Modelling of a Thermally Insulated Solar Hydrogen System: Utilizing the Operational Heat

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Introduction – Motivation

Increasing demand for clean & sustainable energy sources

Solar PV → Intermittent

Solar PV → Storage → Hydrogen

Electrolyzer → Hydrogen

Hydrogen → Fuel Cell

→ Carbon-free fuel

High altitudes → Difficult fuel supply

High altitudes → Extreme temperatures

High altitudes → Low oxygen levels

(Source: internet)

Introduction – Objectives

Solar Hydrogen System → Electricity | Hydrogen | Oxygen

Solar Hydrogen System → Round-trip efficiency = 35-50%

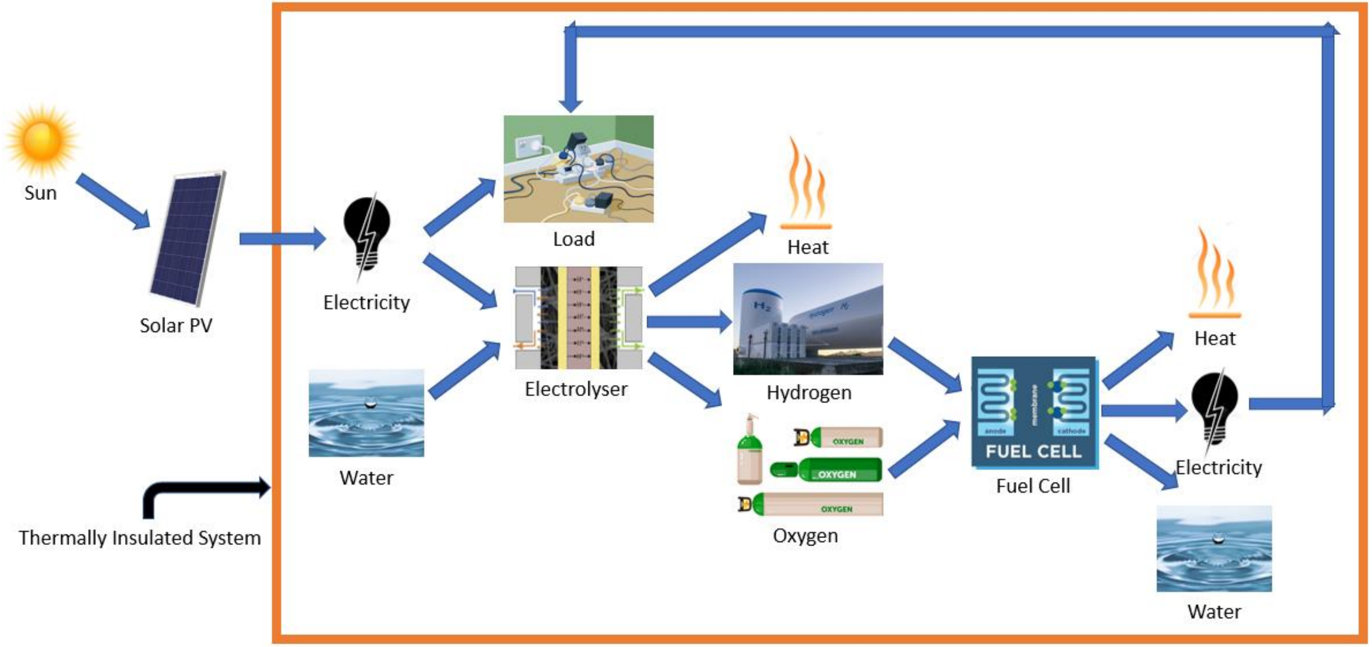
Thermally Insulated Solar Hydrogen System →
- All the above positives
- Heat
- Aim: Round-trip efficiency = 80-90%

→ Armed forces
Local communities

↓

- Quality of life
- Comfort and survivability
- Reduced supply chain costs

System Design – Working

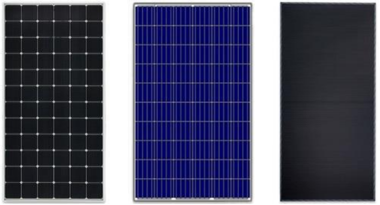


(Source of individual images: internet)

Highly interdependent energy flow!

Solar PV Selection

Monocrystalline Si | Polycrystalline Si | Monocrystalline Si PERC | Thin Film | Perovskite



Monocrystalline, polycrystalline, and thin film solar modules
(Source: internet)

Peak Power P_{max} (W)	315	320	325	330	335	340
Max Voltage V_{mpp} (V)	37.5	37.7	37.8	38	38.1	38.2
Max Current I_{mpp} (V)	8.4	8.5	8.6	8.7	8.8	8.91
Open Circuit Voltage V_{oc} (V)	45.8	46	46.2	46.3	46.5	46.7
Short Circuit Current I_{sc} (A)	8.92	9.03	9.13	9.24	9.35	9.46
Module Efficiency (%)	16.23	16.49	16.75	17.01	17.26	17.52

Vikram Solar polycrystalline Si PV modules
(Source: Vikram Solar datasheet)

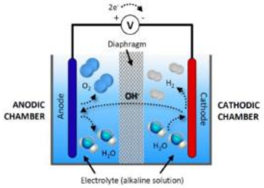
Peak Power P_{max} (W)	365	370	375	380	385
Max Voltage V_{mpp} (V)	39.8	40.0	40.1	40.2	40.3
Max Current I_{mpp} (V)	9.17	9.26	9.36	9.46	9.56
Open Circuit Voltage V_{oc} (V)	48.3	48.5	48.7	48.8	48.9
Short Circuit Current I_{sc} (A)	9.73	9.84	9.94	10.04	10.14
Module Efficiency (%)	18.81	19.07	19.33	19.58	19.84

Vikram Solar monocrystalline Si PERC modules
(Source: Vikram Solar datasheet)

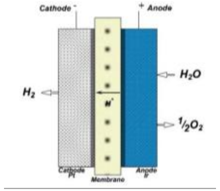
Monocrystalline Si PERC is selected!

Electrolyzer Selection

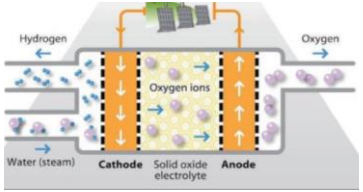
Alkaline | Proton Exchange Membrane (PEM) | Solid Oxide



Alkaline



PEM



Solid Oxide

PEM is selected!

(Source of images: internet)

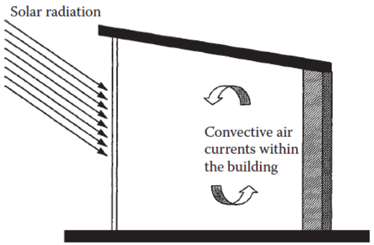
Fuel Cell Selection

PEM | Alkaline | Solid Polymer | Sulfuric and Phosphoric Acid | Solid Oxide | Molten Carbonate

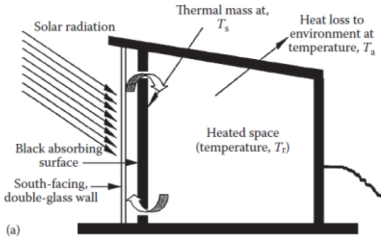
- Alkaline is intolerant to CO2
- Solid polymer have low electrochemical activity
- Acid FCs have bad performing air electrodes
- Molten carbonate and Solid oxide FCs operate at very high temperatures (>800°C)

PEM is selected!

Passive Solar Tent Design



Direct gain



Indirect gain

Goswami, D. Yogi. (2015). Principles of Solar Engineering. 3rd ed. Boca Raton: CRC Press.

