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Design and Simulation of Hybrid Renewable Energy System (HRES) With Hydrogen Storage for Greener Energy

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Abstract: *This work investigates the design and simulation of hybrid renewable energy* system *(HRES)with hydrogen storage for possible application in small rural or buusiness units.Solar photovoltaic-wind turbine-biogas generator-electrolyzer-hydrogen, tank-fuel, cell-converter have been optimized and simulated for an Oregon PackagingCompany,located in Hadimkoy, Istanbul Turkey. Excess power available from solar photovoltaic panels and wind turbine generators were stored in the form of hydrogen gas produced by electrolyzer.When the energy generated from solar photovoltaic and the wind turbine is not enough to meet the load demmand, the stored hydrogenis then converted by the use of fuel cell to generate electricity. The simulation and optimization were carried out using HOMER Pro (Hybrid Optimization Model Electric Renewable). Five different scenarios A, B, C, D, and E were compared using the same variable cases in terms of techno-economical aspects. The simulation result revealed that scenario A is the most optimal and cost- effective, followed by scenario B with net present cost (NPC) of $113,612,$139,822 and cost of energy (COE) of $0.030kWh, $0.084kWh respectively.*

Keywords: HOMER pro, wind speed sources, solar irradiation, biomass sources, net present cost (NPC), cost of energy (COE).

INTRODUCTION

Energy is essential in order to advance environment and value of life by improving fundamental desires such as lighting, heat for cooking, power for entertaining devices and labor-saving applications [1,2, and 3]. Recently,fossil fuels accounted for about 86% of all the energy production globally, the superior part of which was consumed by developed nations.[4]. The amount of energy used around the globe is anticipated to go up around 2% by 2030, if the current global greenhouse gasses emissions continue to rise, with this anticipation,there could be tendency of world temperature to increase by roughly about 1-3.5°C[5]. This could lead to reduced food production, increase the risk of flooding and wildfire [5]. The impact of greenhouse gases emission and the resulting climate change have also a serious consequence on the global economy, [6] hence, researchers have focused on developing a greener, safer, cost-effective renewable energy alternative such as the hybrid system.However, to overcome the problems of fossil fuels and their effects on our environment,it is pertinent to explore the abundant renewable energy sources (RES) that are emission free in the supply of energy. Innovative technologies like hybrid systems are becoming to the fore as suitable alternatives to fossil fuels. The use of Hybrid renewable energy systems (HRES) could reduce carbon footprint by 60%-80% [7, 11]In general, the key reason for the design and simulation of Hybrid renewable energy systems (HRES) including solarphotovoltaic/wind turbine/biogas generator/Electrolyzer/fuel cell with hydrogen storage systems play a crucial role in the supply of energy security, improve power quality, reliability and emmployment opportunity to our teaming youth. Since renewable energy resources are intermittent in nature,therefore, hybridization of two or more power generation technologies along with hydrogen storage can improve systems performance and engender a feeling of confidence of being in control [8, 12, and 13].

In this regard, integrated renewable energy system was designed and simulated for electricity requirements for Oregon Packaging Company, Hadimkoy, Istanbul Turkey to determine the optimal hybrid renewable energy systems that could cover the load of the company using HOMER Pro (Hybrid Optimization Model Electric Renewable). HOMER Pro is a computer model developed by NREL (National Renewable Energy Laboratory United State)and performs techno-economic analyses on proposed power system. The software has been used extensively in various case studies [9, 10, 11, 12, and 15]. The inputs into HOMER Pro include load data, renewable resources data, systems component specification, costs and other information required for optimization. Thus, to obtain the input data for the software,component information and costs were collected from the research literature, publications and manufacturers instruction. HOMER Pro was used for hourly simulations and environmental data assessment of Hybrid renewable energy systems (HRES). The software performed optimization based on net present cost (NPC),cost of energy (COE) and excess electricity production.

