MEMORIAL
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Design and Modelling of a large-scale Solar Water Pumping System for irrigation in Saudi Arabia

Abdulhamid Alshamani
MEng student
Electrical and Computer Engineering Department
Memorial University of Newfoundland
aa7646@mun.ca

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Supervised by:
Prof. Dr. Tariq M. Iqbal

30 minutes

Outline

- Introduction
- System description
- Sizing Optimization
- Results of sizing
- Possible energy storage methods
- The proposed system
- System modelling
- Results of simulation
- Conclusions and Recommendations
- Future work
- Research contribution
- Published work

Introduction

- Agriculture areas; more than 1.5 million hectares.
- Majority located in remote areas.
- High density of sunshine.
- Government support; low-interest loan.

Fig. 1: An agricultural area near of Tabuk city in the northern area of Saudi Arabia.

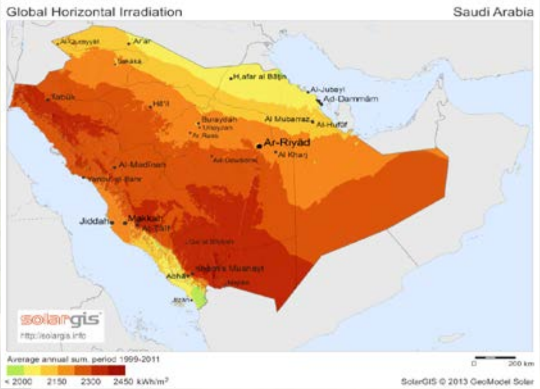


Fig. 2: Global horizontal irradiation of Saudi Arabia.

Introduction

Solar powered water pumping system :

- Appropriate choice for the grid-isolated areas.
- Have the ability to distribute water without any type of additional power or the complicated upkeep.

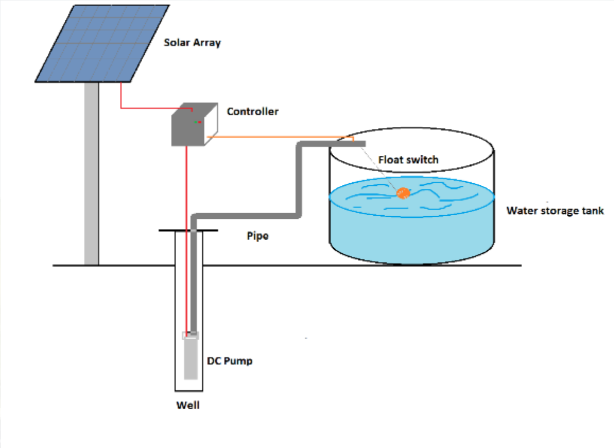


Fig. 3: Constituents of solar powered water pumping systems.

- Many studies of small-scale have been commonly conducted; rarely for large-scale.

System Description (case study)

Water demand:

- 1260 date palm trees
- 95% of the water consumption
- A mature date palm tree consumes 184.4 l/day

Fig. 4: Date palm trees, Riyadh.