Indirect gain – time lag between radiation & heating

Solar tent

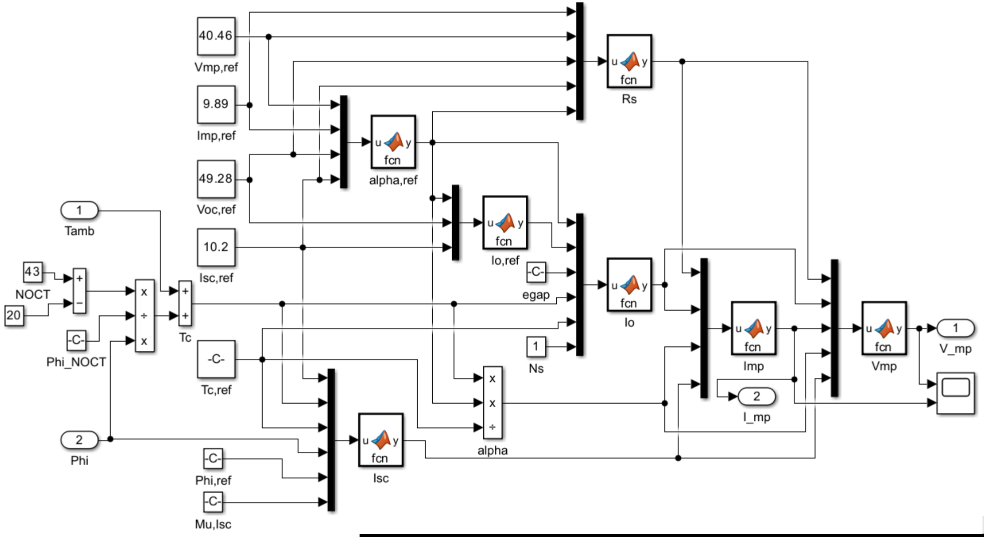
Cylindrical roof – minimize heat loss through surface
Partition – thermal mass, insulating
Modular – less than 30 kgs per part

Wangchuk, Sonam. (2021). The LADAKH Tent | World's 1st Solar Heated Military Tent | Made in India | Sonam Wangchuk. YouTube video, 13:03. Retrieved from https://www.youtube.com/watch?v=IF-IYkU0gmQ&ab_channel=SonamWangchuk

Modelling of System

Solar PV | Electrolyzer | Fuel Cell | Hydrogen Storage | Passive Solar Tent

Solar PV Modelling



$$I = I_{sc} - I_o \left[\exp\left(\frac{V + IRs}{\alpha} \right) - 1 \right]$$

$$T_c = T_{amb} + (NOCT - 20^o C) \frac{\emptyset}{800}$$

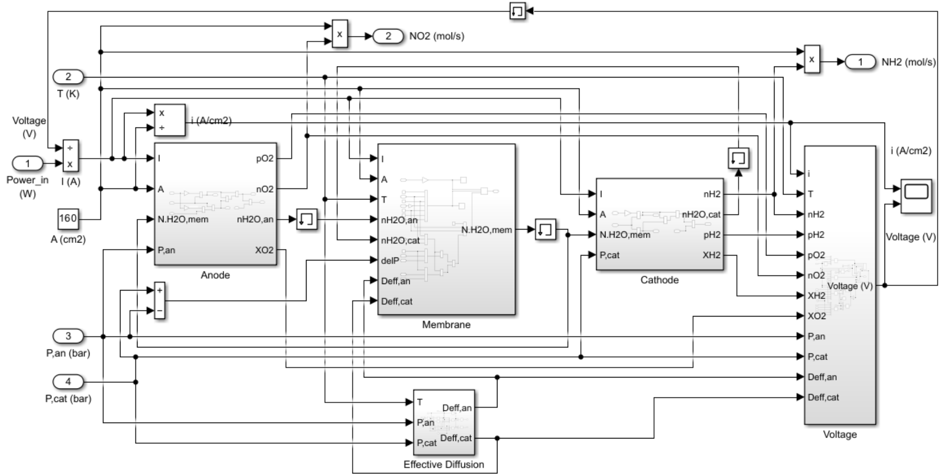
$$P = VI$$

$$\frac{dP}{dI} = \alpha \left(\frac{I}{I - I_{sc} - I_o} + \ln \left(\frac{-I + I_{sc} + I_o}{I_o} \right) \right) - 2IR_s = 0$$

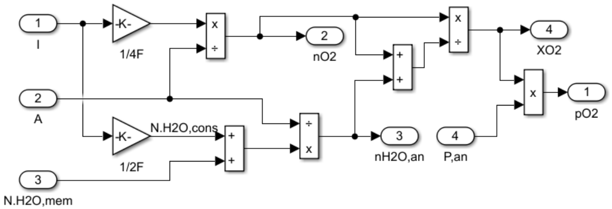
Krismadinata, Nasrudin Abd. Rahim, Hew Wooi Ping, and Jeyraj Selvaraj. (2013). Photovoltaic module modeling using simulink matlab. Procedia Environmental Sciences 17, 537-546. Retrieved from https://doi.org/10.1016/j.proenv.2013.02.069

Electrolyzer Modelling

Anode | Cathode | Membrane | Effective Diffusion | Voltage



Anode



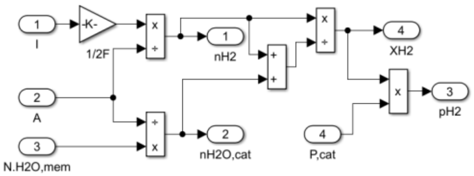
$$n_{O2} = \frac{N_{O2}^{\cdot gn}}{A} = \frac{I}{4FA}$$

$$X_{O2} = \frac{n_{O2}}{n_{O2} + n_{H2O}^{an}}$$

$$n_{H2O}^{an} = \frac{N_{H2O}^{\cdot mem} + N_{H2O}^{\cdot cons}}{A}$$

$$p_{O2} = X_{O2} P_{an}$$

Cathode



$$n_{H2} = \frac{N_{H2}^{\cdot gn}}{A} = \frac{I}{2FA}$$

$$X_{H2} = \frac{n_{H2}}{n_{H2} + n_{H2O}^{cat}}$$

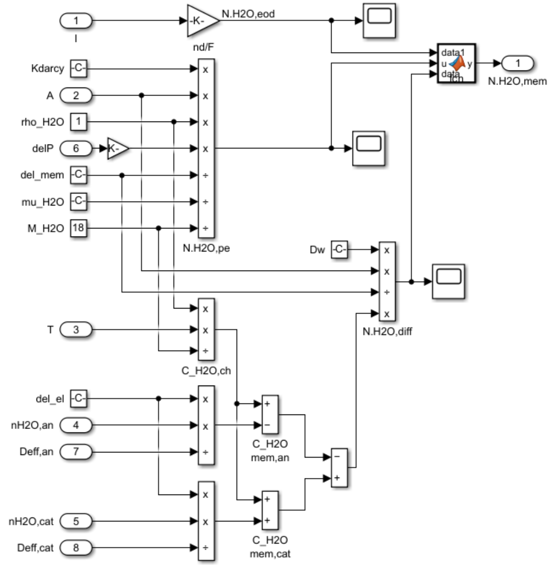
$$n_{H2O}^{cat} = \frac{N_{H2O}^{\cdot mem}}{A}$$

$$p_{H2} = X_{H2} P_{cat}$$

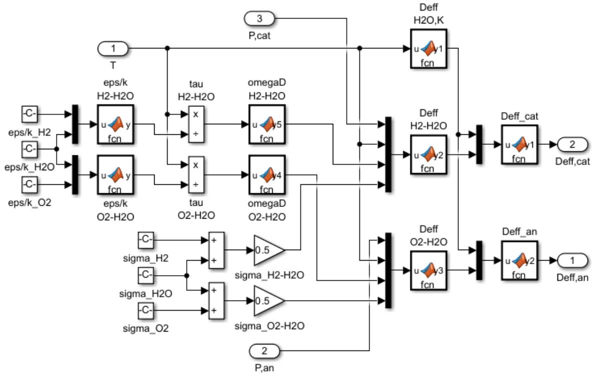
Abdin, D., C.J. Webb, and E.MacA. Gray. (2015). Modelling and simulation of a proton exchange membrane (PEM) electrolyser cell. International Journal of Hydrogen Energy 40(39), 13243-13257. Retrieved from https://doi.org/10.1016/j.ijhydene.2015.07.129