Case Study Area Description

The annual average electric load of Orego packaging Company,was 114.9 Kwh/day.orego is a food packaging and bowl producing company with a capacity of 240,000 units / day. Located at Hadimkoy Tem GiseleriYani, OzdokuBinasi 34555, 34555 Esenyurt Istanbul with the coordinate (41.0909° N, 28.6215o E). The map below shows the location of the company in Turkey (Figure 1)

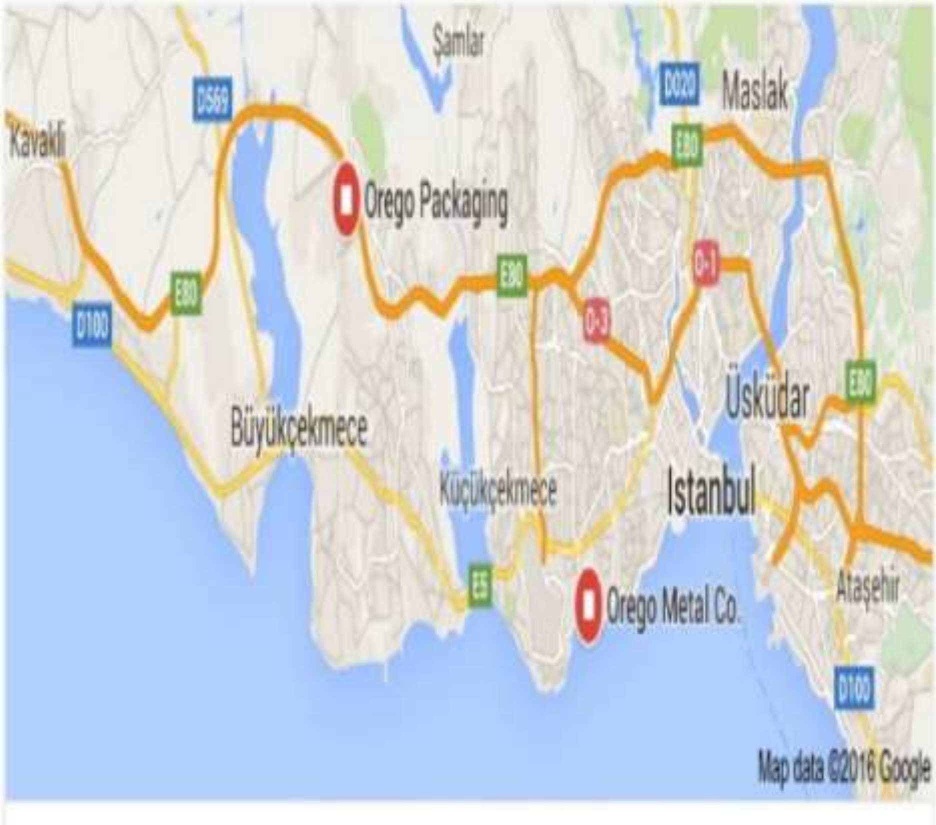
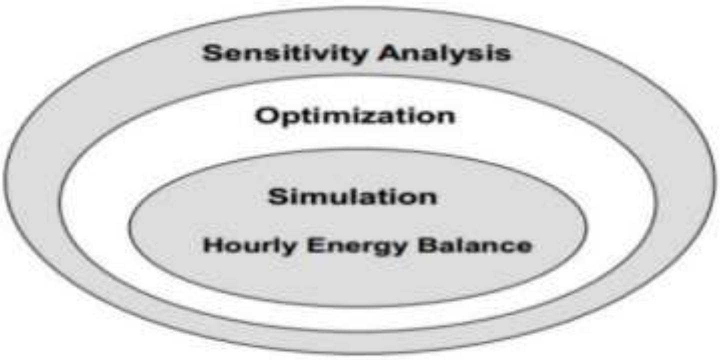


Figure 1. The map of Orego Company, Esenyurt -Istanbul, Turkey.

