Design, Modelling and Performance Analysis of a Residential Grid-Tied Solar Photovoltaic System with Deferrable Load

Presented: Waseem Ijaz (M.Eng Electrical)

Student ID: 202294973

Memorial University Of Newfoundland

Supervisor: Dr. M Tariq Iqbal

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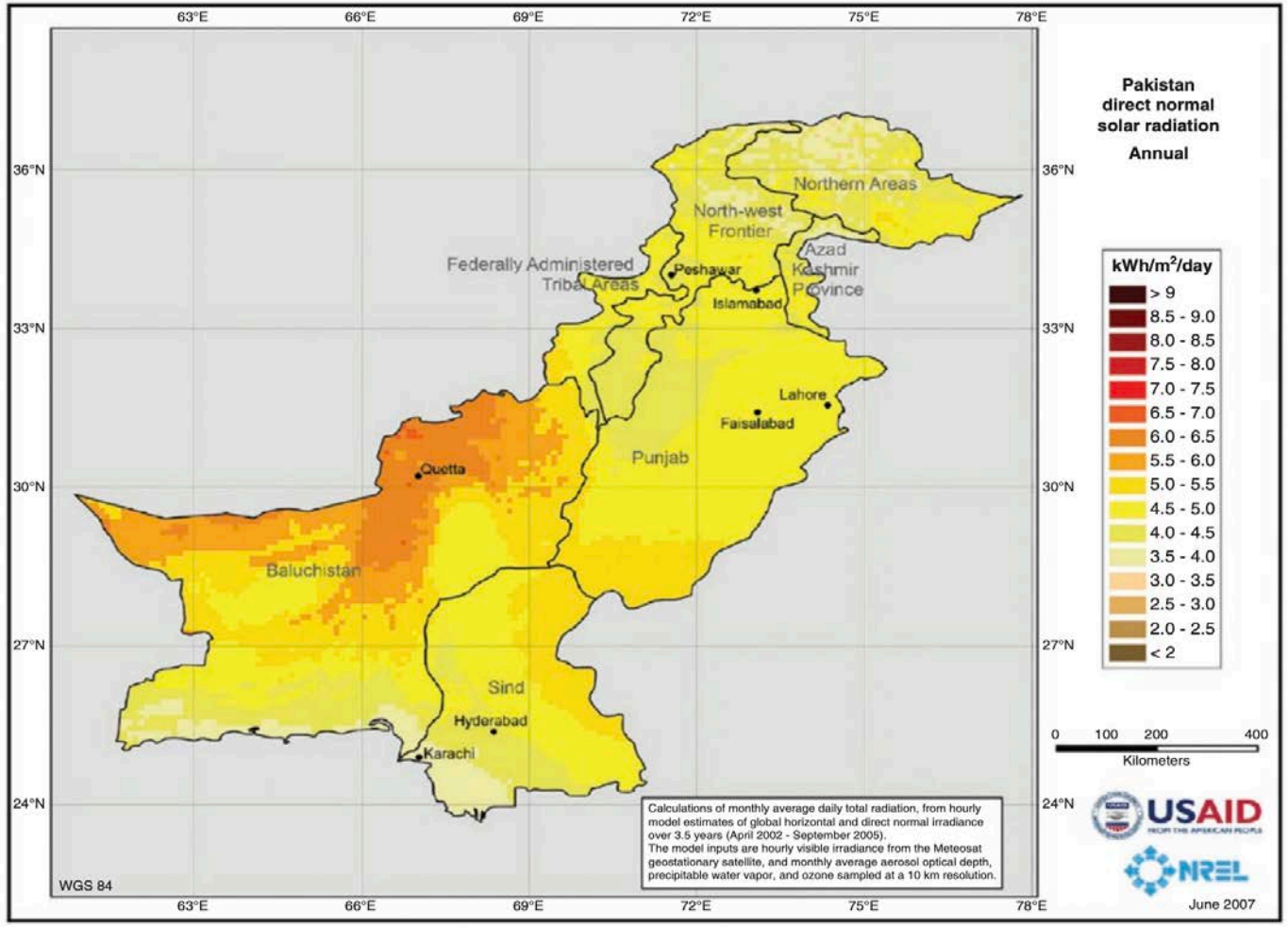
Outline of Presentation

- Introduction
- Literature Review
- Research Objective
- Design and Result analysis of the PV System.
- Dynamic Modelling of the Solar System
- Design and Result analysis of the Solar System with Deferable Load
- Conclusion & Future Work

Introduction

- Ever growing demand of Electricity in Pakistan due to increase in population and growing Economy.
- Heavy reliance on imported fossil fuels that cost government trade deficit.
- Solar and other form of renewable energy are environment friendly because they produce no GHG.
- Power outages due to short-fall of the national grid supply.
- Pakistan is geographically located in a region with abundant Solar Irradiation ranging between 1,600 to 2,200 kWh/m^2/yr. Average Lahore receives around 1806 kWh/$m^{2.}$
- This study aim to design, analyse grid-tied Hybrid system.

Introduction



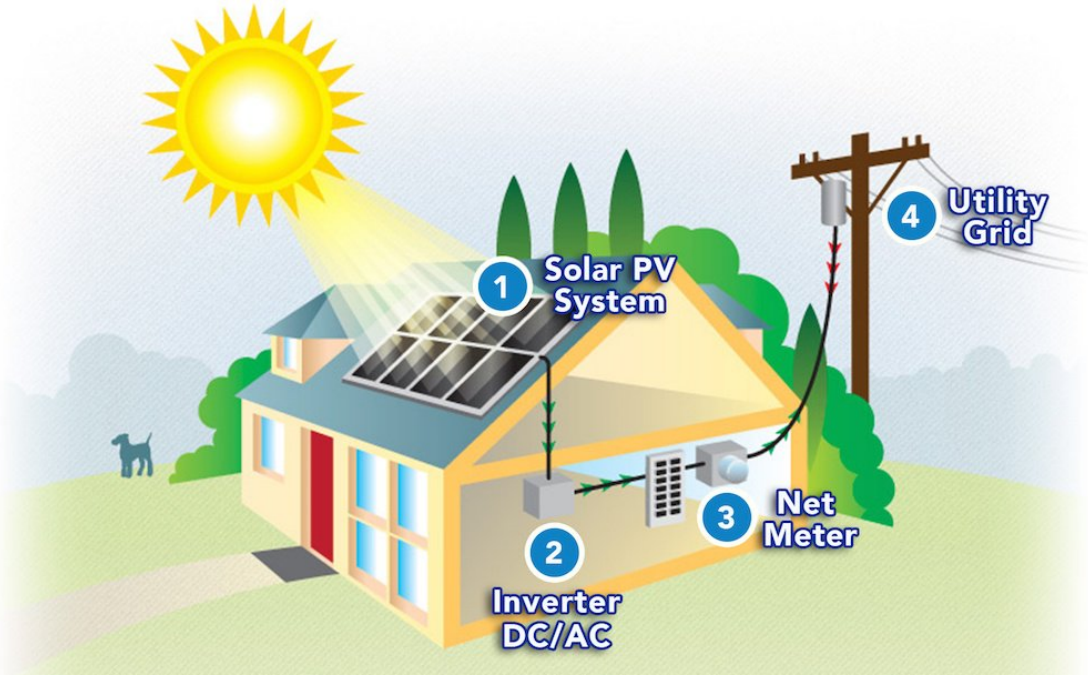
Pakistan Irradiance Map

Introduction

Types of Grid Connected Solar Systems.

Grid-tied Solar System:
These systems are connected directly with grid without battery back-up.
Components of PV System:

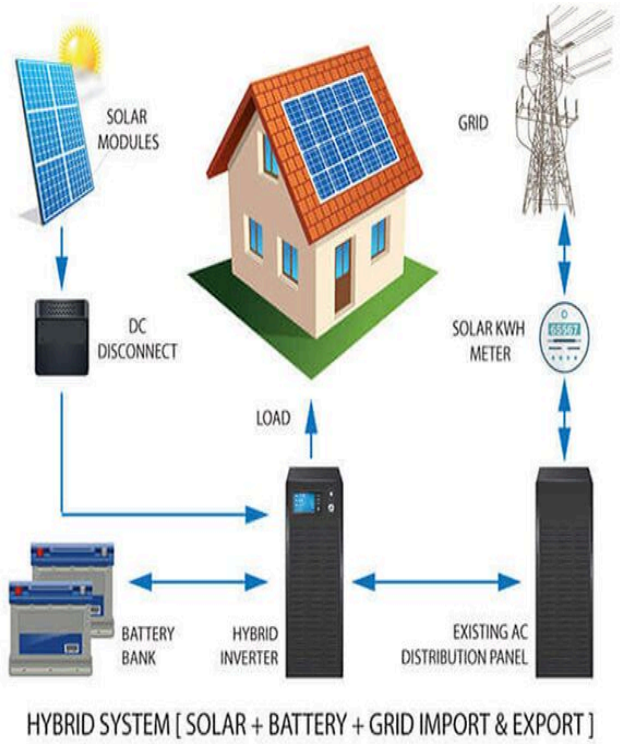
- Solar Panels.
- Inverter
- Load.



Introduction

Grid-tied Hybrid Solar System:
Hybrid Solar system is connected with Grid and also provide load back-up.
Components of PV System.

- PV Panels.
- Batteries.
- Inverter.
- Load.



Literature Review

Paper Reviewed	Deduction
S. U. Rehman, S. Rehman, M. Shoaib, and I. A. Siddiqui	In this paper simulation using HOMER is carried-out to study the impact of different factors that can effect the efficency of PV system
S. Akhtar, M. K. Hashmi, I. Ahmad, and R. Raza	Studying the effect of Concentrated solar energy for production of power in pakistan.
S. Wilkinson, M. John, and G. M. Morrison	Studied the Multi-level perspective of Roof top PV panels in Australia
MP Bakht, Z. Salam, M. Gul	Wind, Solar & Generator based hybrid system that is used in Quetta Pakistan.
H. Ahmad and F. Jamil	Impact of producing expnesive electricity from fossil fuels on economy and power outages.
N. Jamal and O. Hohmeyer	Increasing electricty demand and future of renewable enrgy in Pakistan.
M. Irfan, Z.-Y. Zhao, M. Ahmad, and M. C. Mukeshimana	Economic impact of transformation from traditional fossil fuels to solar energy.
S. Batool	Effective Grid Management and Net metering
M. Shahid, R. A. Butt, and A. Khawaja	Design of Grid-tied Solar system for a house in Karachi, Pakistan.
WA Haider, MA Aqeeq, MY Ayoub	Economic feasbility study of Solar systems at multiple locations in Pakistan
A. H. Tiwana	Studying multiple factors that effect the efficency of PV panels efficency.
A. H. Chohan, Z. A. Memon, A. I. Che-Ani, M. S. Arar, and J. Awad	Design and feasbility study of multiple Grid-tied Solar system homes in UAE.
M. U. Tahir, K. Siraj, S. F. Ali Shah, and N. Arshad	Case study of link between smart load management and solar energy production.
W. ur Rehman, I. A. Sajjad, T. N. Malik, L. Martirano, and M. Manganelli	Feasiability study of grid tied Buliding Integrated PV system.
G. E. Halkos and A. S. Tsirivis	This research study link between growing economy and how it directly Carbon Emission.

Research Objectives

Develop and evaluate a grid-connected solar system for a residential setting in Lahore, aimed at addressing power shortage and enhancing grid efficiency.

- To evaluate the economic benefit of installing an on-grid solar PV system using modelling tools such as SAM and HOMER Pro.
- To develop a computational model of a grid- connected PV System using MATLAB/Simulink and analyze its power generation dynamics, Inverter efficiency and grid interaction.
- To design a grid-tied solar system with deferable air-conditioning loads, incorporating recent regulatory changes by NEPRA and assessing their impact on system performance and Return On Investment (ROI).

Design & Analysis of PV System.