Electrolyzer Modelling

Membrane



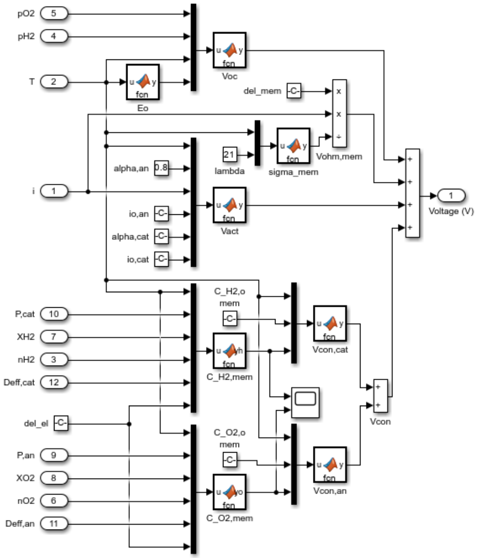
Effective Diffusion



$$\frac{1}{D_{eff}^{an}} = \frac{\varepsilon}{\xi}\left(\frac{1}{D_{eff}^{O2-H2O}} + \frac{1}{D_{eff}^{H2O,K}}\right)$$

$$\frac{1}{D_{eff}^{cat}} = \frac{\varepsilon}{\xi}\left(\frac{1}{D_{eff}^{H2-H2O}} + \frac{1}{D_{eff}^{H2O,K}}\right)$$

Voltage



$$\dot{N}_{H2O}^{mem} = \dot{N}_{H2O}^{diff} + \dot{N}_{H2O}^{eod} - \dot{N}_{H2O}^{pe}$$

$$\dot{N}_{H2O}^{diff} = \frac{AD_w}{\delta_{mem}}\left(C_{H2O,mem}^{cat} - C_{H2O,mem}^{an}\right)$$

$$\dot{N}_{H2O}^{eod} = \frac{n_d I}{F}$$

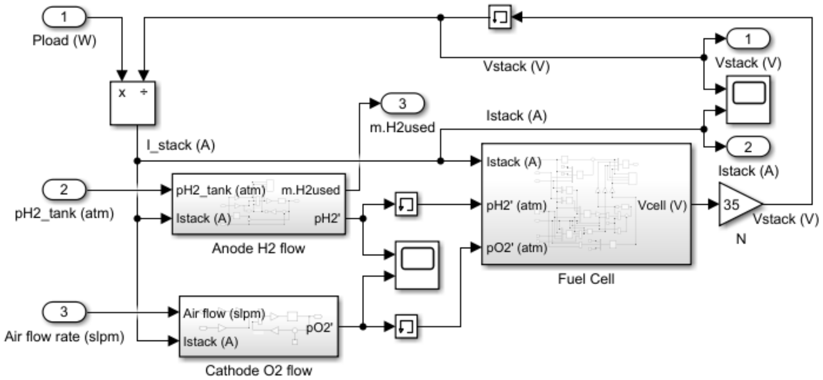
$$\dot{N}_{H2O}^{pe} = \frac{K_{Darcy} A \rho_{H2O} \Delta P}{\delta_{mem} \mu_{H2O} M_{H2O}}$$

$$V = V_{oc} + V_{act} + V_{ohm} + V_{con}$$

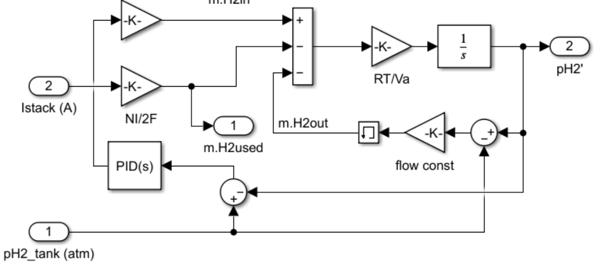
Abdin, D., C.J. Webb, and E.MacA. Gray. (2015). Modelling and simulation of a proton exchange membrane (PEM) electrolyser cell. International Journal of Hydrogen Energy 40(39), 13243-13257. Retrieved from https://doi.org/10.1016/j.ijhydene.2015.07.129

Fuel Cell Modelling

Anode H_2 flow | Cathode O_2 flow | Fuel Cell



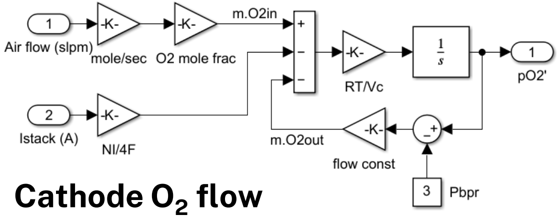
Anode H_2 flow



$$\frac{dP'_{H2}}{dt} = \frac{RT}{V_a}\left(\dot{m}_{H2,in} - \dot{m}_{H2,out} - \dot{m}_{H2,used}\right)$$

$$\dot{m}_{H2,used} = \frac{NI}{2F}$$

$$\dot{m}_{H2,out} = k_a\left(P'_{H2} - P_{tank}\right)$$



Cathode O_2 flow

$$\frac{dP'_{O2}}{dt} = \frac{RT}{V_c}\left(\dot{m}_{O2,in} - \dot{m}_{O2,out} - \dot{m}_{O2,used}\right)$$

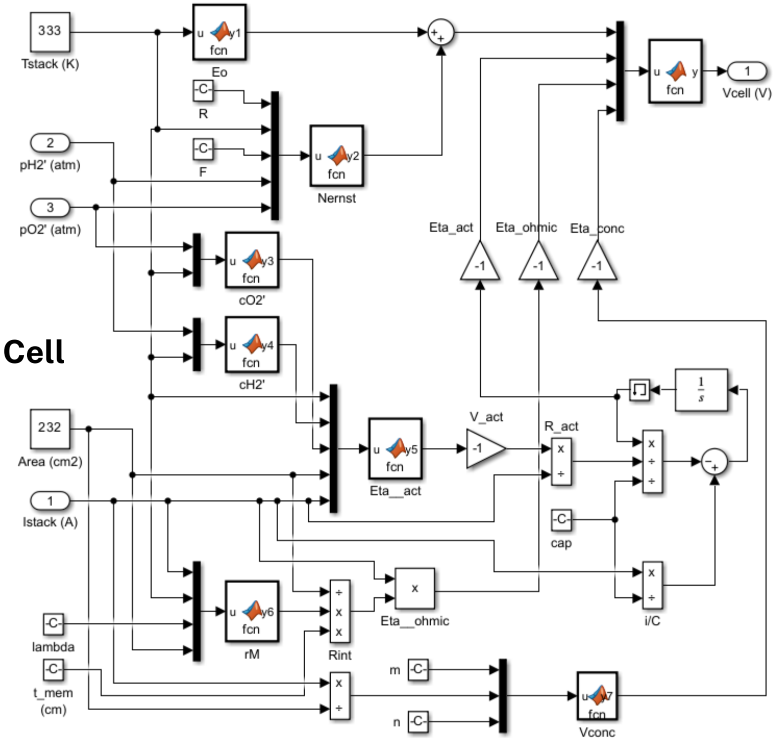
$$\dot{m}_{O2,used} = \frac{NI}{4F}$$

$$\dot{m}_{O2,out} = k_c\left(P'_{O2} - P_{bpr}\right)$$

Khan, M.J, M.T. Iqbal. (2005). Modelling and Analysis of Electro-chemical, Thermal, and Reactant Flow Dynamics for a PEM Fuel Cell System. Fuel Cells 5, 463-475. Retrieved from https://doi.org/10.1002/fuce.200400072

Fuel Cell Modelling

Fuel Cell



$$V_{cell} = E_{Nernst} + \eta_{act} + \eta_{ohm} + \eta_{con}$$

$$E_{Nernst} = E_o + \frac{RT}{nF}\left(\ln\left(p'_{H2}\sqrt{p'_{O2}}\right)\right)$$