Homer SoftwareOverview



Simulation: It compares the energy supply from the system and the load demand in 1hour, of the 8,760 hours. During this time, it decides either to use load following or dispatch strategy to operate batteries and generator. For a system that contains battery and generator requires having dispatch strategy. Dispatch strategies are two types, load following and cycle charging strategies.

Optimization: In this process it simulates each different system configurations in search of the lowest NPC and lists each power system that meets the demand. The reason for optimization is to determine the optimal system based on the decision variables imposed by the designer. Decision variable is a variable that has control by the designer. HOMERs decision variables may include PV array size,quantity of wind turbines, generator size,size of converter, quantity of batteries, dispatch strategy,and etc. Searching the optimal system includes deciding the mix of power components like size,quantity at the same time the dispatch strategy.

Sensitivity Analysis: It examines the effect of external parameters and does optimization for each sensitivity variable. But firstdefining the variables that can affect the system over its entire life is mandatory to input into the software. The sensitivity variables can be climatic data variations,components and fuel cost, interest rate, capacity shortages,operating reserves and others. HOMER does multiple optimizations using various sensitive inputs to see how sensitive output of the power system. The sensitivity results from HOMER are displayed in tabular and graphical forms.
Source: J. F. Manwell and J. G. McGowan, A combined probabilistic/time series model for wind Diesel systems simulation, Solar Energy, Vol. 53, pp. 481-490, 1994

MATERIALS AND METHODS

Materials

The materials used in this work include solar photovoltaic panel (50kw), wind turbine (60kw),biogas generator (10kw), Electrolyzer (100kw), Hydrogen tank (5.6kw), Fuel cell (5kW)Converter (1kw) and HOMER Pro version 3.6.

METHODOLOGY

Different types of renewable energy sources components including solar photovoltaic/wind turbine/biogas generator/hydrogen tank /electrolyzer/fuel cells were integrated for optimal Hybrid renewable energy systems. After a detailed literature review on hybrid renewable energy systems (HRES) applicable for power generation, the case study area was identified, and the demand was conducted by calculating the primary load for each hour of the year at selected sites. The resources assessment was carried out by collecting data on solar irradiation and wind speed through NASA metrological station. The data of biomass resources was estimated based on theavailable biomass feedstock.

The HRES configurations were conducted based on five different scenarios as follows:
1) Solar PV/Wind turbine/Electrolyzer/ Hydrogen tank /Fuel cell (Scenario A)
2) Solar PV/Biogas generator (Scenario B)
3) Solar PV/Biogas generator/ Electrolyzer/Hydrogen tank/Fuel ceII (Scenario C)
4) Solar PV/wind turbine/Biogas generator/ (Scenario D)
5) Solar PV/ wind turbine/Biogas generator/Electrolyzer/Hydrogen tank/Fuel cell (Scenario E)The excess energy produced from solar photovoltaic and wind turbine was consumed by electrolyzer and stored in the formn of hydrogen gas. When the energy generated is not sufficient to meet the demand, the fuel cells then convert the hydrogen gas storedinto electricity [14]. The HOMER Pro software was used for simulation and optimization. The data input for HOMER Pro software is given in Table 1.

Lastly, the different scenarios for the selection of techno-economic HRES architecture were developed and evaluated.

Alkaline Electrolyzer Stack and BOP cost

Based on 2025/2026 data for European project. The European Hydrogen observatory divided electrolyzer CAPEX into four categories: Stack and balance of plant (BOP).[16]

In this research we use 25 kilo watts alkaline electrolyzer with total installation and replacement cost of $800 - $1500 per kilo watt and stack of approximately 30% - 40%. Why so high? Small scale loses economics of scale badly. The 25 to 100 kilo watt is where BOP dominates, however BOP costs run equal to or higher than the stack at less than 100 kilo watts, because you still need;

1. Power electronics; Rectifier and size for variable renewables often 20% - 25% of total
2. Gas processing; Hydrogen and oxygyn separations, gas purification does not scale down well
3. Water treatment, controIs, safety, and storage.