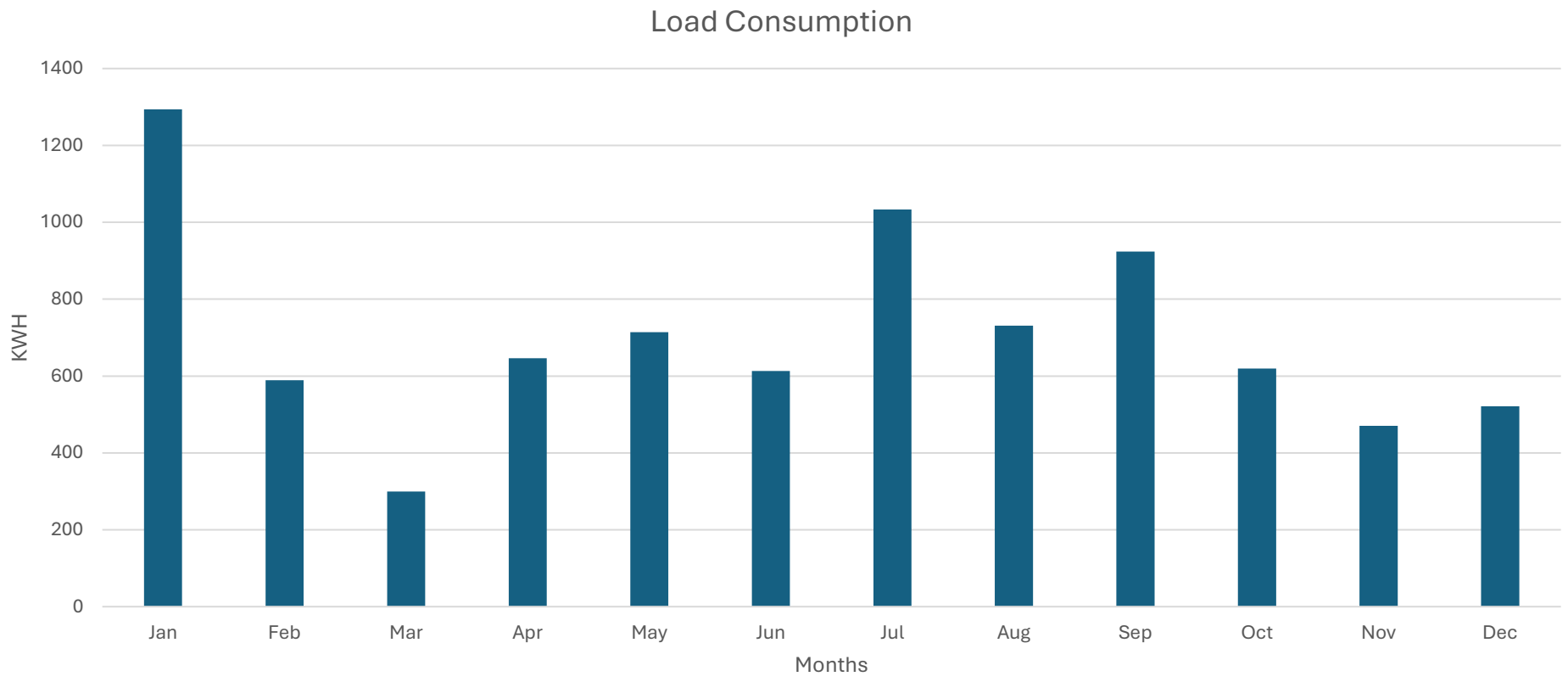
Design and Analysis

Site Location

- Site Coordinates are 31°27'49.0"N latitude and 74°28'25.7"E longitude
- House is in DHA Raya, Lahore.
- Plenty of space on the roof.
- House is occupied by 6 family member.

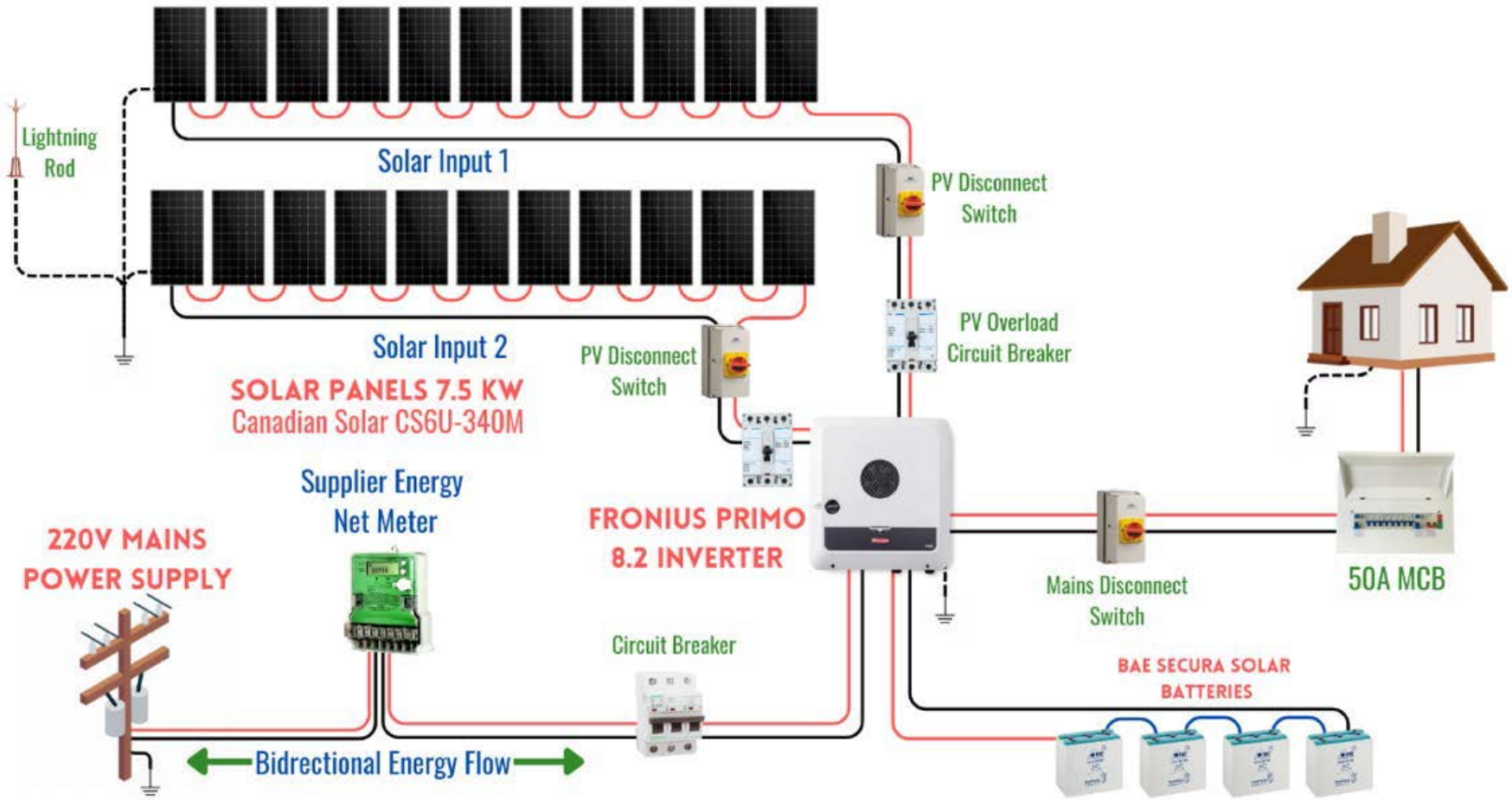
Design and Analysis

Electrical Energy Consumption



Design and Analysis

System Layout



Design and Analysis

Electrical Specification of Solar Panels

Specification	Value
Nominal Max. Power (Pmax)	340 W
Opt. Operating Voltage (Vmp)	37.9 V
Opt. Operating Current (Imp)	8.97 A
Open Circuit Voltage (Voc)	46.2 V
Short Circuit Current (Isc)	9.48 A
Module Efficiency	17.49 %
Operating Temperature	-40°C ~ +85°C
Max. System Voltage	1500 V (IEC) or 1500 V (UL)
Module Fire Performance	TYPE 1 (UL 1703) or CLASS C (IEC 61730)
Max. Series Fuse Rating	15 A
Application Classification	Class A
Power Tolerance	0 ~ +5 W

Design and Analysis

Specification of Inverter

Type	Rating
Maximum Output Power	8.2 kW
Efficiency	98%
Input Voltage Range	80 V - 1000 V
MPPT Voltage Range	270 V - 800 V
Maximum Input Current	33 A
Number of MPP Trackers	2
Nominal Input Voltage	710 V
AC Nominal Output	8200 W
Maximum PV Generator Power	12.3 kW
Maximum Output Power	8200 VA
AC Voltage Range	180 V - 270 V
Frequency Range	45 - 65 Hz
Total Harmonic Distortion	<3%
Protection Rating	IP65
Operating Temperature Range	-40°C to 55°C
Dimensions	645 x 431 x 204 mm
Weight	21.5 kg

Design and Analysis

Specification of PV System

Component	Specification
Number of Panels	22 (2 strings of 11 panels each)
Rated Power per Panel	340 W
Total Solar Power Output	7,480 W (7.48 kW)
Inverter	Fronius Primo 8.2
Maximum Output Power	8.2 kW
Number of MPPT Inputs	2
Battery Model	BAE Secura PVS 12 V 3 PVS 210
Number of Batteries	4 (connected in parallel)
Total Battery Voltage	48 V
Battery Capacity per Unit	211 Ah
Total Battery Capacity	10.13 kWh

Design and Analysis

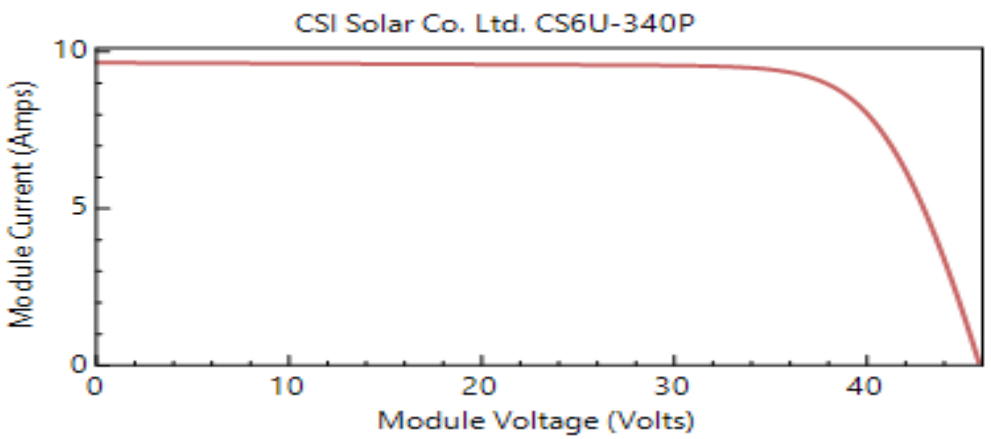
System Performance Analysis

- **System Advisor Model (SAM)**
  - It is software developed by National Renewable Energy Laboratory (NREL).
  - Goal of software is to encourage the examination and financial analysis of renewable system.
  - Modeling of PV system and batteries storage can be done on software.

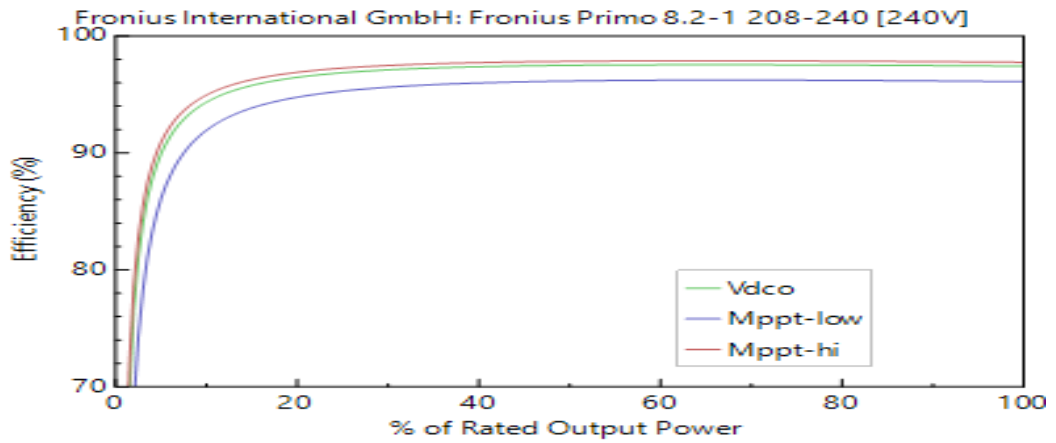
- **HOMER Pro**
  - HOMER Pro is all-round tool to design hybrid system.
  - Assist in finding cost-effective energy solution.
  - Utilize online solar irradiance and temperature to simulate system performance.
  - Software provide optimized solution of combination of different energy sources.

Design and Analysis

System Advisor Model (SAM)



Curve of Solar Panel simulated in SAM.



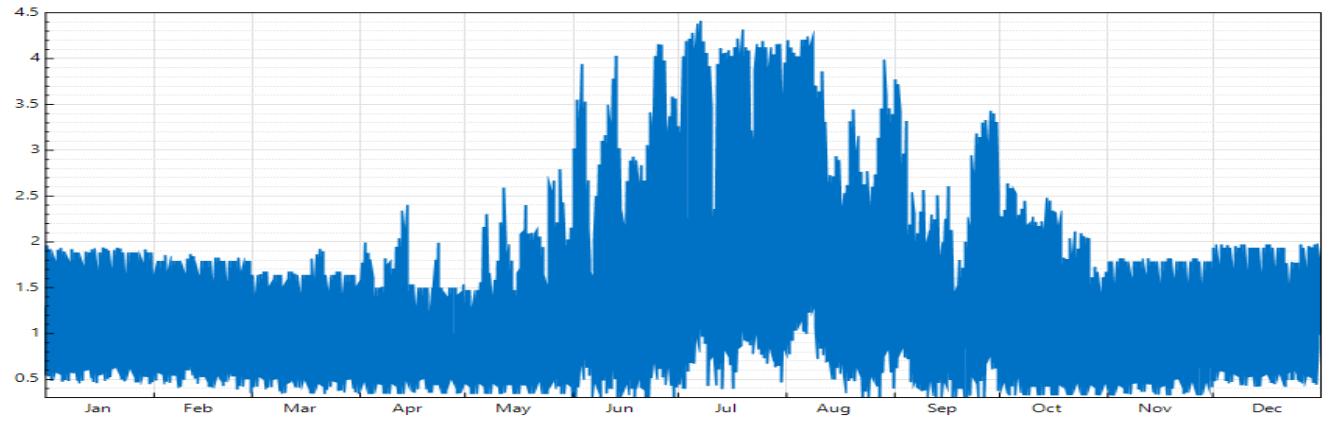
Inverter efficiency with respect to output voltage.

Design and Analysis

System Advisor Model (SAM)

- Electricity price was selected based on Peak and Off-peak rates.
- Electricity off-peak rate of 0.18/kWh.
- Electricity peak rate of 0.22/kWh.

