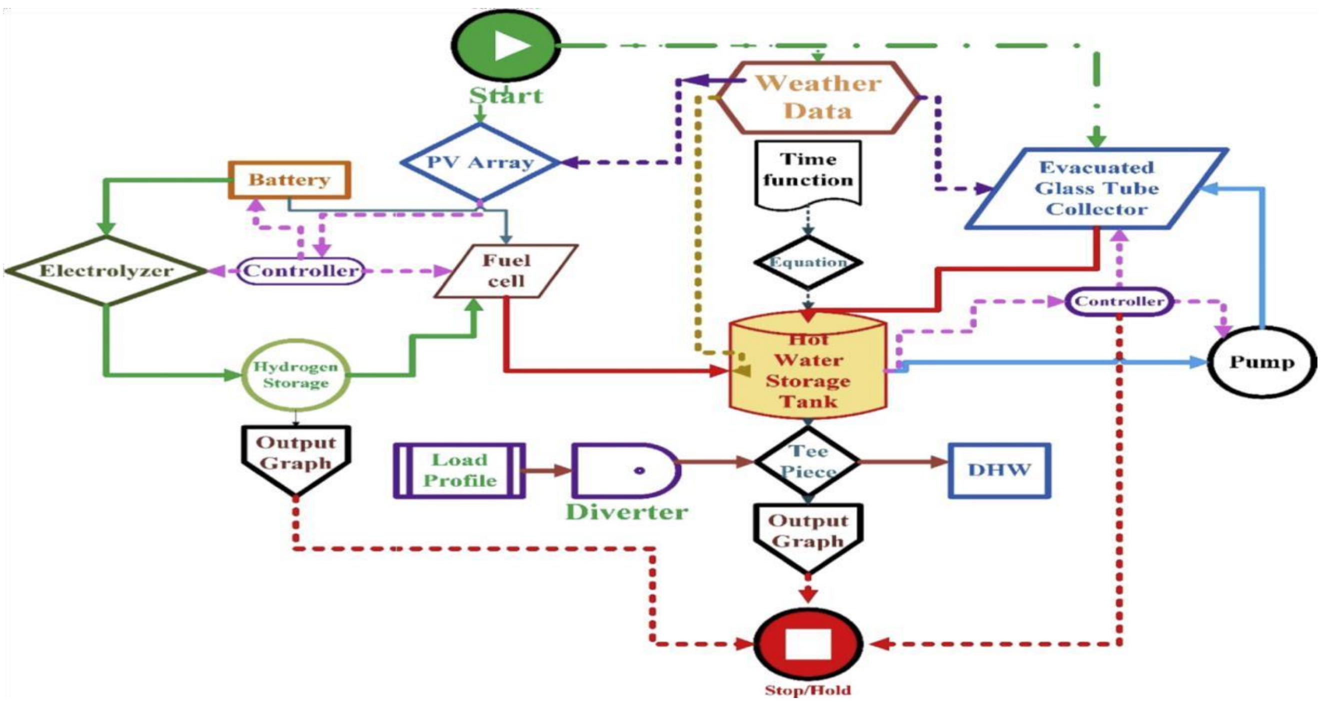

Fig. 5: Flow Diagram of hybrid system modelled in TRNSYS.

3.4 TRNSYS simulation

To observe the effect of working fluids on water heating loop with Evacuated Glass Tube solar collector, thermal properties of each fluid are loaded in the loop one by one and remaining other parameters are kept constant in TRNSYS. Hybrid system for hydrogen production is composed of electrolyzer, which performs electrolysis of water and produces hydrogen. This produced hydrogen is then stored in storage tank which may also be transported for other applications. In this model, hydrogen is then supplied to fuel cell as energy fuel to produce useful heat and energy. Heat is delivered to storage tank with internally immersed heat exchangers to heat the water for domestic water supply.