For 25 to 100 kilo watt hybrid system in 2026
Stack only $200 - $500 per kilo watt
BOP; $300 - $ 800 per kilo watt dominate at small scale
For renewable integration; if you coupling to hybrid system solar/wind you need extra BOP for intermittent operation- bigger rectifier range, buffer tanks that pushes BOP percent.[17]

Biogas Generator, Conversion, and Efficiency

A biogas generator is really twvo systems:
Digesterr-Bioga-> Genset-> Electricity
The digester part determines what biomass we can use. In this work the genset used does not eat biomass directly, it burns biogas. Therefore, we need an anaerobic digester first.[18]

Anaerobic Digestion Process

The process occurs in a closed container called a **digester** and involves four main stages:[19]

· **1. Hydrolysis**

· Complex organic matter (carbohydrates, proteins, fats) is broken down into simpler soluble compounds (sugars, amino acids, fatty acids).

·2. Acidogenesis

·These simple compounds are converted into volatile fatty acids, alcohols, hydrogen, and CO2 by bacteria.

· 3. Acetogenesis

·The products from acidogenesis are further converted into **acetic acid,** hydrogen, and CO2.

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4.Methanogenesis
Methanogenic bacteria convert acetic acid and hydrogen into **methane (CH4)** and CO2 Ñthis forms **biogas.**
The generator usually has a spark ignition ICE turned for biogas.YouH2Sremoval+moisture removal before the genset

Conversion Efficiency: Biomass → Biogas
This is how much of the energy in your feedstock ends up as methane.
Conversion Efficiency: Biomass → Methane

Feedstock Type	Typical Methane (m3/kg VS)	Yield Energy Conversio CH4(%)	n to Remarks
Cow dung (manure)	0.20-0.30	45-60%	Stable, widely used
Poultry droppings	0.30-0.50	55-70%	Higher nitrogen content
Food waste	0.40-0.60	65-85%	Highly biodegradable
Crop residues (e.g.straw)	0.15-0.30	40-60%	Requires pre-treatment
Sewage sludge	0.25-0.35	50-65%	Common in wastewater plants
Agricultural waste mix	0.30-0.50	55-75%	Co-digestion improves yield

Compare chain with the different end energies

The end of system chain A is chemical **energy stored in Hydrogen: Power** -> Electrolyzer -**>Hydrogen** -> **Fuelcell** -> **Chemical energy**
The end **of the system chain B is electrical energy power from biogas generator: Biomass -** >Biogas→Genet **-> Electricity**

In this study it's not possible to compare electrolyzer and generator directly, they produce **different energy carries with different uses, so we consider normalizing** to a common final **service to pick the end service we needed, assume we need one** kilo watt per hour of dispatchable electricity.

Chain A already gives electricity,cost=LCOES/kWh

Chain B takes hydrogen, runs it through a fuel cell.
cost=LCOHS/kN/h+fuelcelIAPEX/OPEX=LCOES/kWh, **now both are $/kWh and comparable**

RESULT AND DISCUSSIONS

The system was designed with the help of HOMER pro. After introducing all of the input variables into the modeling tool, (Table 1), the software was run repeatedly to get the feasible results.Optimization results were displayed in categorized form (Table 2), which shows the most feasible power systems architecture that meets the load and the input constraints made by the modeler. The feasible solutions were presented in an increasing order of the net present cost from top to bottom (Table 2). The most cost-effective combinations from among all component's setup is shown in Table 2. Power systems were selected after simulation based on the following parameters,i.e. less energy cost (COE), less net present cost (NPC), less operating cost (OC), and low excess electricity generation. These parameters were used for comparison of power generating schemes, and the system with optimum efficiency was selected. The graphical abstract was shown in Figure 2 below.