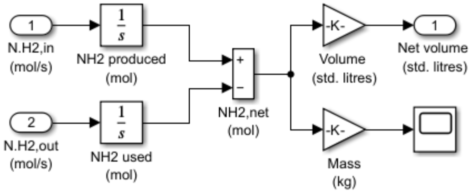
$$\eta_{act} = \xi_1 + \xi_2 T + \xi_3 T(\ln(c'_{O2})) + \xi_4 T(\ln(I))$$

$$\eta_{ohm} = -iR_{int}$$

$$\eta_{con} = N * m \exp\left(\frac{nI}{A}\right)$$

Khan, M.J, M.T. Iqbal. (2005). Modelling and Analysis of Electro-chemical, Thermal, and Reactant Flow Dynamics for a PEM Fuel Cell System. Fuel Cells 5, 463-475. Retrieved from https://doi.org/10.1002/fuce.200400072

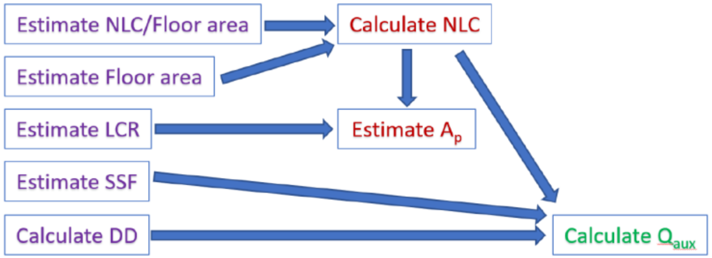
Hydrogen Storage Modelling



$$\int \dot{N}_{H2}^{in}\,dt \;-\; \int \dot{N}_{H2}^{out}dt \;=\; N_{H2}^{net}$$

$$Vol_{H2}^{std} \;=\; \frac{N_{H2}^{net}RT}{P}$$

Passive Solar Tent Modelling



NLC/floor area = 115 kJ/C-day-m^2

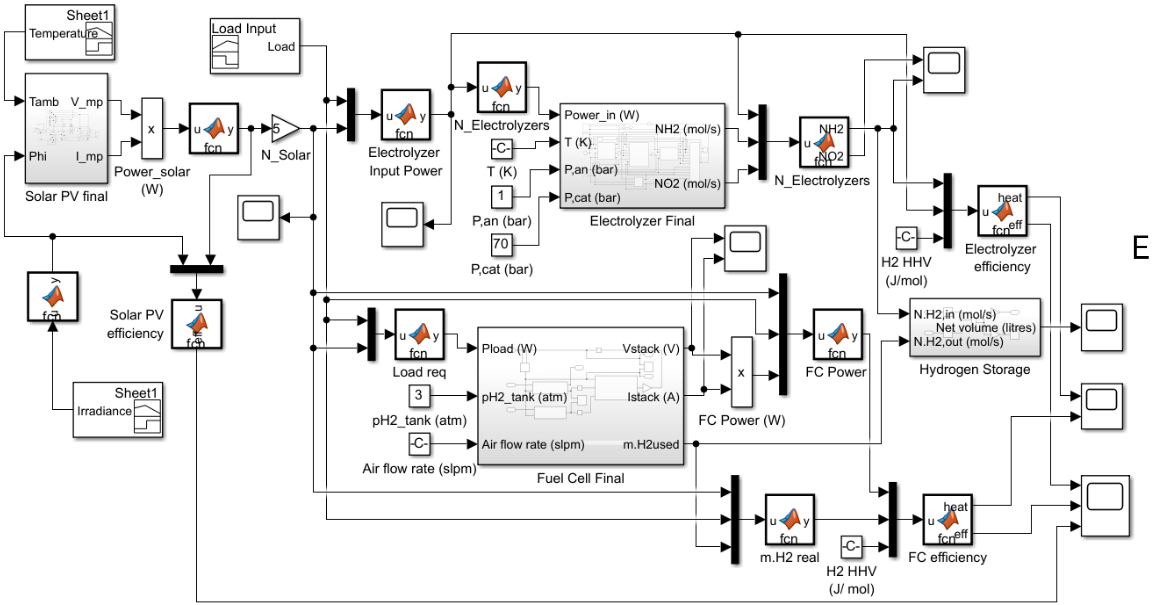
$$DD = \left(T_{base} - \frac{T_{max} + T_{min}}{2}\right)(No. of\ days) \;= 2896 \text{ C-days}$$

$$SSF = 1 - \frac{Q_{aux}}{Q_{net}} = 0.75$$

$$Q_{aux} = (1 - SSF) * \left(\frac{NLC}{Floor\ Area}\right) * Floor\ Area * DD$$

Goswami, D. Yogi. (2015). Principles of Solar Engineering. 3rd ed. Boca Raton: CRC Press.

Overall Model



Overall system – 2 kW

Solar PV – 5 x 400 W panels in series

Electrolyzer – Upto 5 cells depending on P_{input}

Fuel Cell – 1 stack

Function blocks to manage flow of power

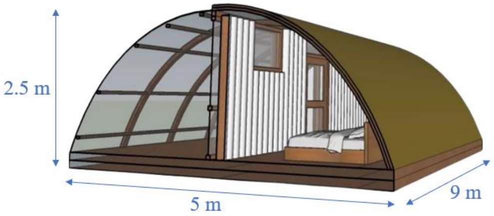
Functions for heat and efficiencies

Results & Discussion

Solar Tent | Solar PV Array | Electrolyzer | Fuel Cell | Overall System

Ladakh – 5.5 kWh/m^2-day, 300 sunny days ➔ 1 kW solar PV – 1650 kWh/y ➔ 2 kW system – **3300 kWh/y**

Results – Solar Tent



Floor area = 9 * 5 = 45 m^2

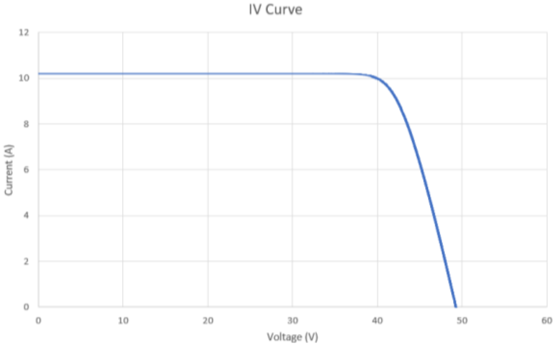
Q_{aux} = (1–0.75) * 115 * 45 * 2896 = 3747.7 MJ/year = **1041 kWh/year**

Average daily heating load = 2.85 kWh/day

Hence, Q_{aux} < 3 x generated solar power

Auxiliary heating devices – space heating devices like electric heater, kerosene, firewood