- **245 m3; The typical desirable amount of water per day.**

System Description

System layout

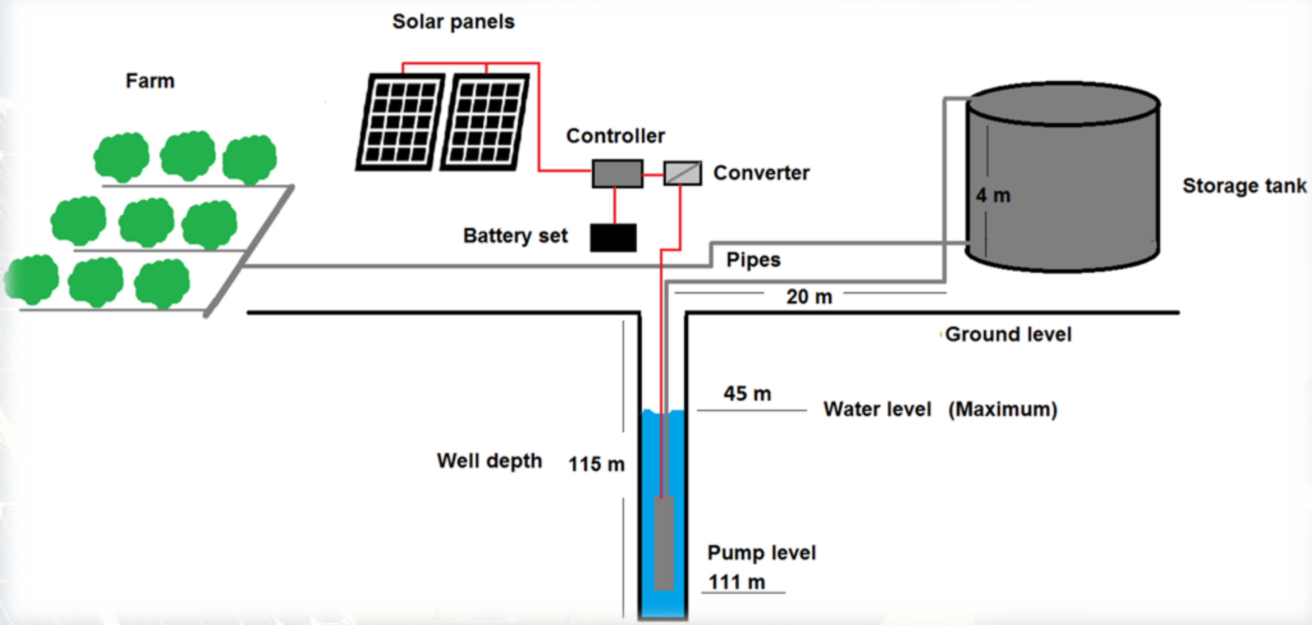


Fig. 5: Schematic diagram of the required Solar Water Pumping System

System sizing

Sizing tools

- HOMER; developed and tested by National Renewable Energy Laboratory (NREL)
- PVsyst; designed to be used by architects, engineer, and researchers.

System sizing

Pump sizing

The following expressions are used to determine the pump size.

$$P_{hyd} = \rho g H Q \text{ (W)} \qquad (1)$$

$$P = \frac{\rho g H Q}{\eta} \qquad (2)$$

where

ρ is the density of water (kg/m^3),

g is the gravitational acceleration (m/s^2),

H is the total head (m), and

Q is the volumetric flow rate of water (m^3/s).

TDH = 111 m (vertical) + [(1.8 x 3 elbows) + 20 m] x 20% + 4 m (vertical) = 120.08 ~ 120 m