Operating mode 0 of the solar collector model inputs the properties of the fluid. This mode offers the flexibility to user to input the fluid thermal parameters [2]. For this simulation, two different weather data illustrations are designated in TRNSYS. The

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1stweek of January plot hours 1 to 168 is chosen as cold weather period data and 1st week of July plot hours 4344e4512 as hot weather period data to observe system performance under both climate crests.

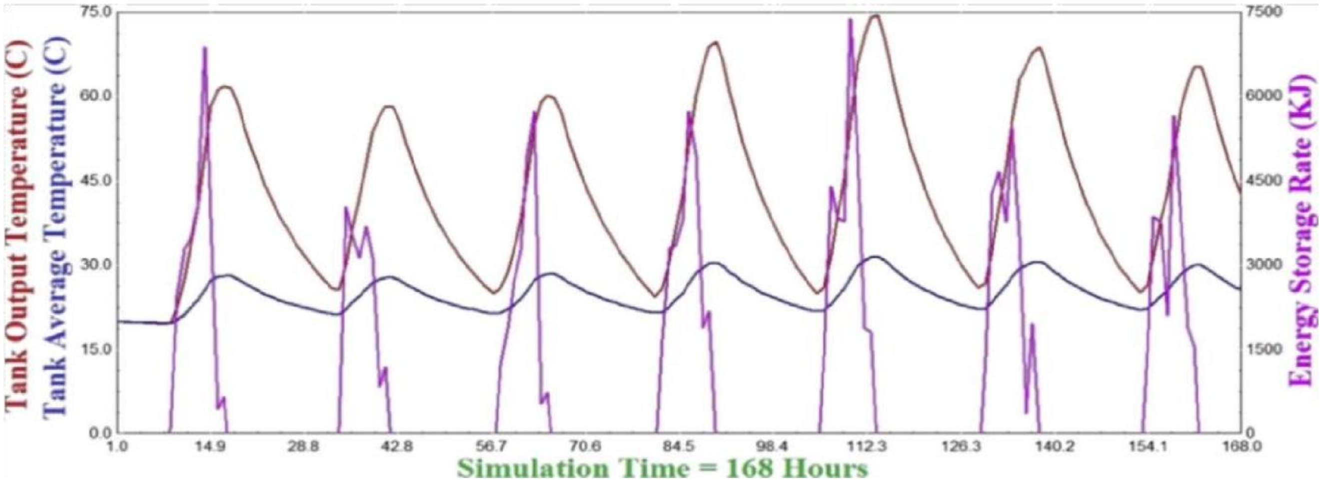

Fig.6: System output for ammonia (January week).

3.5 Hybrid solar-hydrogen energy generation system

In this study a hybrid solar collector is used to simulate hydrogen production system through water electrolysis.

Hydrogen (H2) is a sustainable source of chemical energy storage for long duration without dripping [88]. Its generation is quite laidback and can easily be converted to other sources of energy like thermal energy and electrical energy [5]. For the time being hydrogen energy production systems are relatively very expensive than other fuel generation systems [6]. A hybrid hydrogen system production is simulated in TRNSYS by joining components of thermal and hydrogen system libraries. Components used for hydrogen energy production are an electrolyzer (Type100), PV Array (Type94).