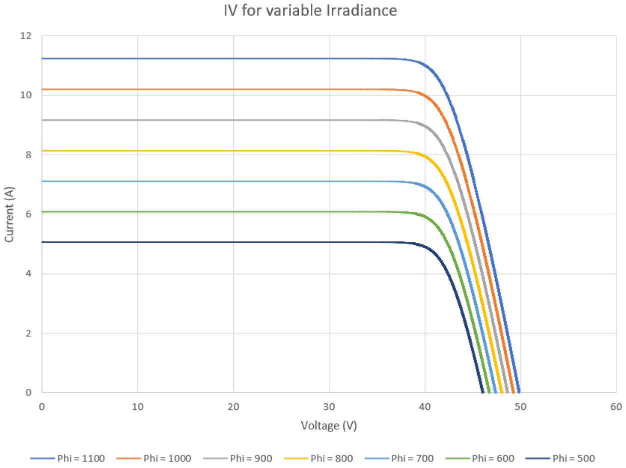
Results – Solar PV Array



STC

I_{sc} = 10.2 A
V_{oc} = 49.28 V
I_{mp} = 9.9 A
V_{mp} = 40.42 V

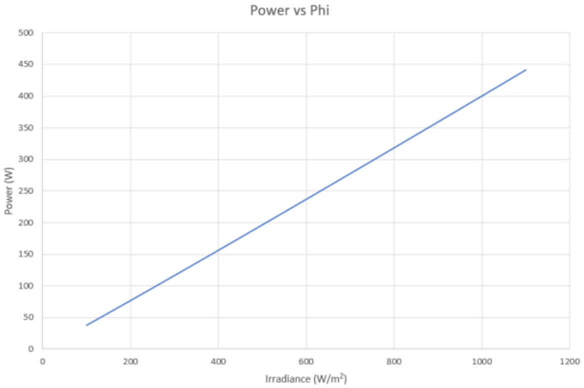
Very close to manufacturer's data



T_{amb} = 269.25 K

I_{sc} more sensitive to irradiance

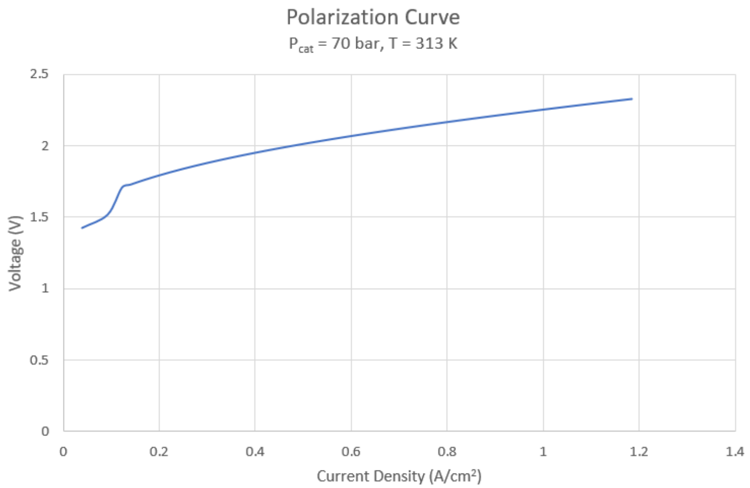
V_{oc} less sensitive to irradiance



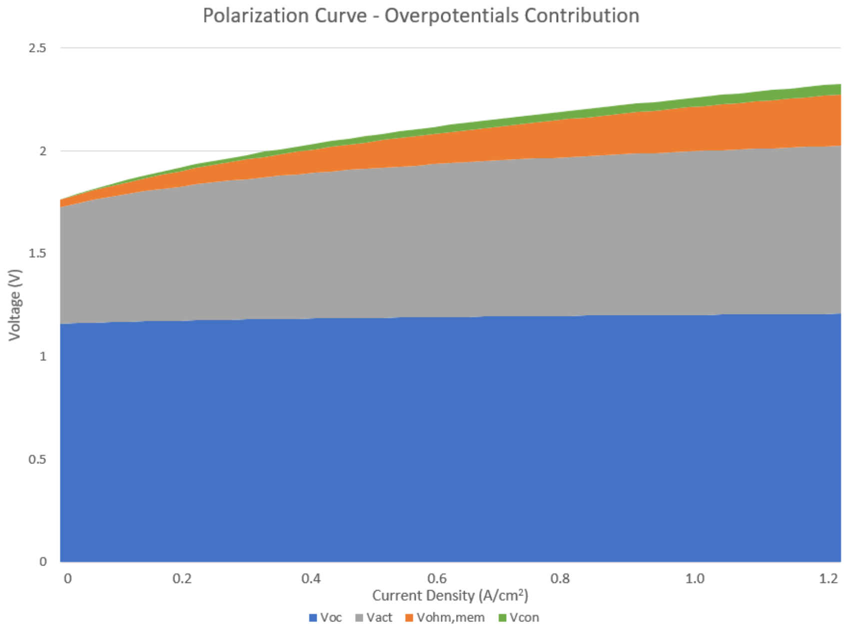
T_{amb} = 269.25 K

Power linearly increases with irradiance

Results - Electrolyzer

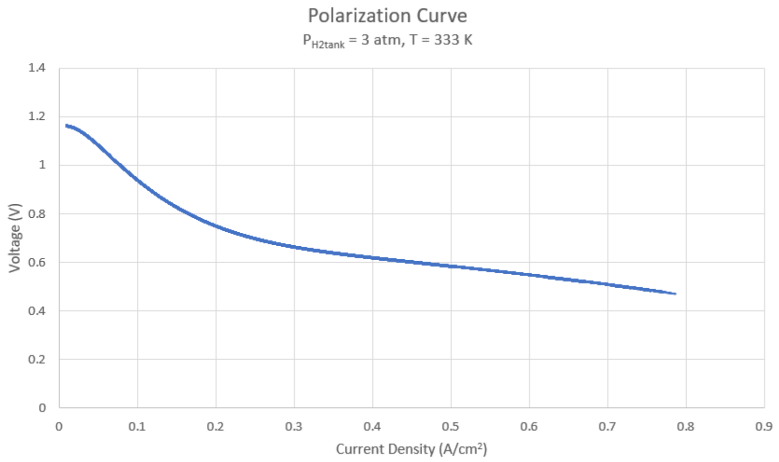


Input Power varied from 10 W to 440 W

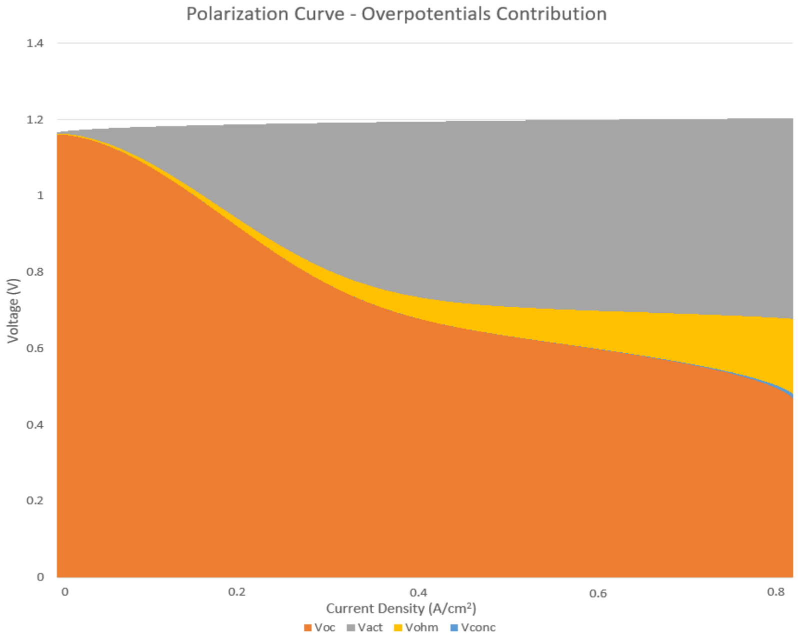


Contribution of V_{oc} > V_{act} > V_{ohm} >V_{con}