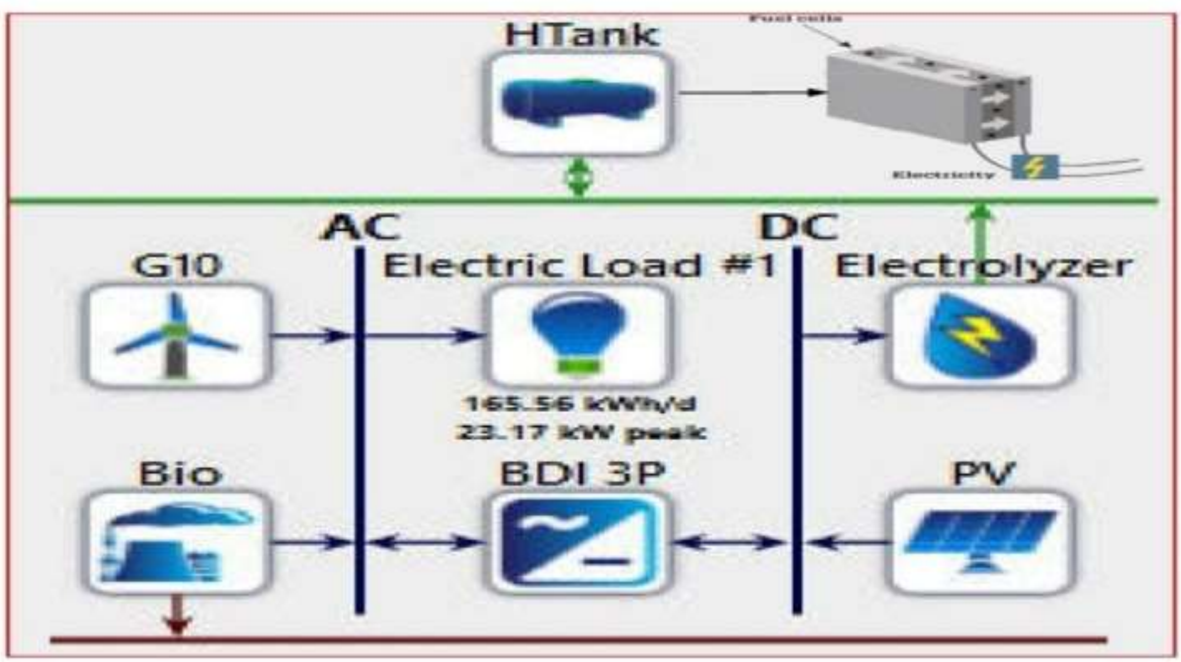

Figure 2. Graphical abstract of Hybrid Renewable Energy Systems

Table 1. Input into HOMER Pro software Oregon packaging company

	PV Module	Wind Turbine	Biogas Generator	Electrolyzer	Hydrogen Tank	Fuel cell	Converter
Size (kW)	50	60	10	25	5.7kg	2	1
Capital ($)	28,500	111,000	6000	38,000	2000	3,200	800
Replacement Cost ($)	28,000	105,000	5500	38,000	2000	1,600	600
O$M Cost $/year	10	300	0.5$/hr	10	0	128$/yr	0
Size Considered (kW)	0,100,200	0,10,20,30....	0,40,80,100,.....	0,40,80,100,...	0,1,2,3,4,5	0,1,2,3,5..	1,100,150,200,....
Quantities Considered		0,20,40,80		20,30,40,50,...			
Life Time	20years	20years	3years	4.5years	20years	5years	15years

Table 2. Results of the simulation in categorized form (HOMER Pro)