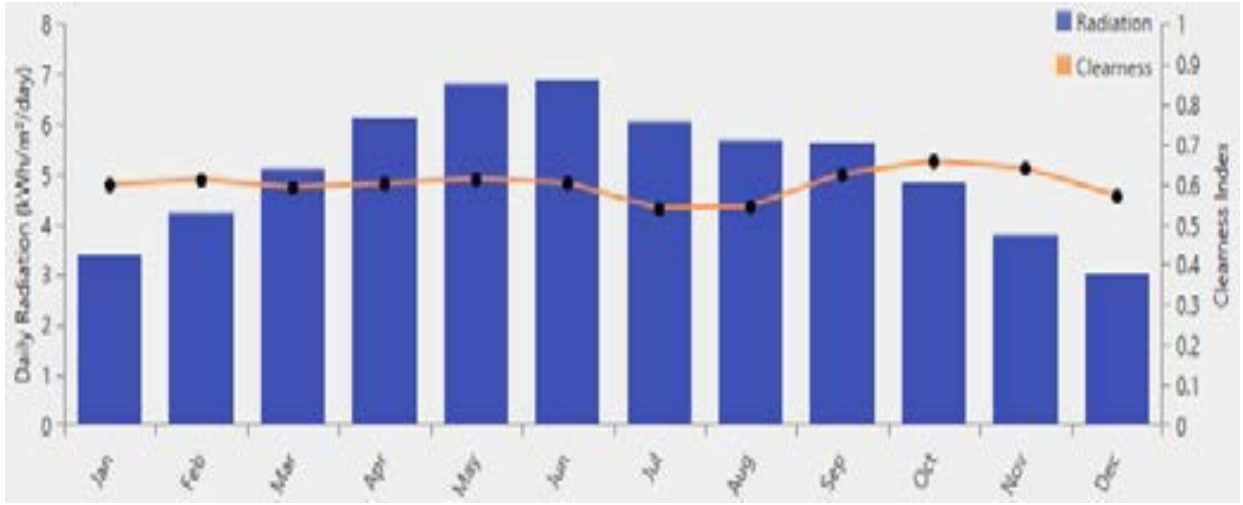
	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1	1

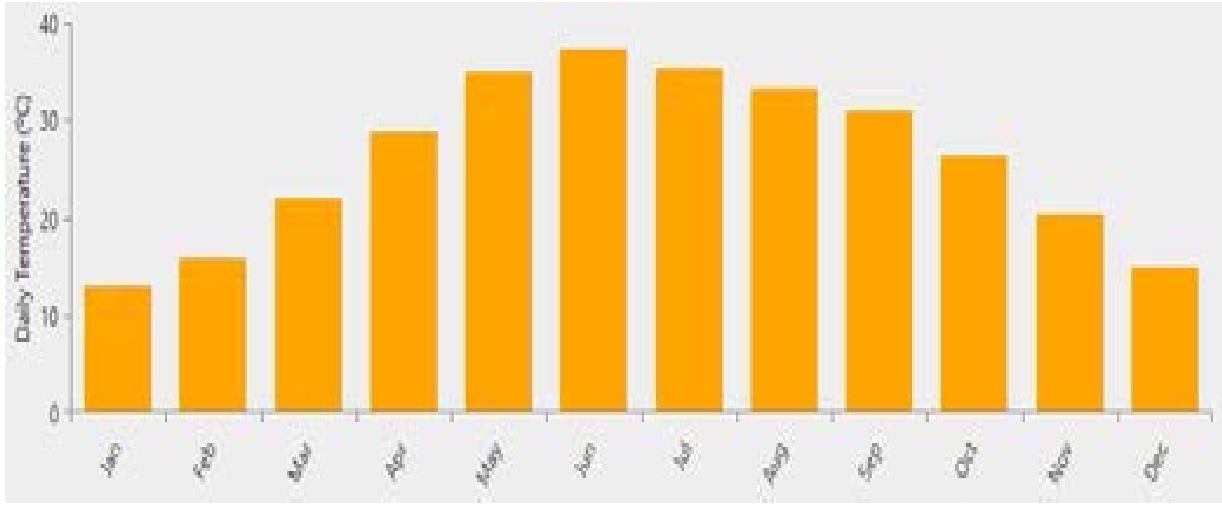


Design and Analysis

HOMER Pro

- Irradiance and Temperature of the selected site by HOMER Pro.

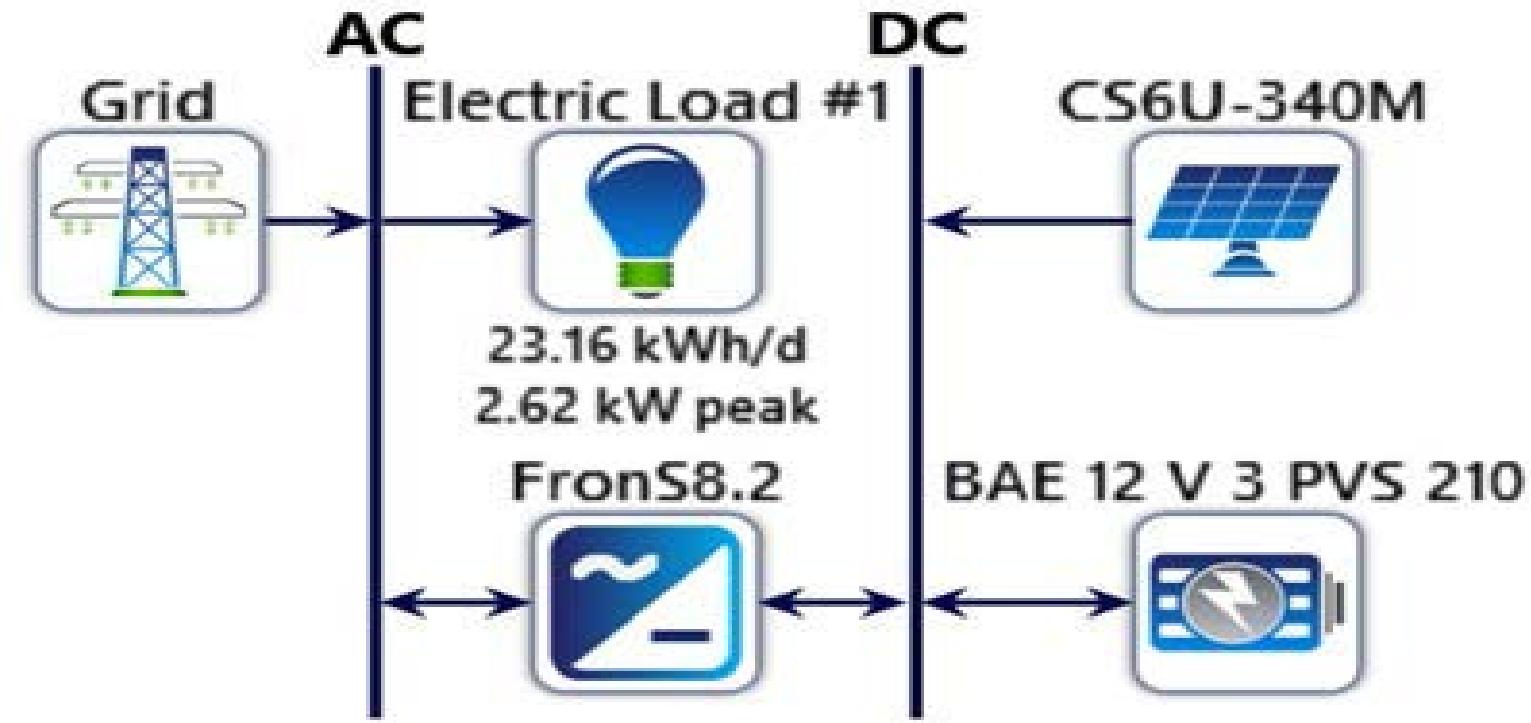




Design and Analysis

HOMER Pro

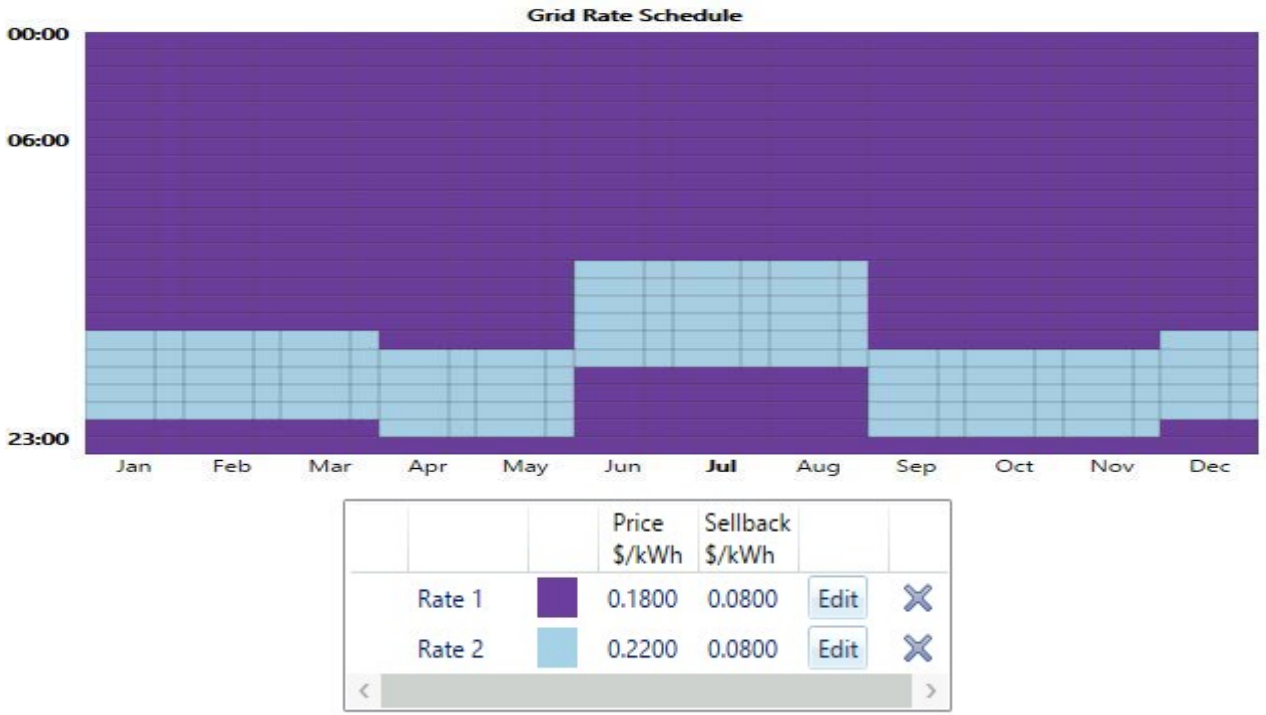
- System Block Diagram



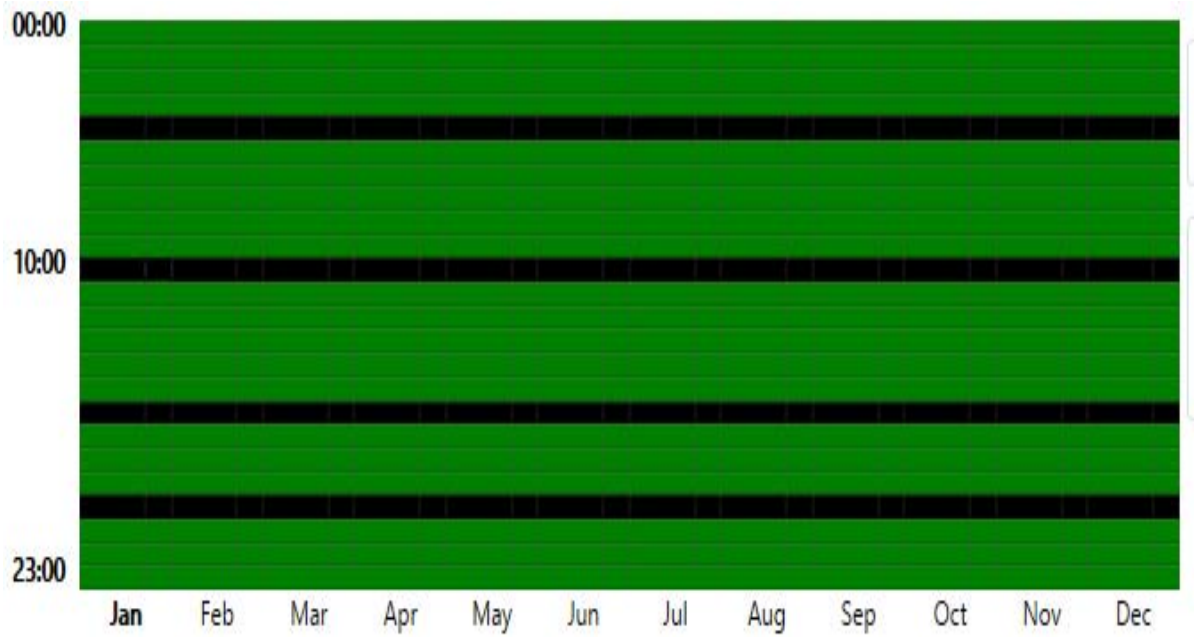
Design and Analysis

HOMER Pro

- Grid Tariffs & Schedule Outages



		Price $/kWh	Sellback $/kWh		
Rate 1		0.1800	0.0800	Edit	
Rate 2		0.2200	0.0800	Edit	