Results – Fuel Cell

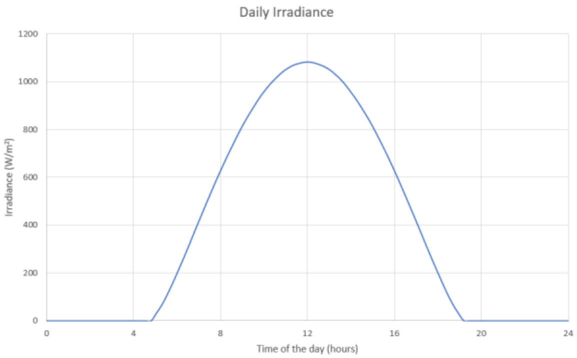


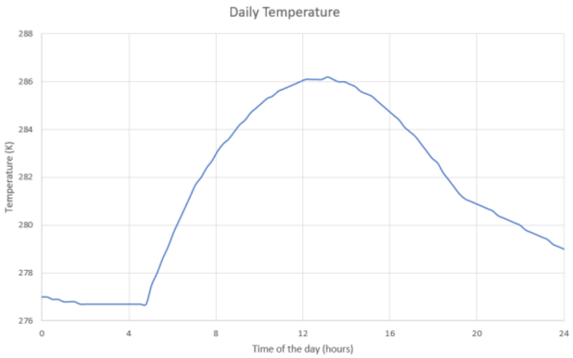
Input Power varied from 3 W to 3000 W

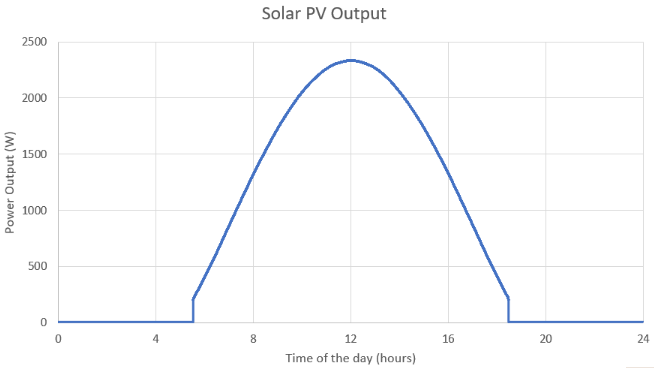


Effect of V_{act} > V_{ohm} >V_{con}

Results – Overall Model







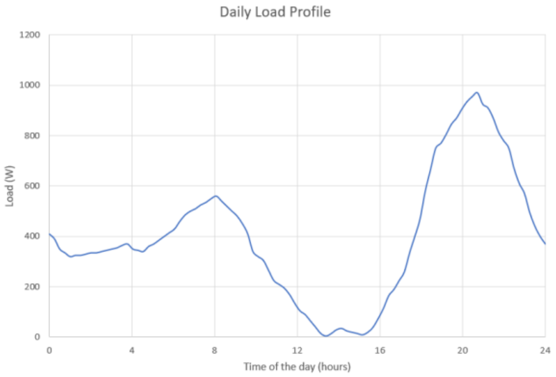
Input chosen for irradiance and temperature: 21 June, Ladakh

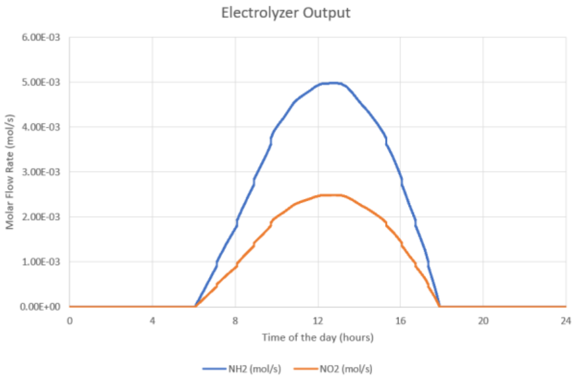
3 load scenarios – variable load, no load, constant load

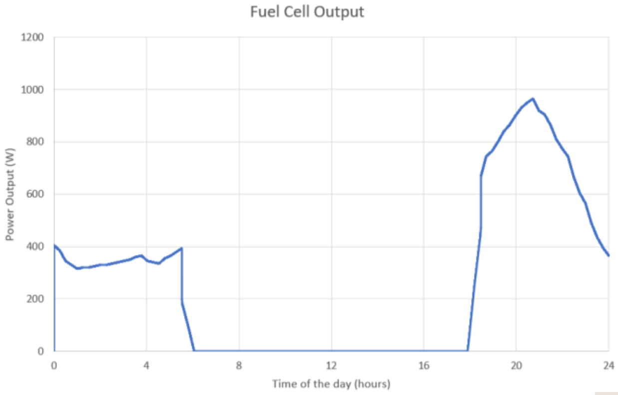
The input irradiance, temperature, and solar output are same for all scenarios

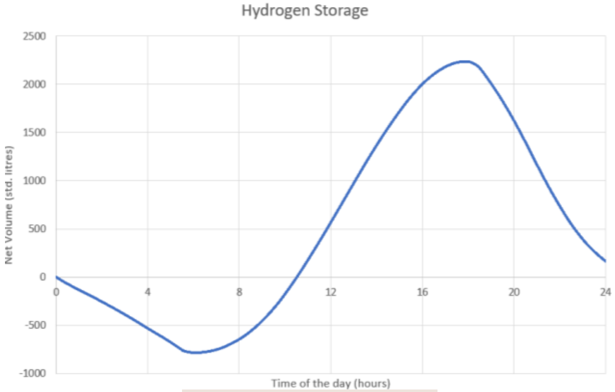
Total solar energy output = **19.61 kWh**