Architecture	PV (kW)	Wind turbine	Bio (kW)	Electroyzer (kW)	Htank (Kg)	Fuel cell (kW)	Converter (kW)	COE ($)	NPC ($)	Operating Cost($)
PV/wind-Electrolyzer -HTank-Fuelcell(Scenario A)	50	20		40	2	2	15	0.030	113,612	1,287
PV-Biogas (Scenario B)	20		10				5	0.084	139,882	8,037
PV-Biogas-Electrolyzer-HTank-Fuelcell(Scenario C)	15		10	25	2	4	8	0.045	170,343	8,643
PV-wind-Biogas (Scenario D)	30	10	10				10	0.039	191,504	8,649
PV-wind-Biogas-Electrolyzer -Htank-Fuelcell (Scenario E)	40	20	10	30	2	6	15	0.103	222,651	9,225

Table 3. Excess Electricity Production (HOMER Pro)

Scenario	Excess Electricity Production kWh/yr	%
Scenario A	35,473.0	10.8
Scenario B	20,896.0	13.9
Scenario C	20,980.0	13.9
Scenario D	36,211.0	8.8
Scenario E	21,878.0	7.7

Statistical Analysis and Comparative Evaluation

Descriptive Statistics

Table 4.1: Descriptive Statistics for Cost of Energy (COE)

Statistic	Value
Mean	0.0602
Standard Deviation	0.0316
Minimum	0.030 (Scenario A)
Maximum	0.103 (Scenario E)
Range	0.073

Table 4.2: Descriptive Statistics for Net Present Cost (NPC)

Statistic	Value
Mean	167,598.40
Standard Deviation	42,820.60
Minimum	113,612 (Scenario A)
Maximum	222,651 (Scenario E)
Range	109,039

Table 4.3: Descriptive Statistics for Operating Cost

Statistic	Value
Mean	7,168.20
Standard Deviation	3,058.40
Minimum	1,287 (Scenario A)
Maximum	9,225 (Scenario E)
Range	7,938

Excess Electricity Production

Statistic	Value
Mean	27,087.60
Standard Deviation	7,180.50
Minimum	20,896 (Scenario B)
Maximum	36,211 (Scenario D)
Range	15,315

Comparative Ranking of Scenarios

To evaluate overall system performance, scenarios were ranked based on economic indicators (COE,NPC, and Operating Cost), where lower values indicate better performance.

Table 4.5: Ranking of Scenarios Based on Economic Performance

Scenario	COE Rank	NPC Rank	Operating Cost Rank	Overall Rank
A	1	1	1	1 (Best)
B	4	2	2	2
C	3	3	3	3
D	2	4	4	4
E	5	5	5	5 (Worst)

4.3 Percentage Improvement Analysis

To quantify performance gains, Scenario A (best-performing scenario) was used as the reference.

Table 4.6: Percentage Improvement of Scenario A Relative to Other Scenarios

Metric	VS B	vs C	VS D	VS E
COE	64.3%	33.3%	23.1%	70.9%
NPC	18.8%	33.3%	40.7%	49.0%
Operating Cost	84.0%	85.1%	85.1%	86.0%

DISCUSSION OF RESULTS

The statistical results indicate that Scenario A consistently provides the most optimal performance across all economic indicators. It recorded the lowest cost of energy(COE=0.030), which is approximately 70.9% lower than Scenario E, demonstrating significant cost efficiency. Similarly,

Scenario A achieved the lowest net present cost(NPC=113,612)and operating cost (1,287),confirming its superiority in both capital investment and operational expenditure.
The variability observed in COE(SD=0.0316) reflects moderate dispersion among scenarios,largely influenced by the high value recorded in Scenario E. A similar trend is evident in NPC and operating cost, where Scenario E consistently shows the highest values,indicating poor economic performance.

Although Scenario D achieved the highest excess electricity production (36,211 kWh/yr), this did not translate into economic efficiency. This suggests that higher energy surplus does not necessarily imply better system performance, as it may be associated with increased costs.Therefore, optimal system design should focus on balancing energy production with economic efficiency.

The ranking results further confirm that Scenario A is the most efficient configuration, followed by Scenarios B and C, while Scenario E is the least efficient. This consistent pattern across all metrics strengthens the reliability of the proposed evaluation.