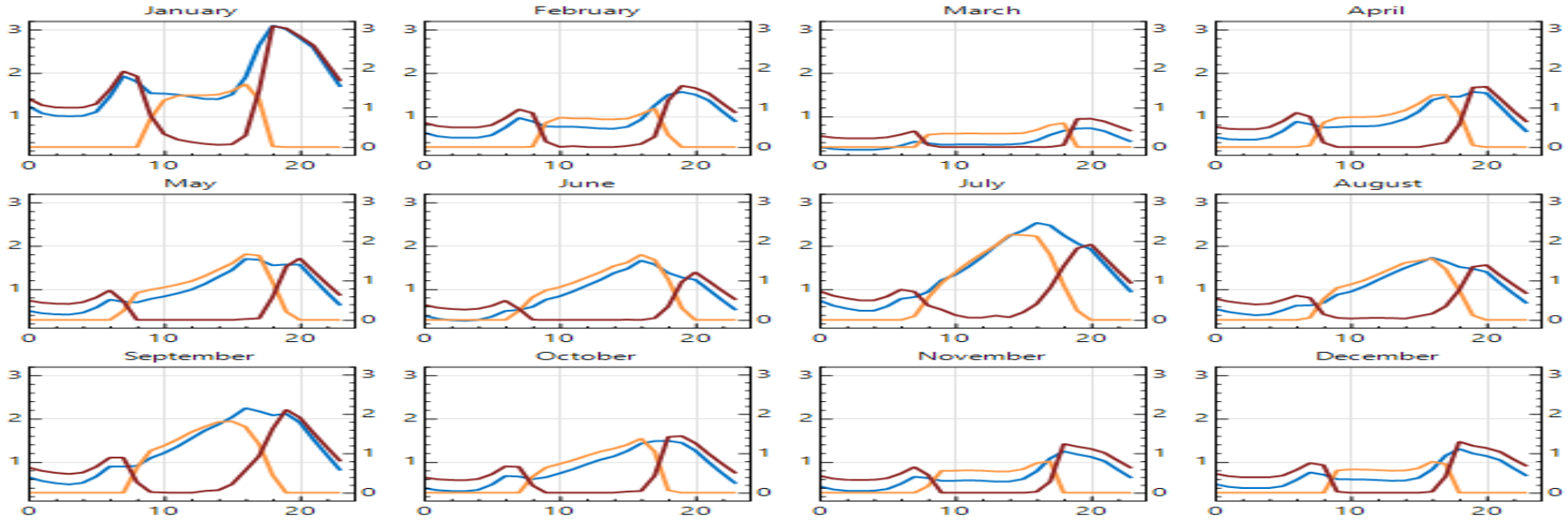
Design and Analysis

Results- SAM

Metric	Value
Annual AC energy in Year 1	10,026 kWh
DC capacity factor in Year 1	15.30%
Energy yield in Year 1	1,339 kWh/kW
Performance ratio in Year 1	0.69
LCOE Levelized cost of energy nominal	6.22 ¢/kWh
LCOE Levelized cost of energy real	2.95 ¢/kWh
Electricity bill without system (year 1)	$1,638
Electricity bill with system (year 1)	$370
Net savings with system (year 1)	$1,269
Net present value	$56,825
Simple payback period	2.7 years
Discounted payback period	3.1 years
Net capital cost	$5,989
Equity	$5,989

Design and Analysis

Results- SAM
Monthly Load Profile.

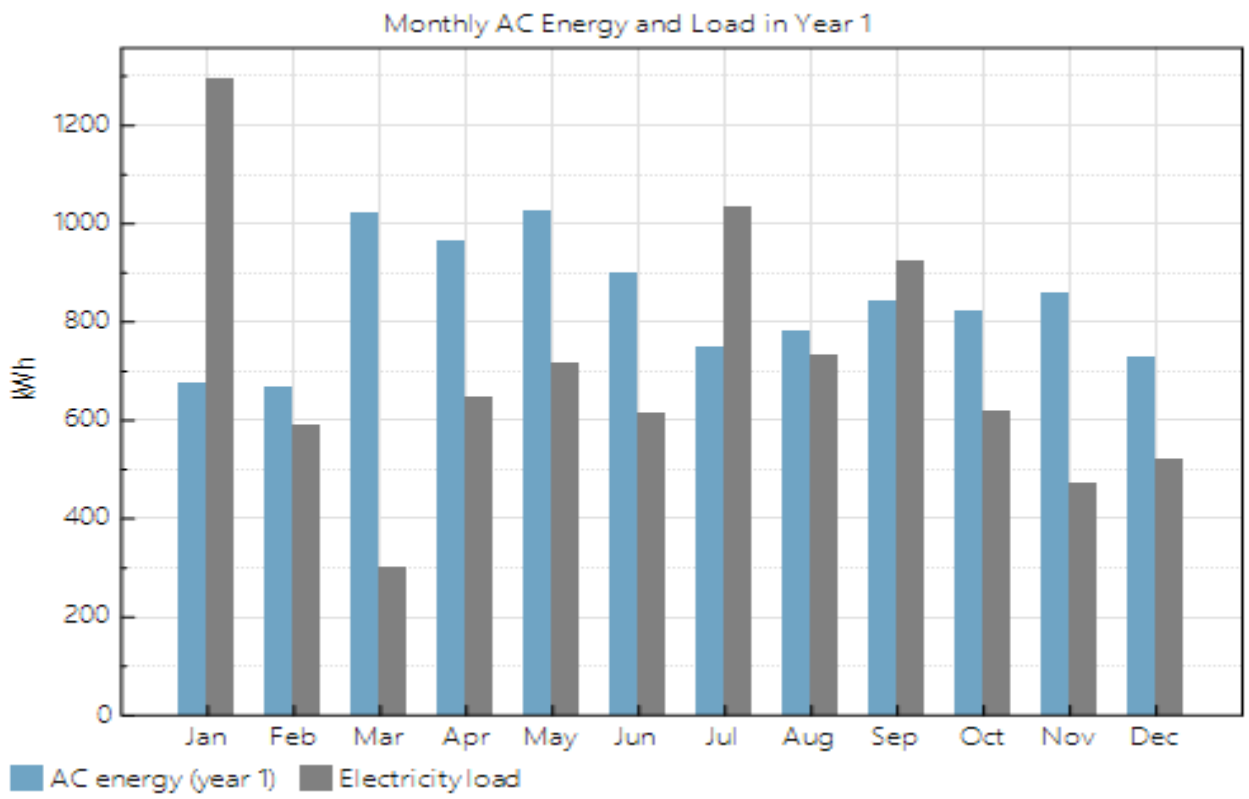


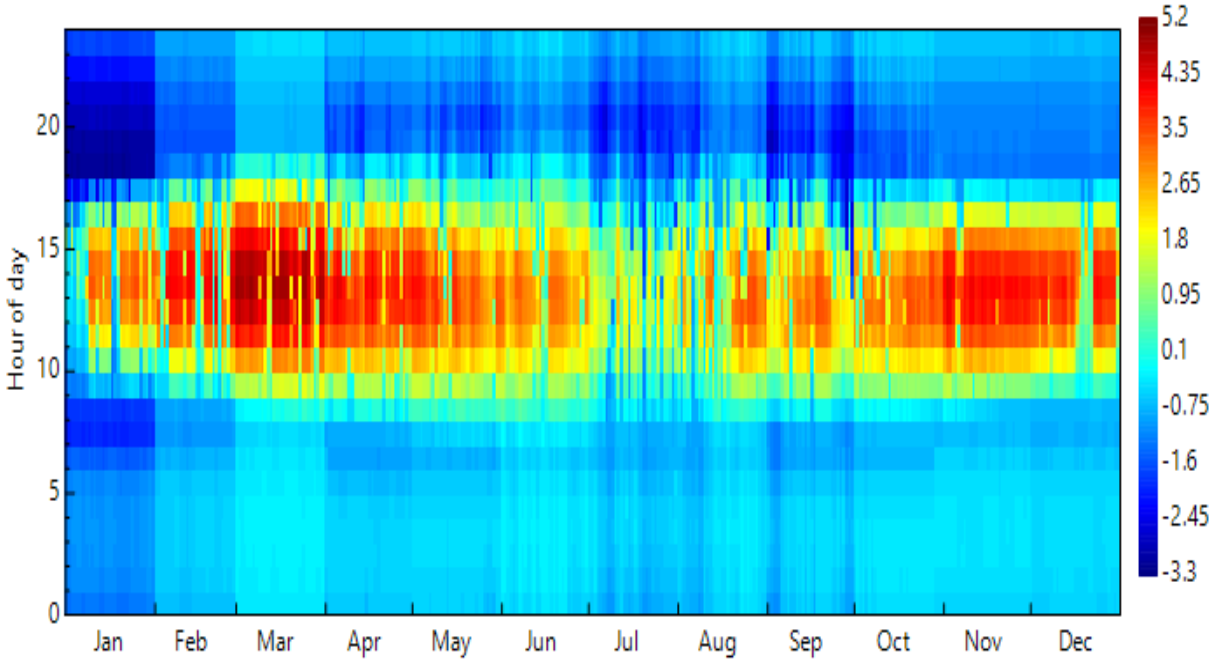
- Demand of Electricity (Blue).
- PV Electricity production (Orange).
- Power From Grid (Brown).

Design and Analysis

Results- SAM

PV Energy production VS Load.





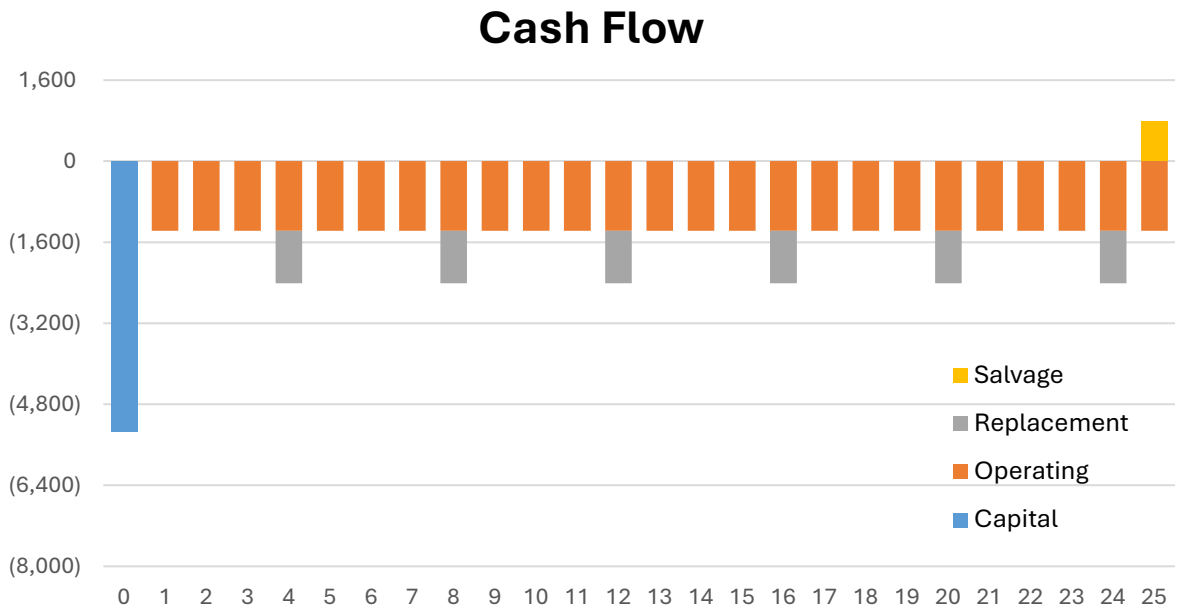
Design and Analysis

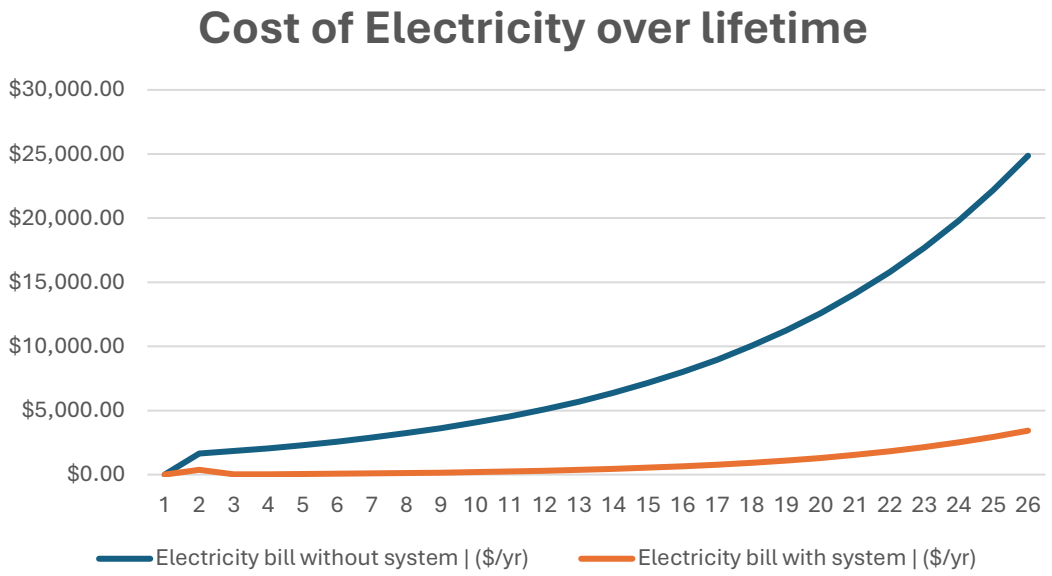
Results- SAM
Energy Flow

Month	DC energy	AC energy	Load	Electricity to/from grid
Jan	708.674	674.497	1293	-618.503
Feb	702.061	668.041	589	79.0414
Mar	1067.86	1019.53	299.5	720.027
Apr	1013.28	965.1	646.3	318.8
May	1074.28	1023.35	714.1	309.246
Jun	944.115	898.251	612.75	285.501
Jul	789.571	748.419	1033.2	-284.781
Aug	823.888	781.482	730.85	50.632
Sep	882.857	840.705	924.15	-83.4447
Oct	863.086	822.264	619.15	203.114
Nov	898.49	857.817	470.6	387.217
Dec	761.551	726.436	521.05	205.386