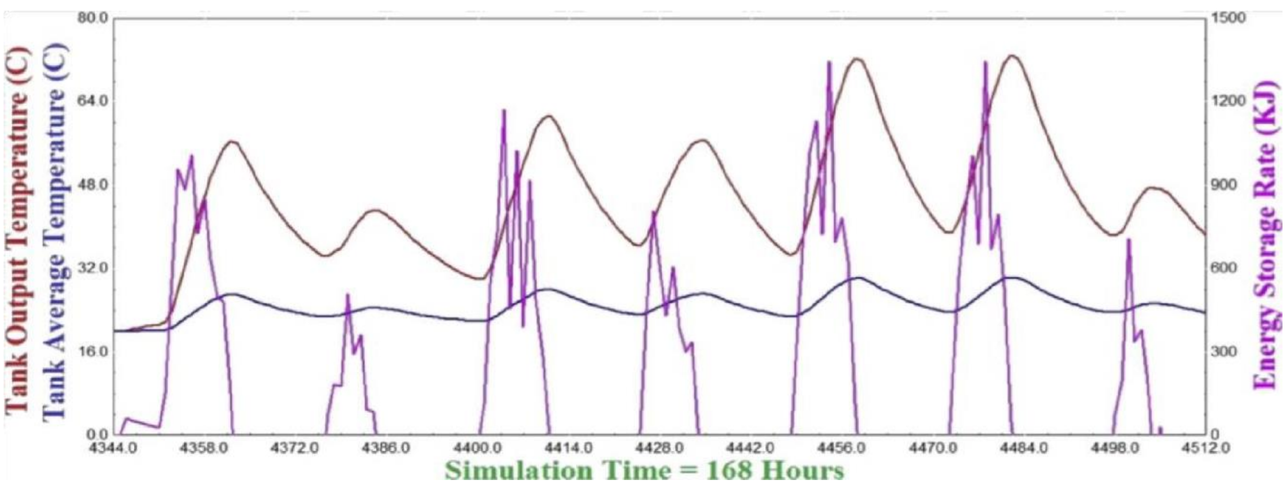

Fig.7: System output for R123 (January week)

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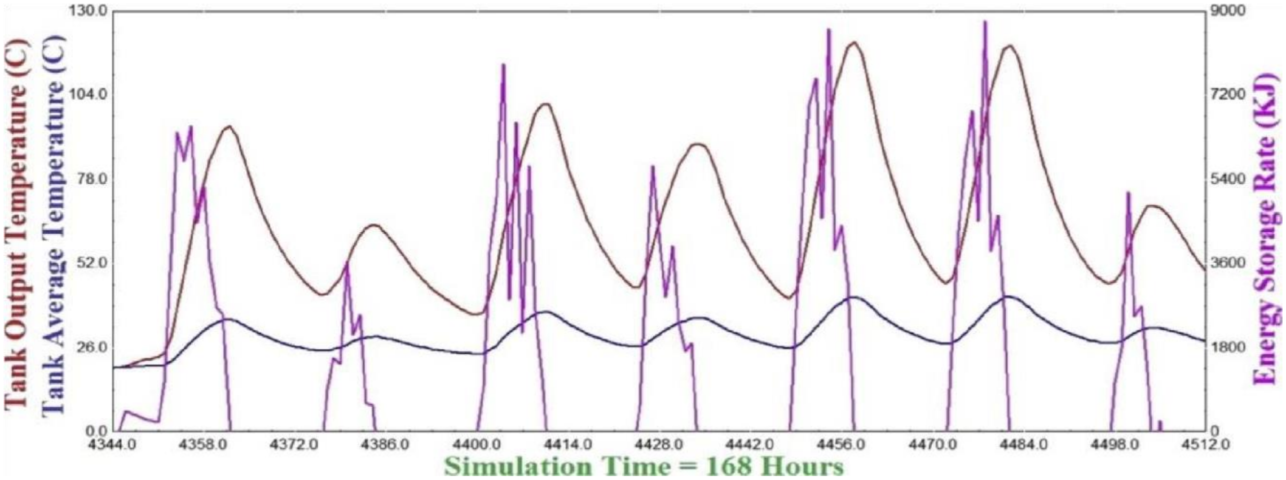

Fig.8: Collector output for ammonia (July week)