SUMMARY OF KEY FINDINGS

Scenario A is economically optimal across all metrics
Scenario E is consistently the least efficient
There exists a trade-offbetween excessenergy production and cost efficiency
Lower COE strongly correlates with lower NPC and operating cost

The annual electric load of Orego packaging Company, Istanbul, Turkey.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Average
Kwh	1926.7	2986.7	2602.1	2431.6	2193.2	2912.5	3339.9	2725.2	2939.6	2802.8	3234.5	3040.4	2761.3
Kwh/day	80.28	122.4	108.4	101.3	9$*38	121.2	139.2	113.5	122.5	116.8	165.8	134.8	118.9

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REFERENCES

[1] Akpinar, A., Komurcu, M. I., Kankal, M., Ozolcer, I. H., Kaygusuzs, K. Energy situation and renewable in Turkey and environmental effects of energy use. Renewvable and Sustainable Energy Reviews, 12, 2013-39.(2008).
[2] Keles, S., Bilgens, S. Renewable energy sources in turkey for climate change mitigation and energy sustainability (2012).
[3] Mohamme Y.S., Mustafa M.W, Bashir N,Hybrid renewable energy systems for off-grid electric power: Review of substantial issues:(2014).
[4] Francis, M.V, Louis, D.A., Largus, and T.A. Energy System Engineering: Evaluation and Implementation.McGraw Hill, 107-123. (2016).
[5] Gunnar Boye Olesun, INFORSE. Improving energy access, the possibility of the contribution of RETs to poverty alleviation. In: International conference for renewable energies. Bonn, Germany,1-4 (2004).
[6] VijayaVenkataraman S, Iniya S, Goic R. Areview of climate change, Mitigation and adaptation.Renewable and Sustainable Energy Reviews 16:878-97 (2012).
[7] Alison Riddell, Steve Ronson, Glenn Counts, Kurt Spenser. Schneider, Towards Sustainable Energy: The current Fossil Fuel problem and the prospects of Geothermal and Nuclear power, 375(2014).
[8] Zoulias E.I., Lymberopoulos N. Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems. Renewable Energy 32680-696(2007).
[9] Diaf S, Notton G, Belhamel M, Haddadi M, Louche A. Design and techno-economical optimization for hybrid PV/wind system under various meteorological conditions. Apply Energy 85(10):968-87(2008).
[10] Farret, Felix A. Integration of alternative sources of energy. Wiley-Inter science; (2006).
[11] Baharamara, Haghifam. Optimal planning of hybrid renewable energy and Sustainable Energy Reviews.62:609-620 (2016).
[12] Yildiz K, Ibrahim D. Techno-economic analysis of a Stand-alone hybrid renewable energy system with hydrogen production and Storage options. International Journal of Hydrogen Energy. 40, issue 24, 7652-7664(2015).
[13] Khosravi A, Pabon J.J.G. Energy, Exergy and economic analysis of a hybrid renewable energy with hydrogen storage system. Energy. 148. 1087-1102 (2018).
[14] Khalid F, Aydin M, Dincer I, Rosen MA. Comprehensive assessment of two integrated hydrogen energy systems using electrolyzer and fuel cells. International Journal of Hydrogen Energy. 41(44), 19836-19846,(2016).

[15] Bhandari B,Kyung-Tae lee, Gil-young lee, Young-Mancho, Sung-Hoon Ahn. Optimization of hybrid renewable energy power systems: A review. International Journal of Precision Engineering and Manufacturing-Green Technology. 2 Issue1, 99-112 (2015)
[16] mdpi.com: Simulation. Based performance and cost optimization
[17] Observatory-clean-hydrogen. Europa.eu elctrolyzer cost/European hydrogen observatory
[18] MDPI, Journal/clean technology/Volume 8/ Issue 1. Food waste to biogas. 2026
[19] Boonsita Nammana et, al. Water science technol. 2025 Sept. Feasibilit biogas production and recycled paper industry slugde.