Design and Analysis

Results- SAM
Projected Cashflow

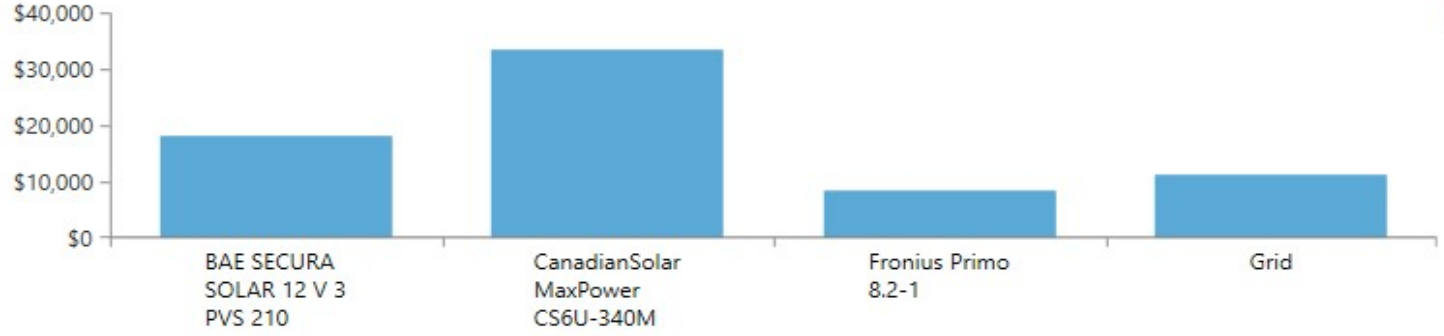




Design and Analysis

Results- HOMER Pro
System Structure & Cost Summary

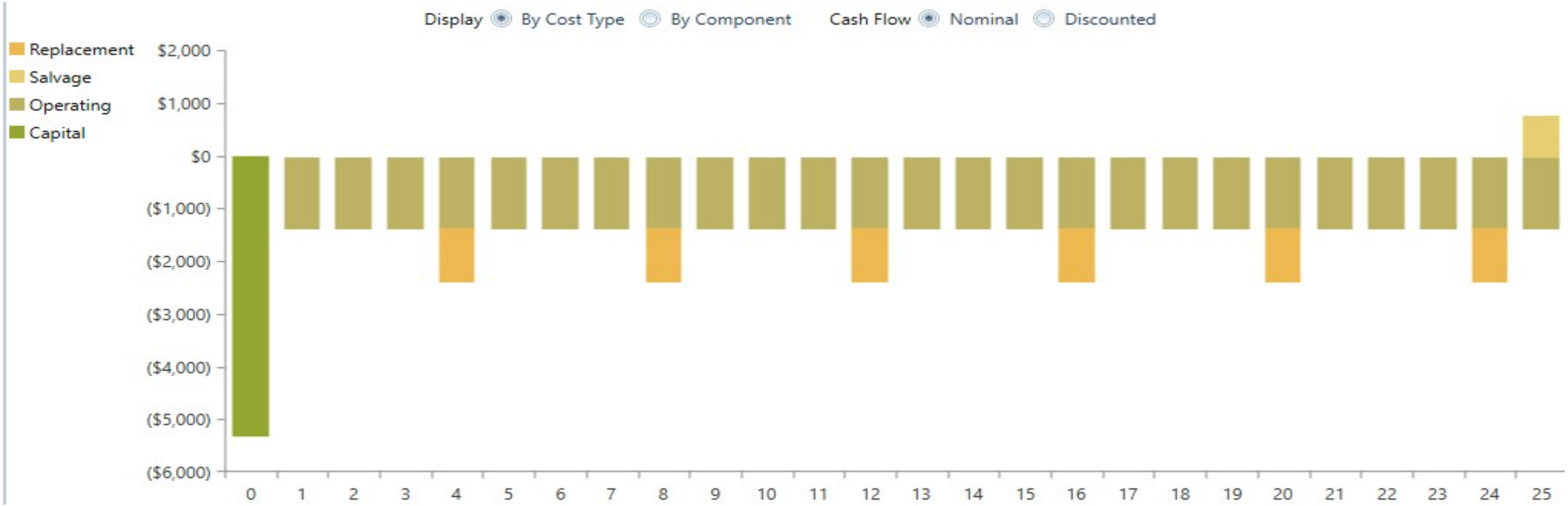
- Total Capital Cost is $ 5,340.
- Replacement Cost of the battery is $ 10,819.
- Total cost of the system through out the lifetime $ 71,485.
- Significant portion of cost comes from Solar Panels & Batteries.
- Batteries require replacement every four year.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
BAE SECURA SOLAR 12 V 3 PVS 210	$1,040.00	$10,819.59	$8,384.59	$0.00	($1,969.09)	$18,275.10
CanadianSolar MaxPower CS6U-340M	$2,100.00	$0.00	$31,442.23	$0.00	$0.00	$33,542.23
Fronius Primo 8.2-1	$2,200.00	$0.00	$6,288.45	$0.00	$0.00	$8,488.45
Grid	$0.00	$0.00	$11,179.73	$0.00	$0.00	$11,179.73
System	$5,340.00	$10,819.59	$57,295.00	$0.00	($1,969.09)	$71,485.50

Design and Analysis

Results- HOMER Pro
Cash Flow



Design and Analysis

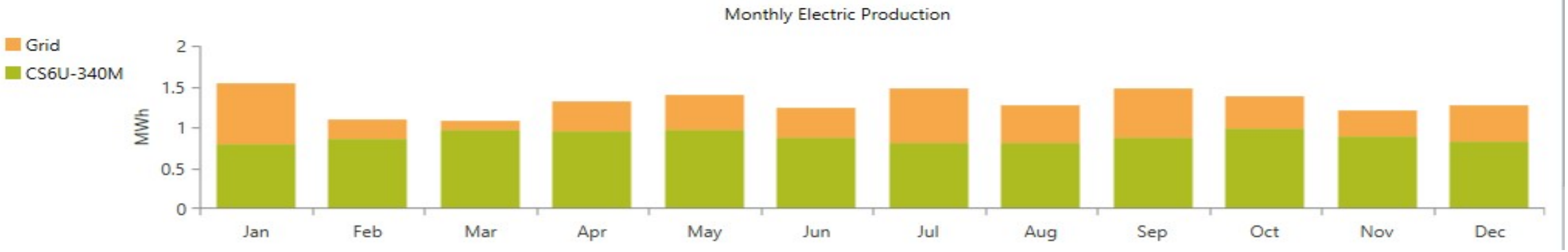
Results- HOMER Pro
Electrical Production

Production	kWh/yr	%
CanadianSolar MaxPower CS6U-340M	10,540	67.1
Grid Purchases	5,176	32.9
Total	15,716	100

Consumption	kWh/yr	%
AC Primary Load	8,453	61.2
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	5,365	38.8
Total	13,819	100

Quantity	kWh/yr	%
Excess Electricity	1,252	7.97
Unmet Electric Load	0	0
Capacity Shortage	0	0

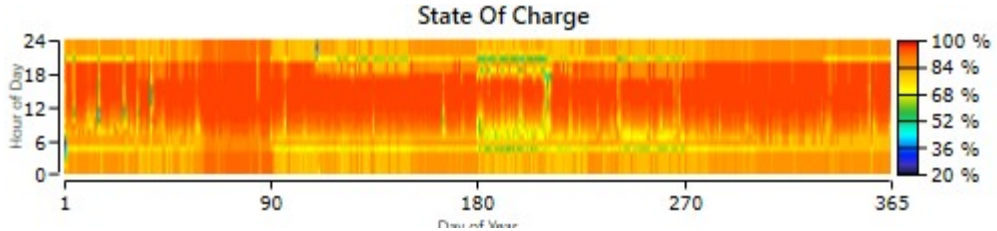
Quantity	Value	Units
Renewable Fraction	62.5	%
Max. Renew. Penetration	1,250	%

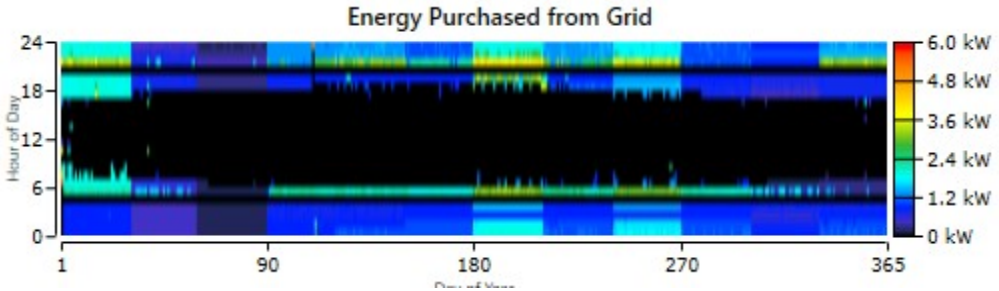


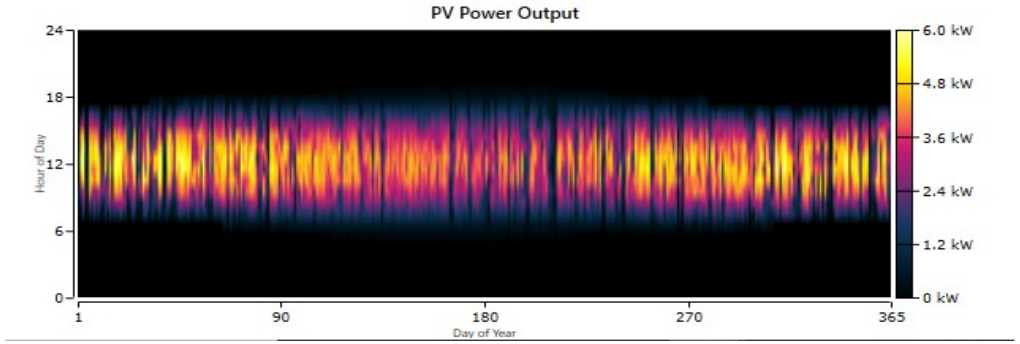
Design and Analysis

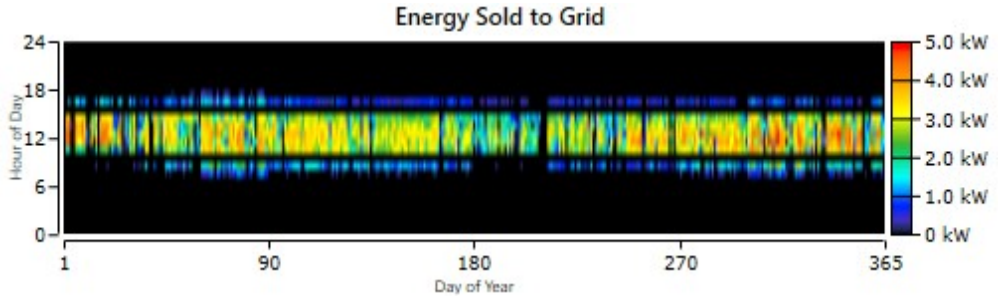
Results- HOMER Pro

PV Power Output, Power Grid Import , Export Graph & Battery SOC



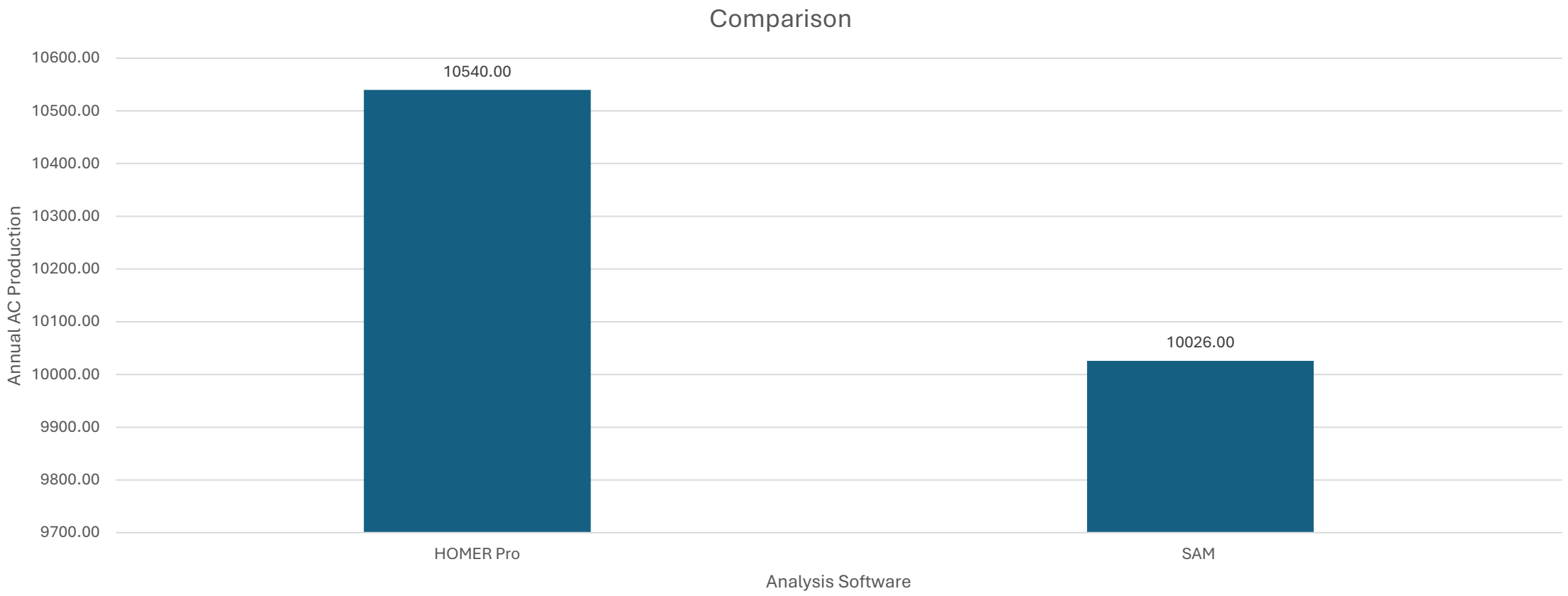






Design and Analysis

Comparison



Modelling & Simulation of Grid-Tied Solar System

Modelling & Simulation

- **MATLAB/ SIMULINK**
  - It provides versatile platform for system modelling.
  - Ideal of Power systems. Including Solar Systems(PV panels, Grid, Batteries)