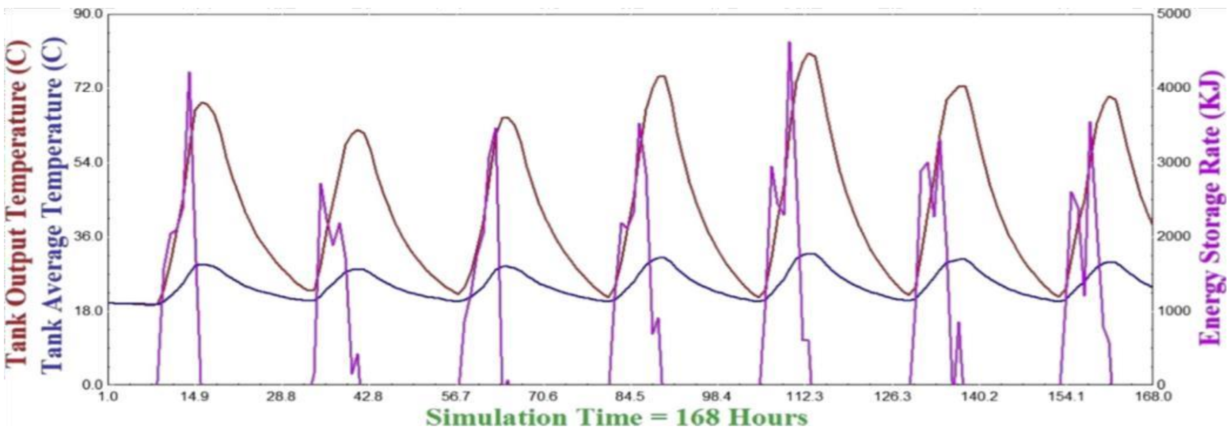

Fig.9: System output for R123 (July week).

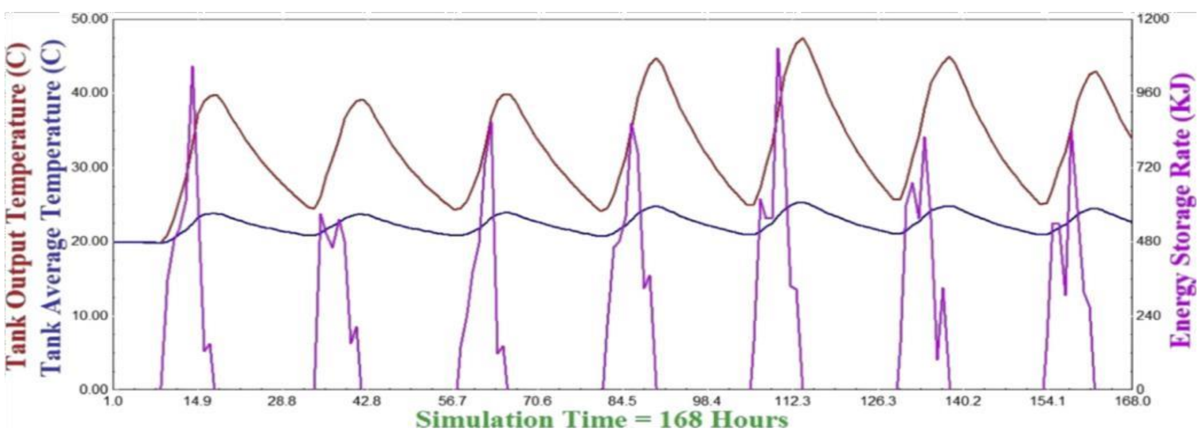

Fig. 10: System output for ethane (January week).

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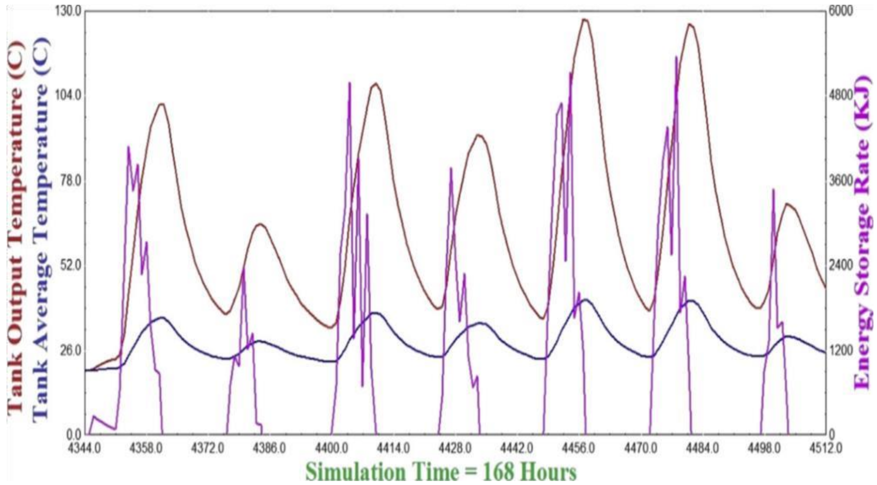

Fig. 11: Collector output for ethane (July week).