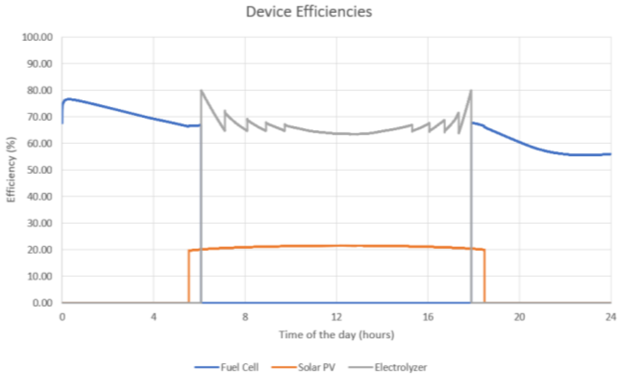
Results – Variable Load

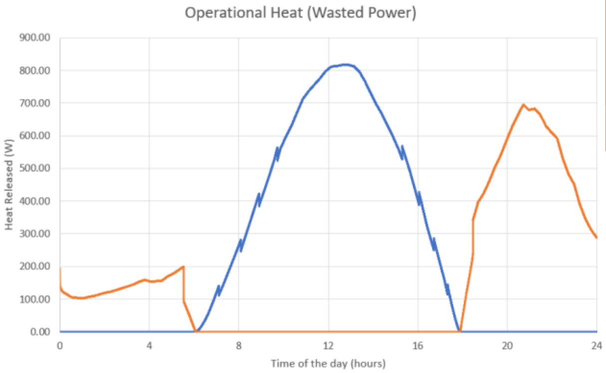










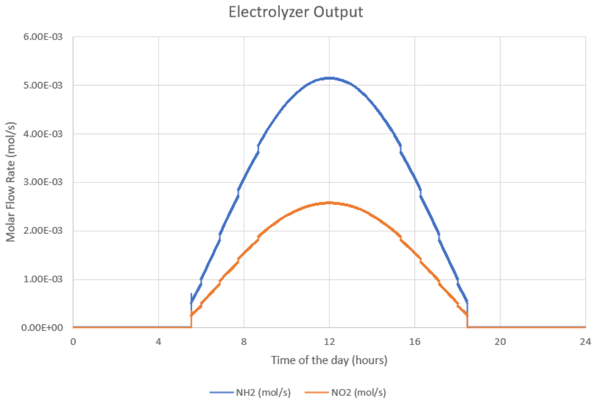


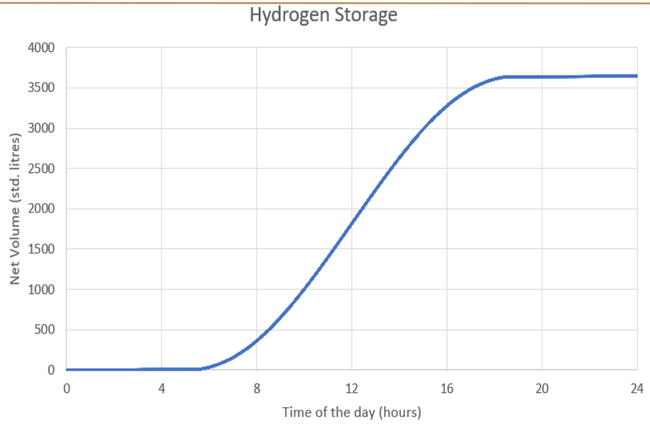
EOD: 164 std. litres

η_s = 19.65-21.55%, η_e = 63.5-80%, η_f = 56-76%

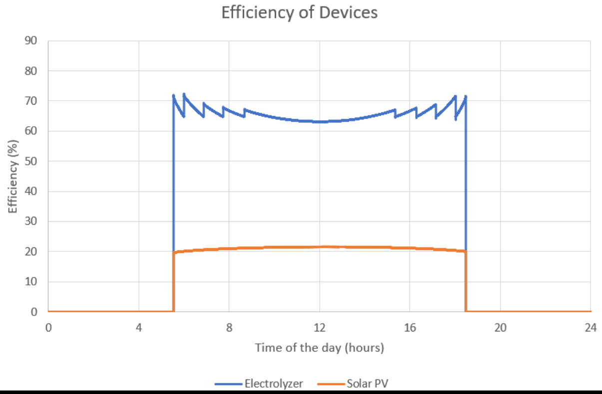
Q_e = 5.63 kWh, Q_f = 3.77 kWh

Results – No Load



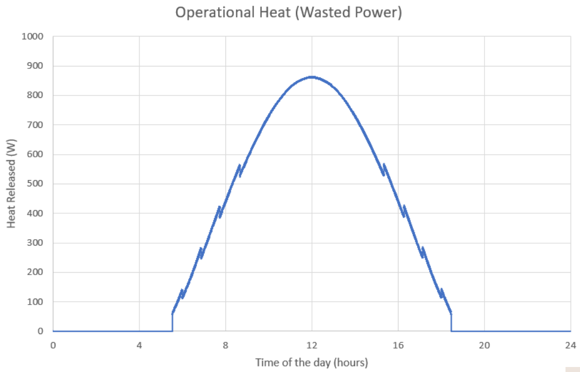


EOD: 3645 std. litres

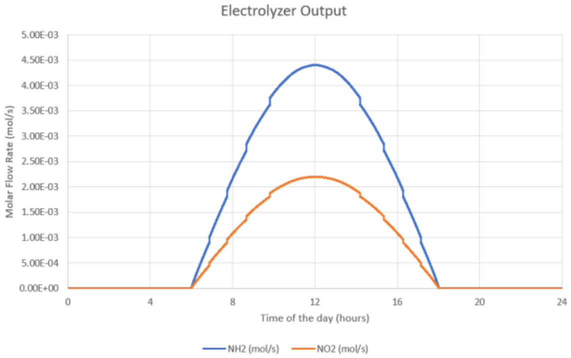


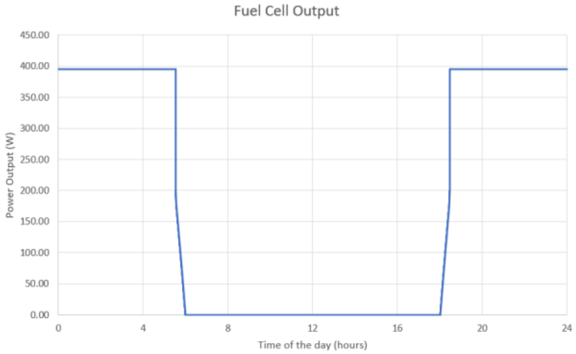
η_e = 63.1-80%

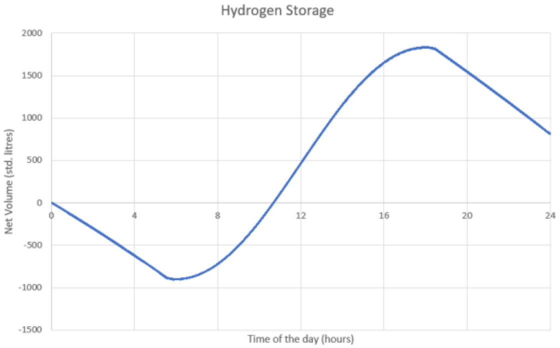
Q_e = 6.86 kWh

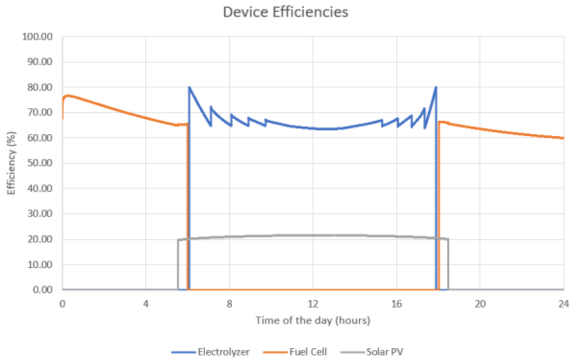


Results – Constant Load (400 W)





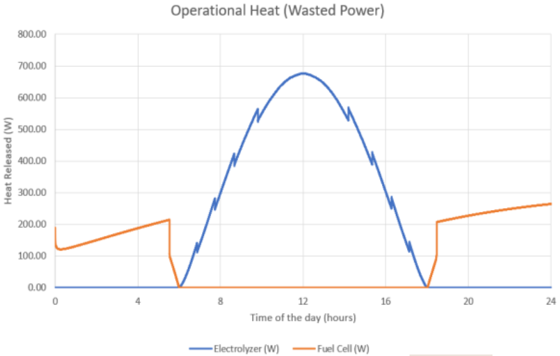




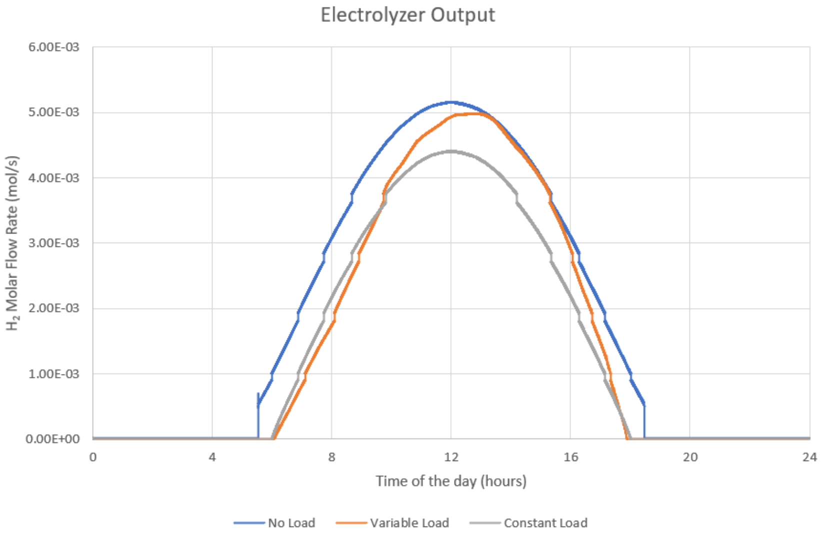
EOD: 812 std. litres

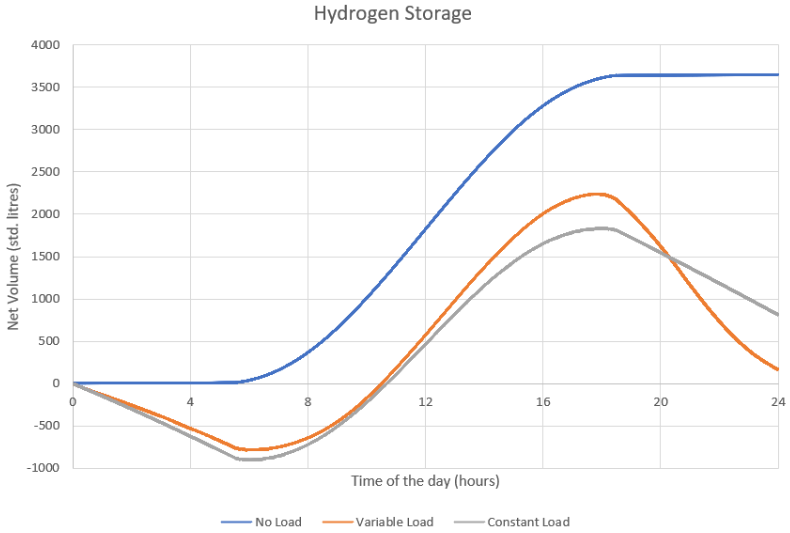
η_e = 63.7-80%, η_f = 56-76.6%

Q_e = 4.91 kWh, Q_f = 2.28 kWh



Results – Comparison





Net volume of hydrogen at EOD reaches zero for ~ 495 W constant load

Efficiency of heat utilization = 60% (considered)

$\eta_{variable\_load}$ = 80.8%, η_{no_load} = 86%, $\eta_{constant\_load}$ = 85.3%

Conclusions

- The integration of solar & hydrogen technologies showcases a promising pathway towards achieving sustainable energy solutions for high-altitude locations, benefiting both the armed forces & local communities.
- This system is versatile, capable of generating electricity for general usage and electrolysis, producing hydrogen and oxygen, and providing thermal comfort within the tent.
- The net volume of hydrogen in all the scenarios is positive indicating that the system is capable of accumulating hydrogen over time, ensuring a continuous energy supply even on non-sunny days.
- Efficiency of the overall system in no load scenario > constant load scenario > variable load scenario.
- Effective load management strategies are required to maximize system efficiency since overall system performance increases when load profile matches the solar output.
- Thermally insulated solar hydrogen systems provide an overall energy utilization of 80-90%, which is much higher compared to a conventional solar hydrogen which have efficiency of 35-50%.
- The overall system efficiency can be further improved with advanced thermal insulation technologies.