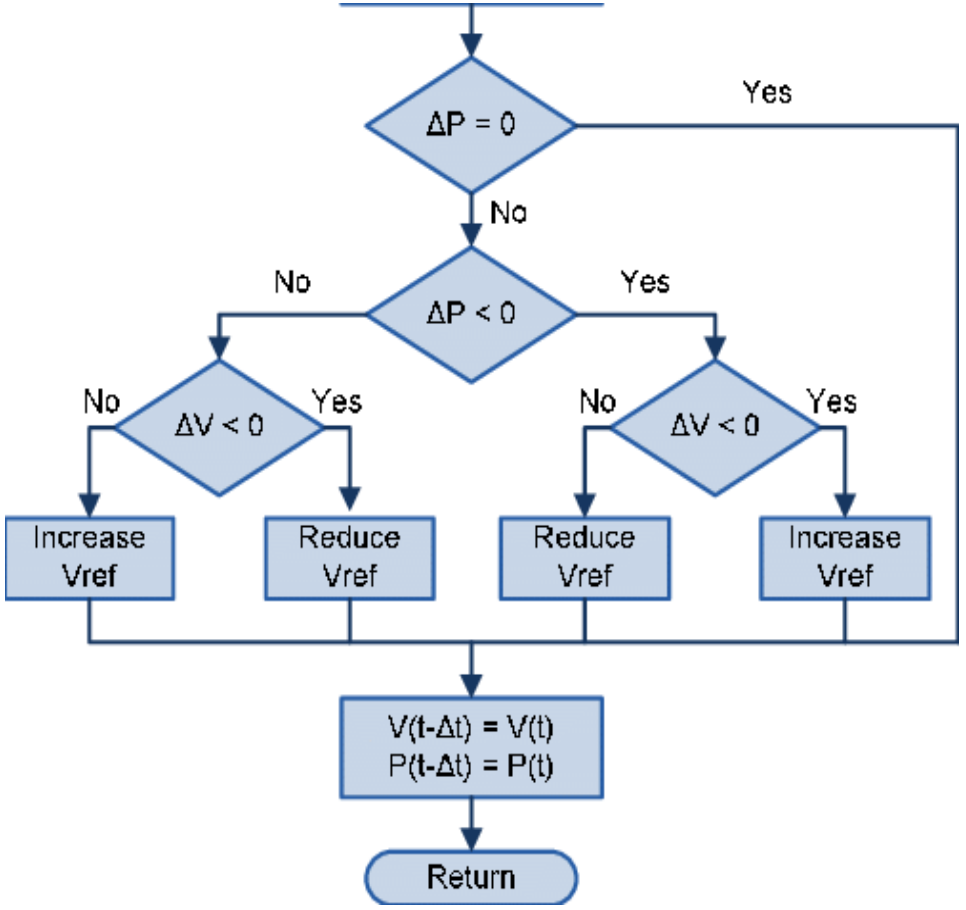
- **Focus of Work**
  - Modelling and simulation of Grid-tied Solar Inverter, with real-time Dynamics.

Modelling & Simulation

- **Key Components of Hybrid Power System.**
  - Photovoltaic Panels.
  - Maximum Power Point Tracking (MPPT).
  - Buck Converter.
  - Batteries with Charge Controller.
  - Boost Converter.
  - DC- AC Inverter.
  - Phase Lock Loop.
  - Load.

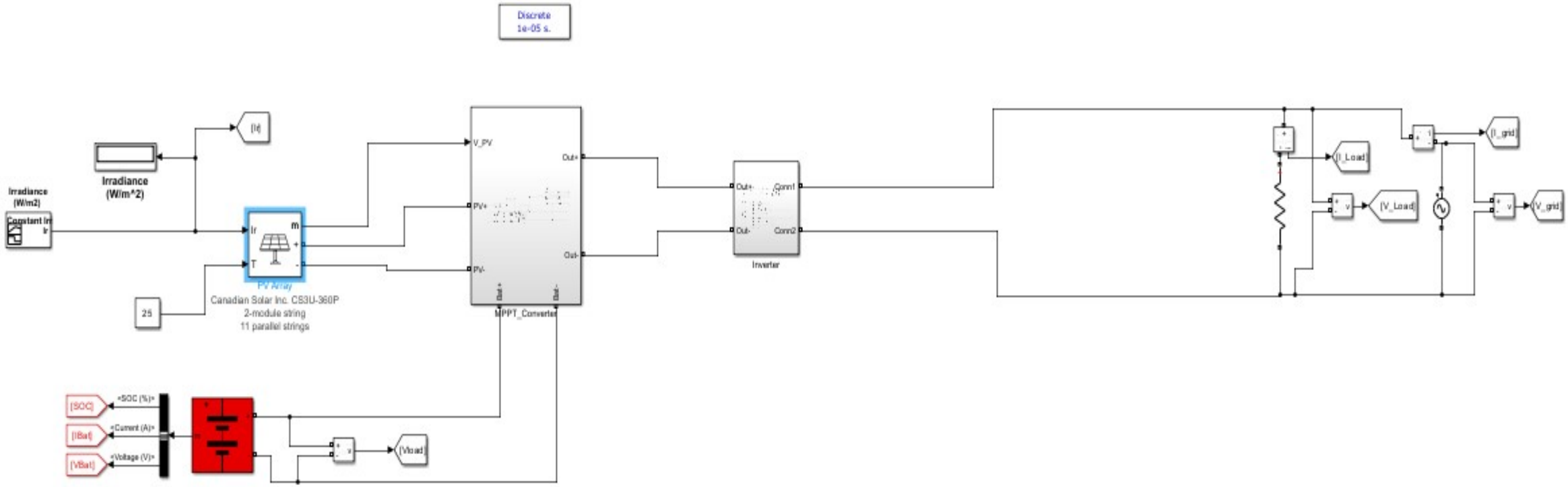
Modelling & Simulation

- **MPPT Algorithm**
  - To track the Maximum power point the algorithm used in modelling is P&O (Pertub and Observe) Algorithm.