Hydrogen energy storage (Type164), a fuel cell (Type173) and battery (Type47).

Thermal energy generated by fuel cell system is transmitted to hot water storage tank where it is exchanged with water inside the tank through immersed heat exchanger. Metrological weather data for study of system is selected as Lahore, Pakistan and Fargo, North Dakota being hot and cold climates correspondingly. Mathematically, pressure p of a real gas inside the storage tank may be calculated using the van der Waals equation of state [8]:

$$p = \frac{n.R.T_{gas}}{Vol - n.b} - \frac{a.n^2}{Vol^2}$$

Where n is number of moles of gas, R is the universal gas constant, Vol is the volume of the storage tank, and Tgas is the temperature of the gas. The second term (comprising the constant a) account for the intermolecular attraction forces, while b accounts for the volume occupied by the gas molecules. Chemical reaction inside the fuel cell is given by [8]:

$$H_{2(g)} + \frac{1}{2}O_{2(g)} = H_2O$$

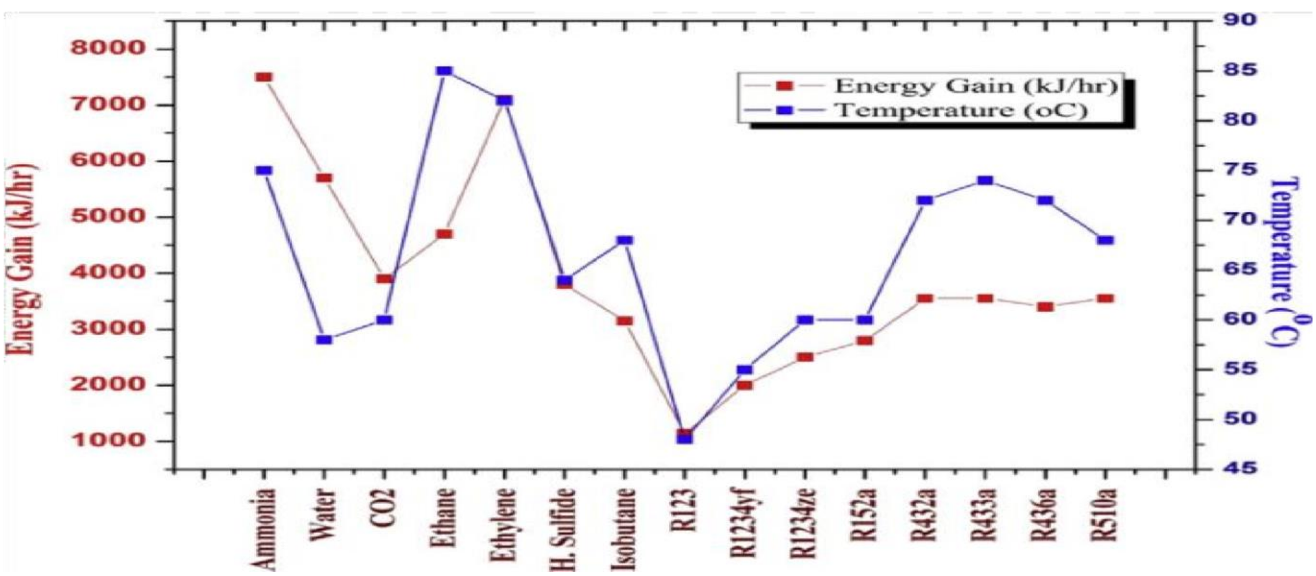

Fig. 12: Plot of energy gain and temperature for refrigerants (January week).