Thank You!

Open for questions

Solar Hydrogen System

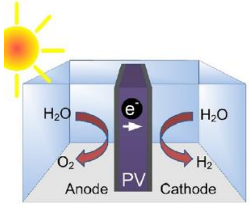
Hydrogen production – Electrolysis of water

$H2O \rightarrow H2 + \frac{1}{2} O2$ $\Delta H = +286$ kJ/mol

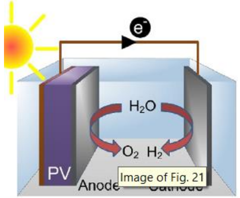
Types of Solar Hydrogen Systems

Photocatalytic | Photobiological | Solar Thermal | Photoelectrochemical (PEC)

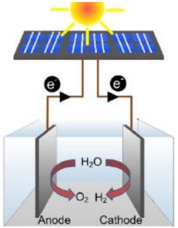
Types of PEC Devices



Fully integrated / Wireless



Partially integrated / Wired



Non-integrated / Modular

Liu, Guanyu, Yuan Sheng, Joel W. Ager, Markus Kraft, and Rong Xu. (2019). Research advances towards large-scale solar hydrogen production from water. EnergyChem 1(2):100014. Retrieved from https://doi.org/10.1016/j.enchem.2019.100014

Solar Hydrogen System – Examples

Components/Project Name	Solar Module/Cell	PV efficiency	Electrolyser	STHmax efficiency	Hydrogen Storage	Fuel Cell
PEM-EC, Solar cells	bifacial Si heterojunction	18.4% (30% albedo)	PEM	15.50%		-
	monofacial Si heterojunction	16.40%		13.70%		
-	InGaP/GaAs/GaInNAsSb triple-junction, highest STH	-	2 PEM	30%		-
	GaInP/GaAs/Ge multi-junction		10 cm2 Ni foam electrodes in 1 M NaOH	22.40%		
	a-Si:H/a- Si:H/ μc-Si:H triple junction		two Ti sheet electrodes loaded with Pt and IrO x catalysts	4.80%		
	Perovskite solar cells		bifunctional NiFe catalyst-loaded Ni foams as electrodes	12.30%		
	III–V solar cells		PEM	18%		
PV cell, photon-enhanced thermionic emission cell, SOEC	multi-junction GaAs PV cell	29.8% and 37.2% for triple-junction & quadruple-junction	Solid Oxide Electrolysis Cell	29.61%		-
FIRST (2000-2004)	1.4 kWp, monocrystalline Si		PEM, 1 kW		Metal hydrides, 30 bar, 70 Nm3 volume cap, 248 kWh	PEM, 0.42 kW
INTA (1989-97)	8.5 kWp	10% (avg)	Alkaline, 5 kW	7.05%	Metal hydrides - pressurized tanks, 200 bar, 24-9 Nm3 volume cap, 85-32 kWh	PAFC-PEM, 10-7.5 kW
PHEOBUS (1993-2003)	43 kWp		Alkaline, 26 kW		Pressurized tank, 120 bar, 3000 Nm3 volume cap, 10638 kWh	PEM, 5.6 kW
SAPHYS (1994-97)	5.6 kWp, monocrystalline Si		Alkaline, 5 kW		Pressurized tank, 200 bar, 12 Nm3 volume cap, 426 kWh	EM, 3 kW

Solar Hydrogen System – Examples

Components/Project Name	Solar Module/Cell	PV efficiency	Electrolyser	STHmax efficiency	Hydrogen Storage	Fuel Cell
SAPHYS (1994-97)	5.6 kWp, monocrystalline Si		Alkaline, 5 kW		Pressurized tank, 200 bar, 120 Nm3 volume cap, 426 kWh	PEM, 3 kW
SCHATZ (1989-96)	9.2 kWp, monocrystalline Si		Alkaline, 6 kW	6.2% (avg)	Pressurized tank, 8 bar, 60 Nm3 volume cap, 213 kWh	PEM, 1.5 kW
Solar house (1992-95)	4.2 kWp		PEM 2 kW		Pressurized tank, 28 bar, 400 Nm3 volume cap, 1418 kWh	PEM, 3.5 kW
Solar hydrogen pilot plant (1990-92)	1.3 kWp	13% (avg)	Alkaline 0.8 kW	9.27% (avg)	Pressurized tank, 25 bar, 200 Nm3 volume cap, 709 kWh	PAFC, 0.5 kW
SWB (1989-96)	370 kWp, monocrystalline, polycrystalline and amorphous Si	9-13% (crystalline) & 5% (amorphous)	Alkaline 100 kW		Pressurized tank, 30 bar, 5000 Nm3 volume cap, 17730 kWh	PAFC, 80 kW
CEC (2007-)	5 kWp		Alkaline 3.35 kW		Metal hydrides, 14 bar, 5.4 Nm3 volume cap, 19 kWh	PEM, 2.4 kW
solar cells, electrolyser, hydrogen storage tank, fuel cell			PEM	CHP fuel cell ~ 72%		PEM, 0.5 kW
PVT modules, electrolyser, fuel cell stack, battery, H2 storage tank, H2 compressor	PVT modules	9% (overall electrical energy efficiency)	PEM	14.5% (max net energy efficiency)		PEM

Most fuel cells - PEM

Newer electrolyzers - PEM

Older electrolyzers - Alkaline

Optimistic STH efficiency = 0.2 * 0.7 = 14%

Parameters

Model	PIL 400HM
Maximum Power, P_{max} (W)	400
Open Circuit Voltage, V_{oc} (V)	49.28
Short Circuit Current, I_{sc} (A)	10.2
Voltage at Maximum Power, V_{mp} (V)	40.46
Current at Maximum Power, I_{mp} (A)	9.89
Module Efficiency (%)	20.12
Coefficient of Short Circuit Current, μ_{Isc} (%/°C)	0.05
Nominal Operating Cell Temperature, *NOCT* (°C)	43

Solar PV

Parameter	Value	Parameter	Value
A (cm^2)	160	ξ	4
δ_{mem} (cm)	0.0254	F (C mol^{-1})	96485
δ_{el} (cm)	0.008	R (J mol^{-1} K^{-1})	8.314
ρ_{el} (Ω cm)	1.06E-05	n_d	7
D_w (cm^2 s^{-1})	1.28E-06	λ	21
K_{darcy} (cm^2)	1.58E-14	$i_{o,an}$ (A cm^{-2})	1.00E-07
ρ_{H2O} (g cm^{-3})	1	$i_{o,cat}$ (A cm^{-2})	1.00E-01
μ_{H2O} (g cm^{-1} s^{-1})	1.10E-02	α_{an}	0.8
ε	0.3	α_{cat}	0.25

Electrolyzer

Parameter	Value	Parameter	Value
N	35	F (C mol^{-1})	96485
A (cm^2)	232	C_{dl} (F)	8.12
l_{mem} (cm)	0.0178	λ	12.5
P_{tank} (atm)	3	V_a (m^3)	0.005
P_{bpr} (atm)	3	k_a (mol s^{-1} atm^{-1})	0.065
Rated Power (kW)	5	V_c (m^3)	0.01
R (J $mole^{-1}$ K^{-1})	8.314	k_c (mol s^{-1} atm^{-1})	0.065

Fuel Cell

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