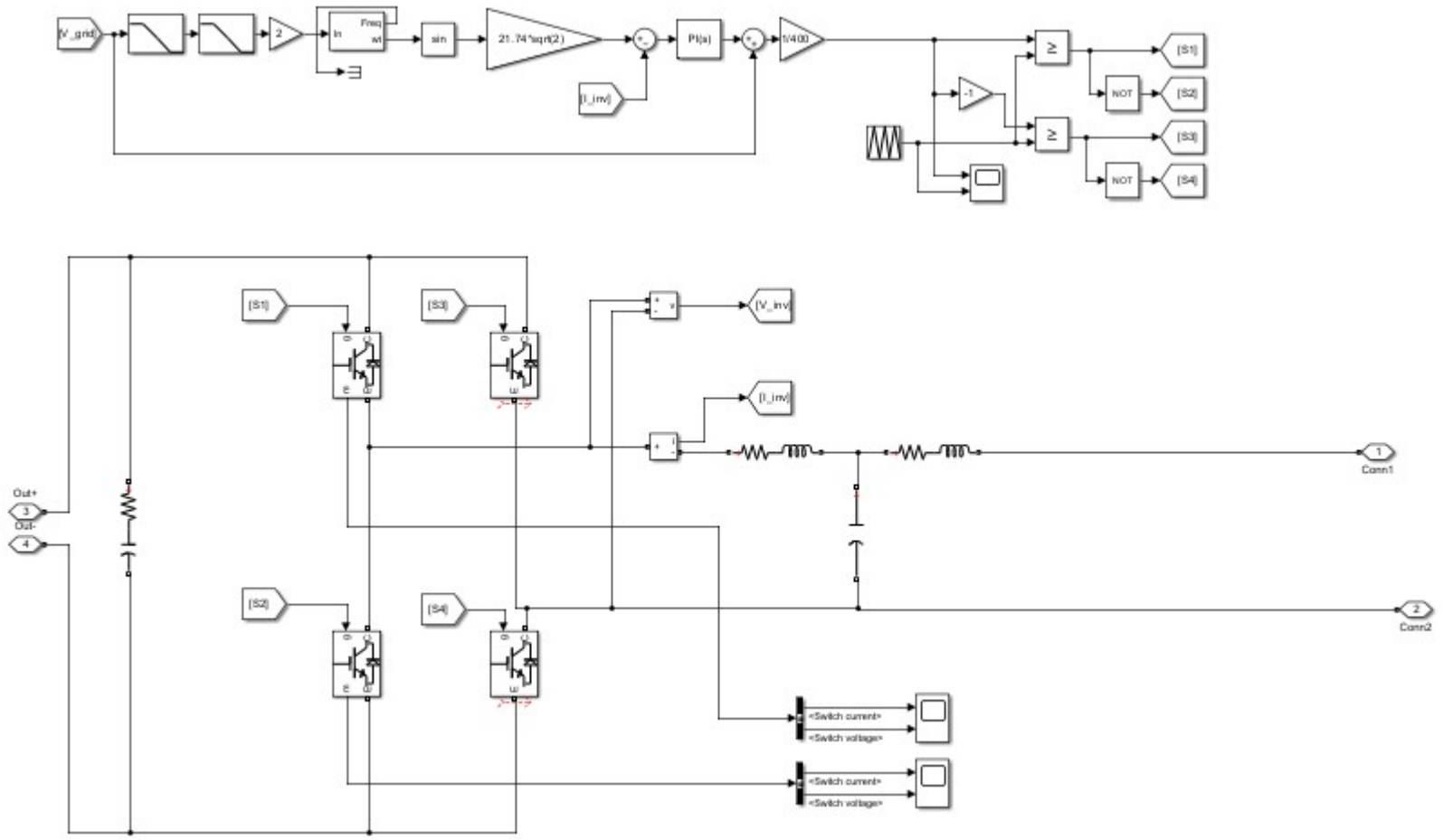
Modelling & Simulation

- **Simulation Model**



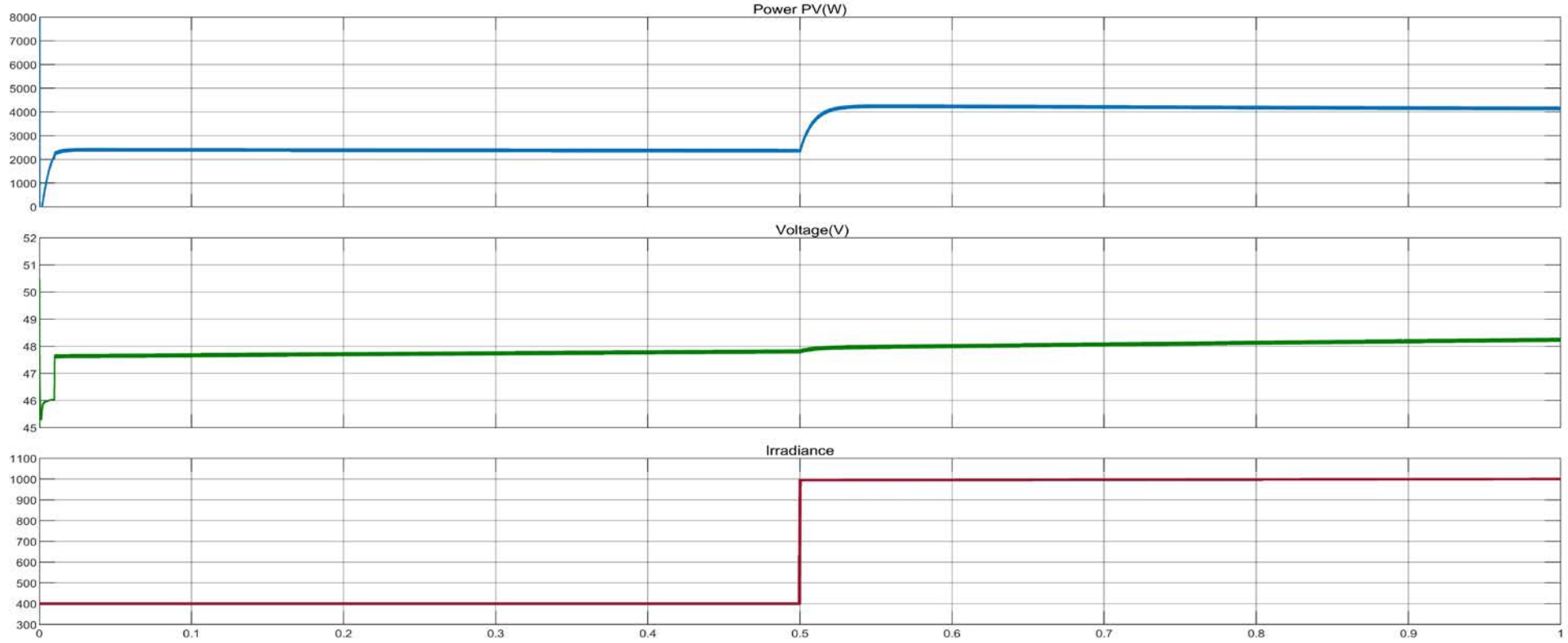
Modelling & Simulation

- **DC- AC Inverter (SPWM)**



Modelling & Simulation

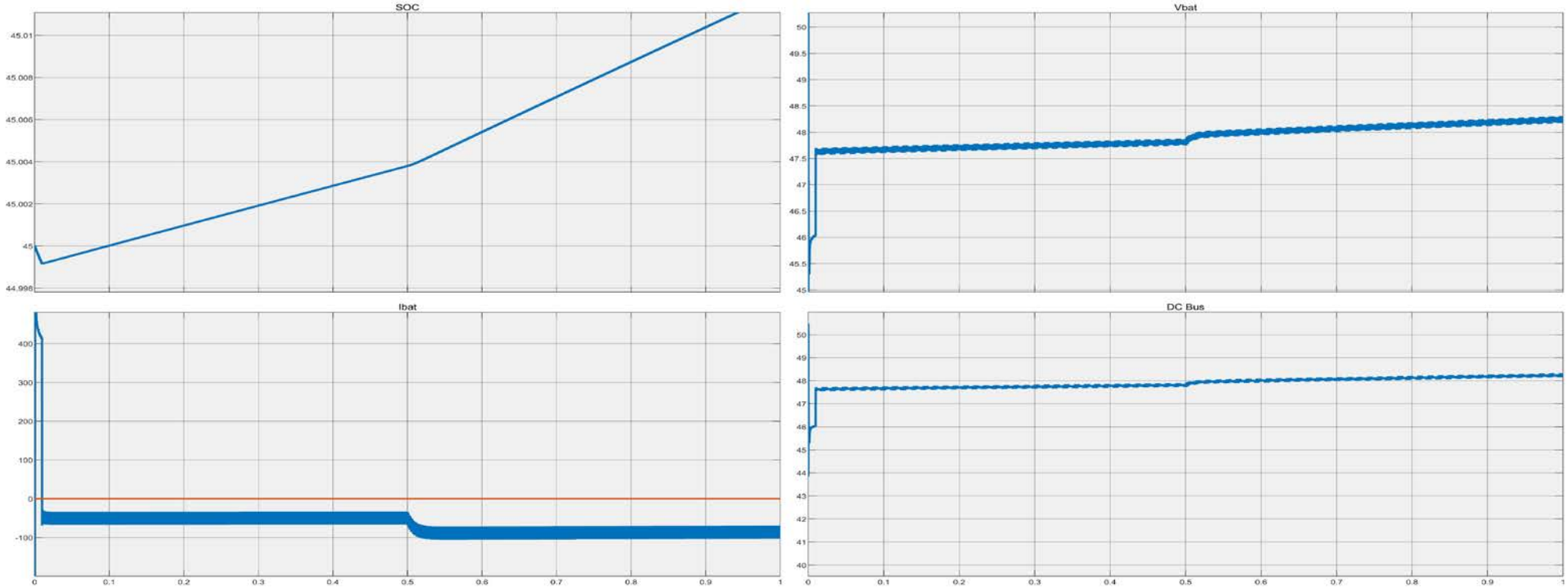
- **Results**
  - Dynamic response with changing Irradiance.



Power from PV Setup

Modelling & Simulation

- **Results**
  - Battery Response with changing Irradiance.

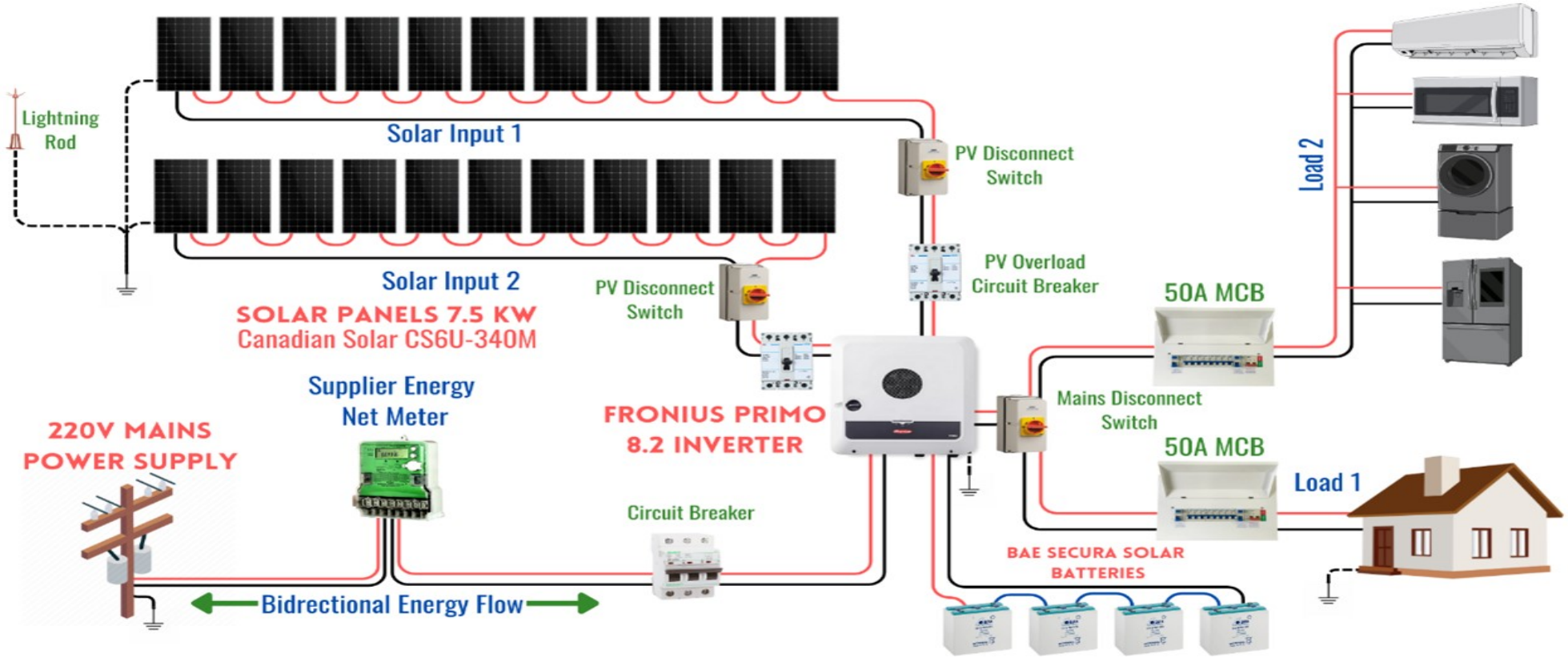


Battery Parameters

Design & Analysis of PV System With Deferable Load.

Design and Analysis

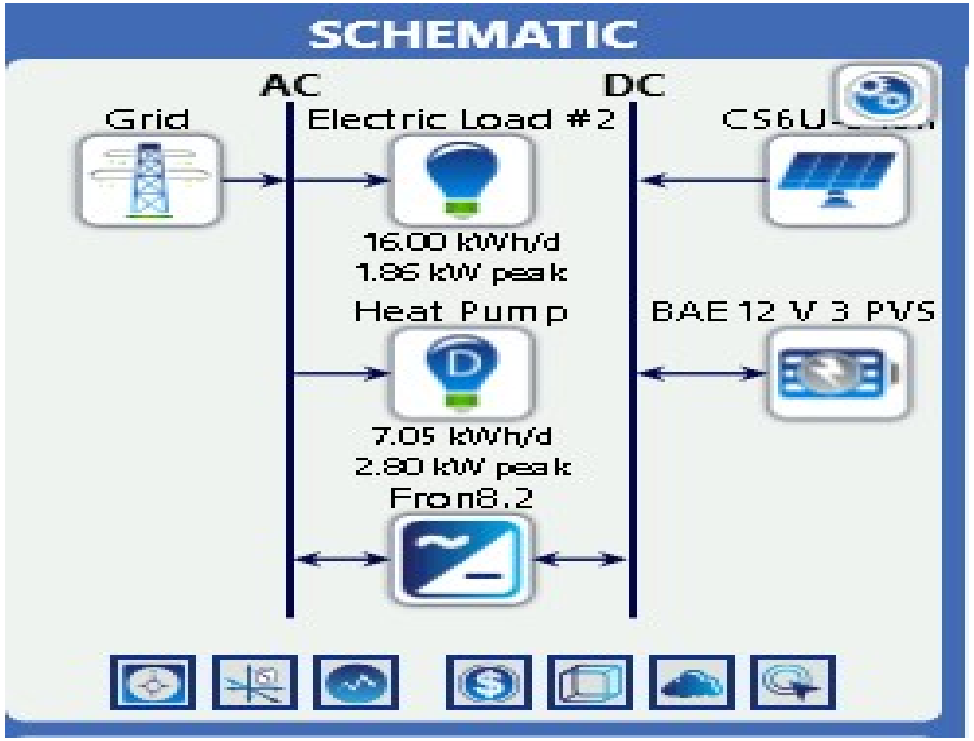
System Layout



Design and Analysis

Schematic of System

- **Components of System**
  - PV Panels.
  - Batteries.
  - Grid Connection.
  - Inverter
  - Electrical Load
  - Deferable Load

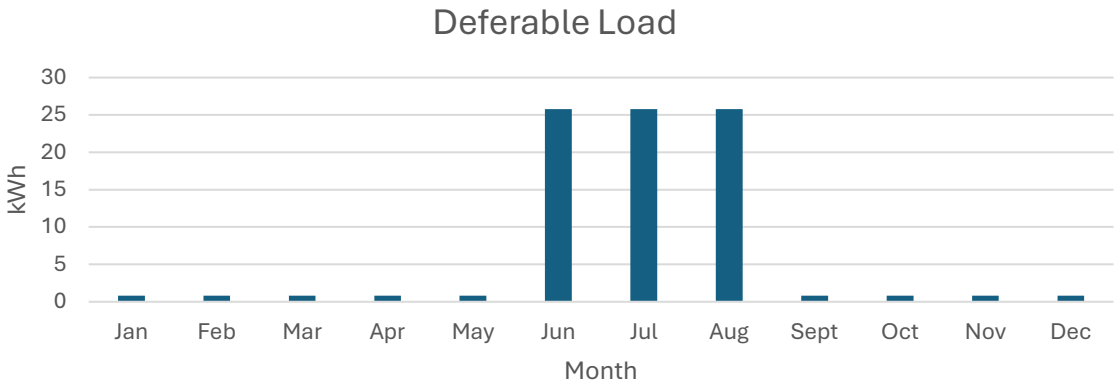


Design and Analysis

Deferable Load

During month of June, July & August Average Deferable load in our study is 25.8 kWh/day. Type of load on Deferable Load are

- Air-conditioner.
- Water Pump.
- Washing Machine.



Month	Average Load (kWh/d)
January	0.800
February	0.800
March	0.800
April	0.800
May	0.800
June	25.800
July	25.800
August	25.800
September	0.800
October	0.800
November	0.800
December	0.800

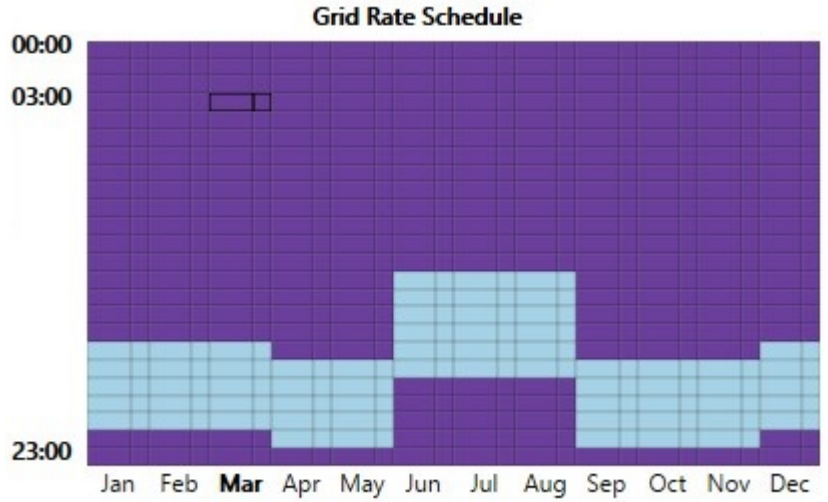
Annual Average (kWh/d): 7.05

Design and Analysis

Grid Revised Rate

Grid Unit rate is same for Off-peak and Peak power consumption.

- Sell Back rate is changed from 0.08 $/kWh to 0.039 $/kWh.