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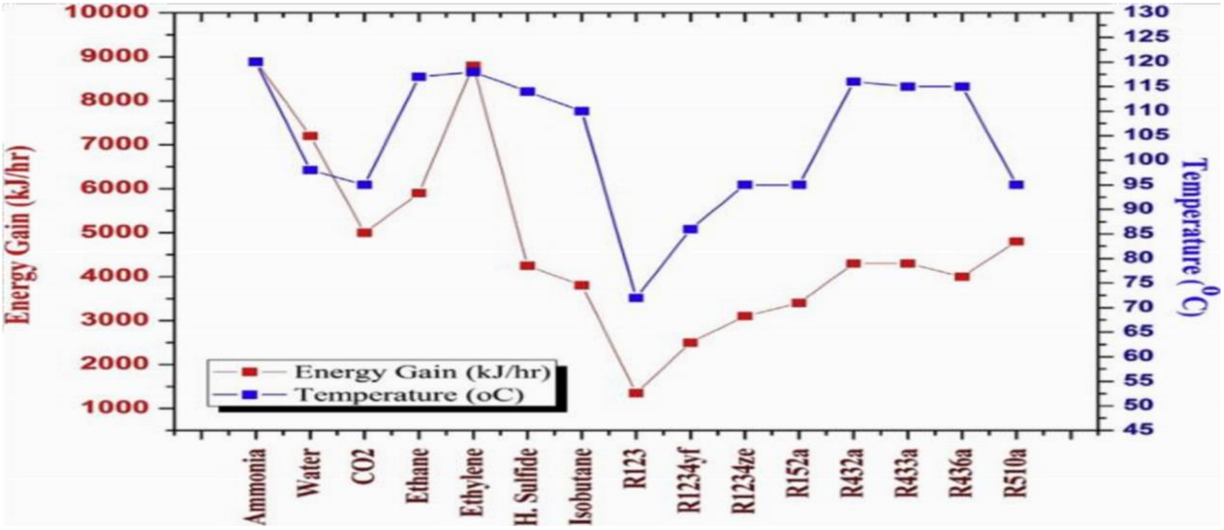

Fig. 13: Plot of energy gain and temperature for refrigerants (July week).