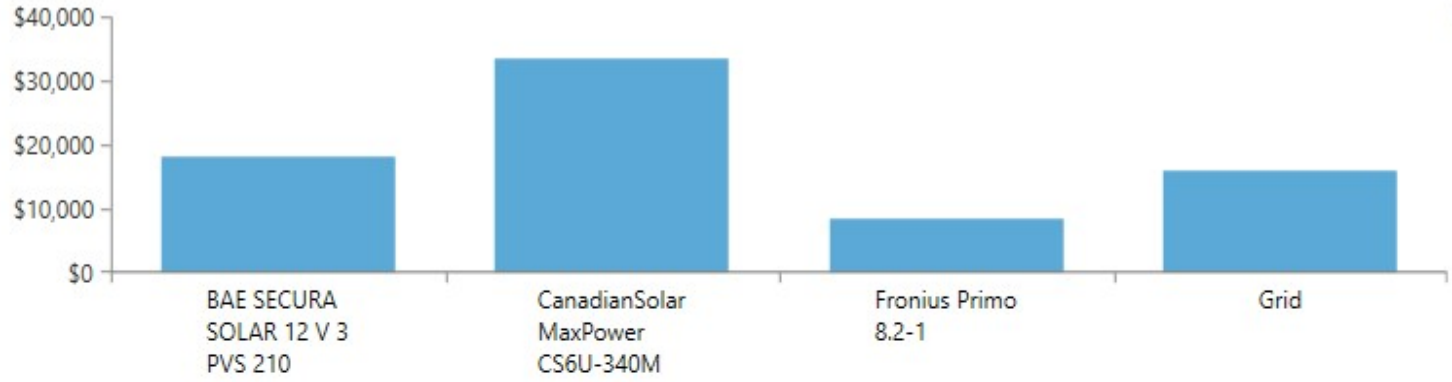


		Price $/kWh	Sellback $/kWh		
Rate 1		0.1800	0.0390	Edit	✕
Rate 2		0.2200	0.0390	Edit	✕

Design and Analysis

Results- Cost Summary

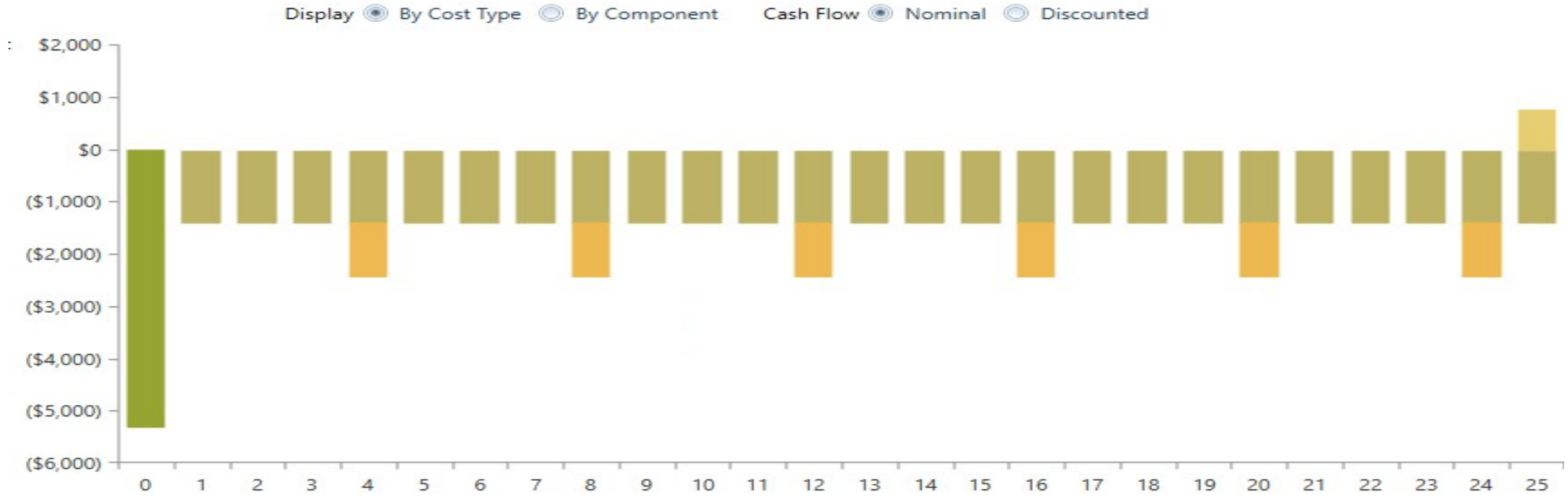
- Total Capital Cost is $ 5,340.
- Replacement Cost of the battery is $ 10,819.
- Total cost of the system through out the lifetime $ 76,120.
- Cost of system has increased because of reduced buy back rate to grid.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
BAE SECURA SOLAR 12 V 3 PVS 210	$1,040.00	$10,819.59	$8,384.59	$0.00	($1,969.09)	$18,275.10
CanadianSolar MaxPower CS6U-340M	$2,100.00	$0.00	$31,442.23	$0.00	$0.00	$33,542.23
Fronius Primo 8.2-1	$2,200.00	$0.00	$6,288.45	$0.00	$0.00	$8,488.45
Grid	$0.00	$0.00	$15,814.67	$0.00	$0.00	$15,814.67
System	$5,340.00	$10,819.59	$61,929.94	$0.00	($1,969.09)	$76,120.44

Design and Analysis

Results- Cash Flow



- System has Capital Cost of $ 5,340.
- Batteries need to be replaced after every 4 Years.

Design and Analysis

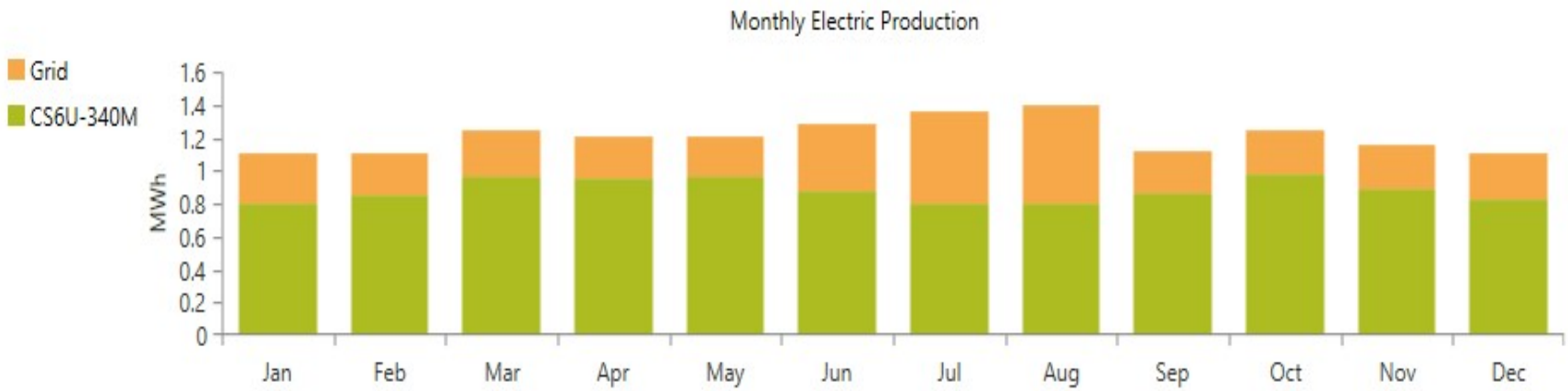
Results- Electrical Production.

Production	kWh/yr	%
CanadianSolar MaxPower CS6U-340M	10,540	7
Grid Purchases	3,941	2
Total	14,480	1

Consumption	kWh/yr	%
AC Primary Load	5,840	45.4
DC Primary Load	0	0
Deferrable Load	2,591	20.1
Grid Sales	4,444	34.5
Total	12,875	100

Quantity	kWh/yr	%
Excess Electricity	1,104	7.63
Unmet Electric Load	0.359	0.00430
Capacity Shortage	0.489	0.00580

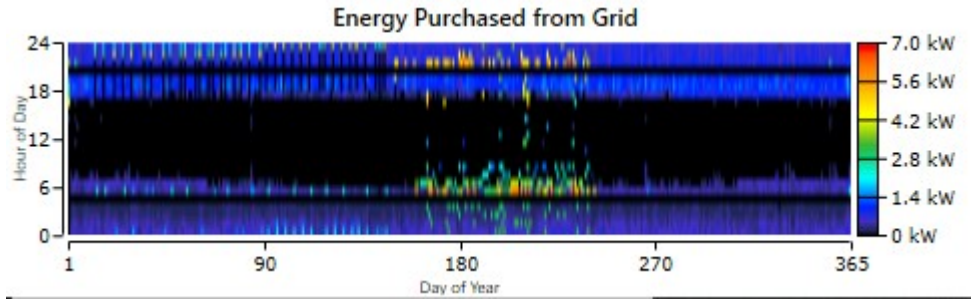
Quantity	Value	Units
Renewable Fraction	69.4	%
Max. Renew. Penetration	1,396	%

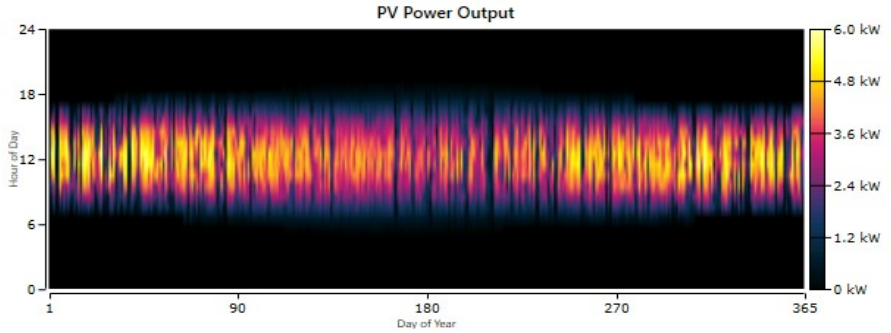


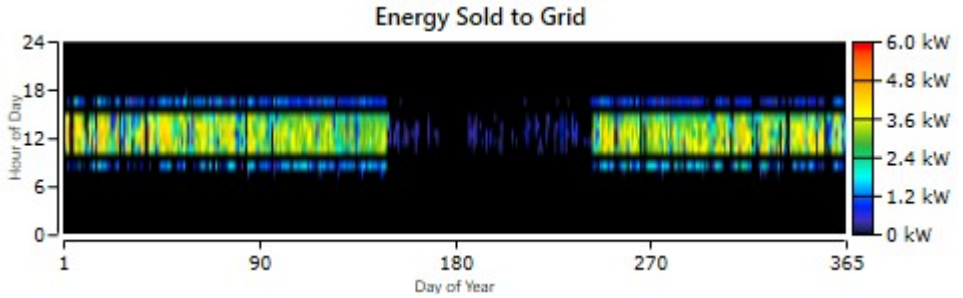
Design and Analysis

Results- HOMER Pro

PV Power Output, Power Grid Import , Export Graph & Battery SOC







Design and Analysis

Results- Conclusion

- Solar System has Peak performance during the summer months because of High Solar Irradiance.
- Using Deferable load helped us to optimize and use maximum energy at the day-time when solar irradiance is high.
- With Reduced net-metering rates the ROI of the system is decreased to 23% from previous ROI of 29%.
- Levelized Cost of Energy is also increased from $ 0.123/kWh to $ 0.141/ kWh because of reduced grid feed rates.
- Using Deferable Load increased the self-consumption of the household load.
- Renewable energy fraction increased to 69.4% from 62.5%.
- Maximum Renewable Penetration is increased from 1,250 % to 1,396 %.
- Total Renewable production divided by load increased from 76.3% to 81.9%.

Conclusion & Future Work.

Conclusion

Design & Analysis of Grid-tied Photovoltaic System

- Designed the system calculating actual load of the house.
- Carried-out simulation of the system using two softwares SAM & HOMER Pro, validating the performance of the system.
- Net-metering option was selected to maximize the solar energy utilizing and increase system viability.

Dynamic Modeling of the System

- Dynamic Performance of the hybrid System was evaluated using MATLAB/SIMULINK.
- Simulation showed us Stable Voltage, State of Charge & Battery Current with Varying irradiance.
- Reliable performance of the system in meeting real world energy needs.

Design & Analysis of Grid-tied Photovoltaic System

- Decreased export rate to grid have negative impact on ROI and decreases the economic feasibility of the system.
- Deferrable load helps optimize the use of renewable energy.
- With Deferrable load no surplus energy was sold to grid in month of June, July & August and was self consumed in house.

Future Work

Advance Load Management

- Using AI/ Machine Learning to study Load pattern of energy consumption.
- Optimizing Deferrable Load scheduling accordingly.
- Intelligent control system that can prioritize between critical and non-critical Load.

Scaling to Diverse Location

- Study system response under different geographical locations.
- Analyze system response under different Temperature & Solar irradiance condition.

Peer-to-Peer Energy Trade

- Research to be carried-out to study peer-to-peer energy trading model.
- Decentralized Energy Distribution.
- It reduces reliance on centralized energy distribution.
- With decreasing export rates this will increase the economic viability of micro grids.

List of Publications

- W. Ijaz and M. T. Iqbal, “Design and Analysis of an On-Grid Solar System House in Lahore Pakistan,” *Eur. J. Electr. Eng. Comput. Sci.*, vol. 8, no. 6, Art. no. 6, Nov. 2024, doi: 10.24018/ejece.2024.8.6.652.

- W. Ijaz and M. T. Iqbal, “Dynamic Modeling of on Grid-Connected Photovoltaic Setup in Pakistan using MATLAB,” *Eur. J. Electr. Eng. Comput. Sci.*, vol. 9, no. 2, Art. no. 2, Mar. 2025, doi: 10.24018/ejece.2025.9.2.681

- W. Ijaz and M. T. Iqbal, “Design and Analysis of A Grid-tied Solar System with Deferable Air-Conditioning Load For Lahore, Pakistan.” is reviewed and accepted by *Eur. J. Of Energy Research* and is under publication phase.

Thank you
For your Attention!!

Any Questions ?