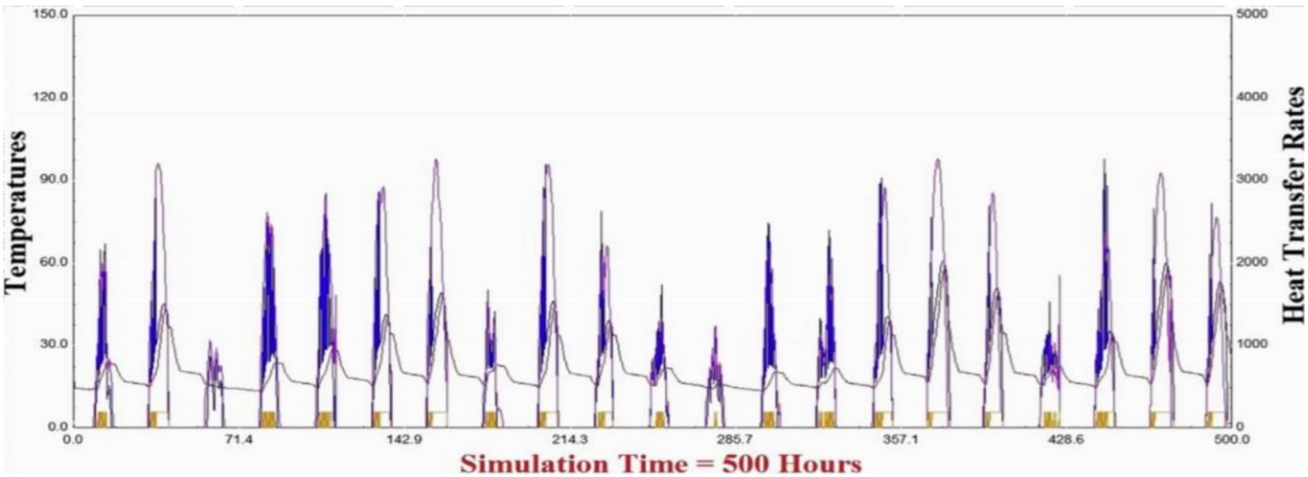

Fig. 14: Output of hydrogen energy system in TRNSYS

4.1 Results and Discussions

The output of a concentrated solar system is measured in terms of useful energy gain (kJ/hr) and peak and average tank output temperatures (°C). This study provides maximum values for energy gain and tank output temperature for various working fluids as obtained from TRNSYS simulations. Figures 11 illustrate the energy gain and temperature changes over time for January and July. Simulation results indicate that ammonia, as the working fluid in the hot water loop, achieves maximum energy gains of 7,500 kJ/h in winter and 9,000 kJ/h in summer, with peak temperatures of 75°C and 120°C, respectively. Ethane reaches a maximum temperature gain of 85°C in early January. Ethylene ranks as the second-best refrigerant, yielding heat gains of 7,100 kJ/h and 8,800 kJ/h during the winter and summer weeks, respectively, with corresponding temperatures of 82°C and 118°C. Conversely, R123 demonstrates the least performance, achieving only 1,140 kJ/h in winter and 1,350 kJ/h in summer, with lower temperatures of 48°C and 72°C. Figures 12 and 13 present cumulative plots for all fluids under study, facilitating a comparison of energy gain and temperature. The results highlight that refrigerants with higher thermal conductivity and lower viscosity enhance heat transfer efficiency.

4.3 Results of hybrid solar-hydrogen loop

Hybrid system for generation of hydrogen energy consists of an electrolyzer and alkaline fuel cell. Output parameters are total output power of fuel cell (W), current density defined as electrical current per square unit of area (cross-sectional area of electrode) measured in mA/cm2, energy efficiency ETAe, total heat energy generated by FC unit measured in Watt, voltage across each FC stack in parallel that is equal to voltage across terminals of FC unit.

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The key finding parameter is output power which is converted to (kWh/kg) standard units by employing unit conversion routine in TRNSYS. Amongst the fuels used, hydrogen is considered as supreme fuel as it is a carbon-neutral, sustainable fuel and owns many distinctive physicochemical properties comprising easy to transport, storage and handling.

Results show that a reasonable amount of energy demand covered by addition of hybrid hydrogen energy production system. Model has showed promising results to fill demand gap by providing 85% of required energy in the summer season due to hot climate.

5.1 Conclusions

A Solar Water Heating (SWH) system was simulated year-round for Karachi's climate. Various parameters were analyzed, including refrigerant selection for optimal heat exchange. Simulations using TRNSYS software plotted energy gain and temperature outputs. Refrigerant properties included specific heat (kJ/kg-K), density (kg/m³), thermal conductivity (kJ/hr-m-K), viscosity (kg/m/hr), and thermal expansion (1/K). Ammonia emerged as the best refrigerant with energy gains of 7.50×10^3 kJ/hr in January and 8.90×10^3 kJ/hr in July. Ethylene followed, while R123 performed the worst. Higher thermal conductivity proved crucial for effective heat transfer. Peak system efficiency occurred in July, with a solar fraction of 0.83 and 43% efficiency, while December showed reduced performance with a solar fraction of 0.41.

A solar-hydrogen co-generation system was also simulated for Lahore, Pakistan (high solar irradiation) and Fargo, North Dakota (low insolation) using water electrolysis. The system, comprising a PV array, electrolyzer, fuel cell, battery, hydrogen storage, and controller, achieved 7.8% efficiency in Fargo and 11.8% in Lahore. Literature suggests solar-to-hydrogen systems can reach up to 13.1% efficiency with optimal design, and efficiency increases with solar flux. The system covered 85% of water demand in summer and 53% in winter due to lower available solar energy.

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