Pump size = 5.448 kW

System sizing

Solar PV, battery, converter sizing Homer software

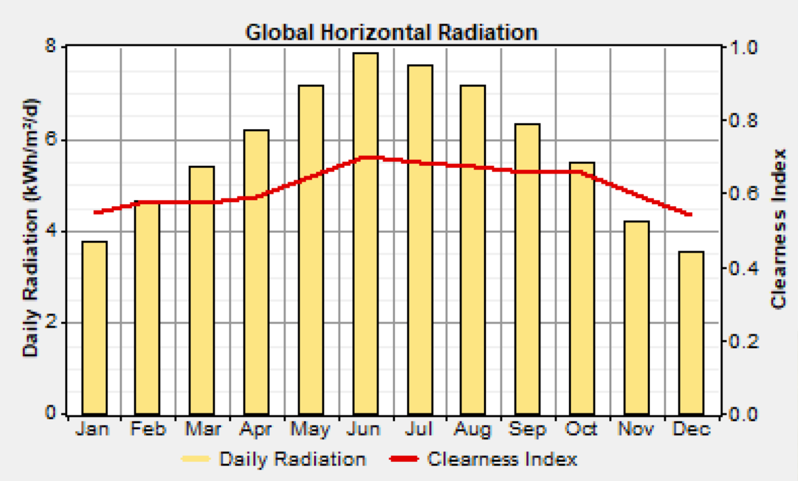


Fig. 6: Solar irradiation in selected site, Riyadh

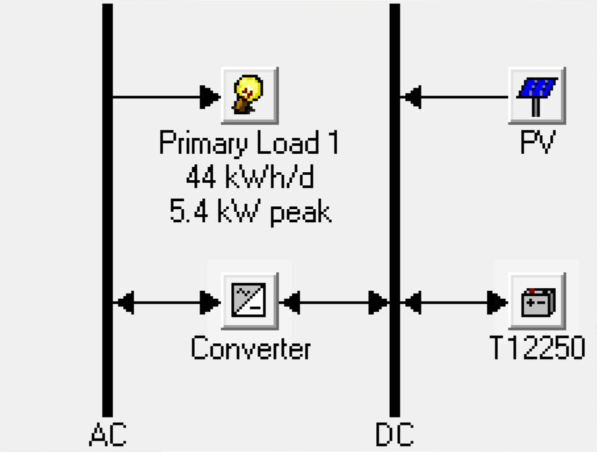


Fig. 7: Schematic of electrical system components connection.

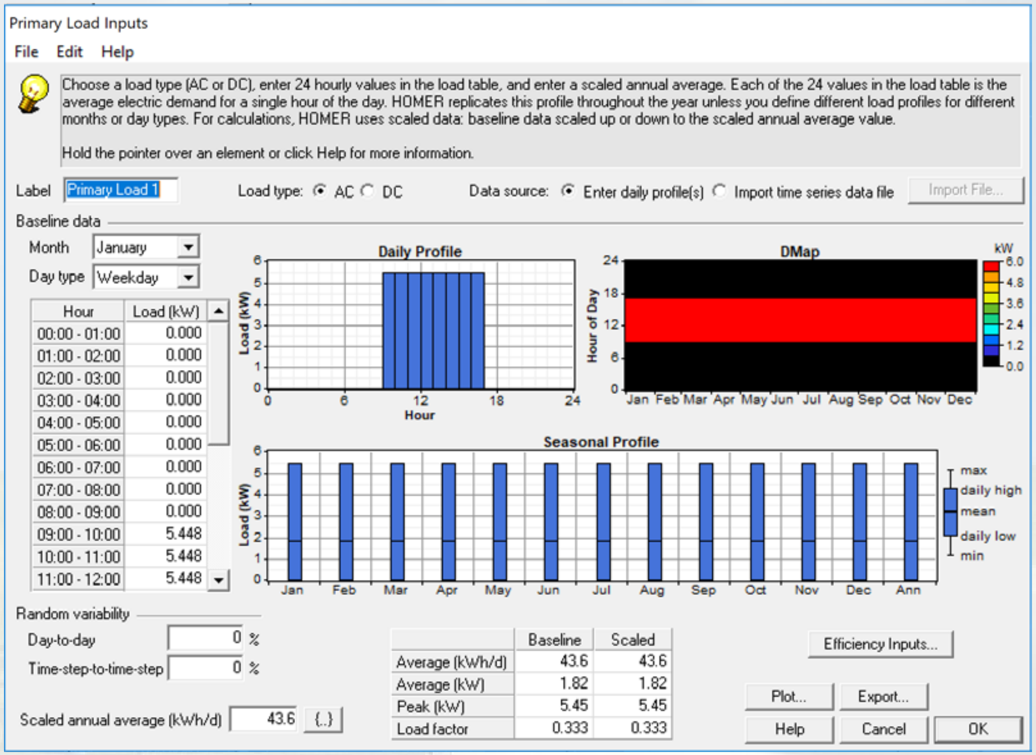
System sizing

Solar PV, battery, converter sizing Homer software

Load inputs:

5.448 kW

8 Operating hours



Choose a load type (AC or DC), enter 24 hourly values in the load table, and enter a scaled annual average. Each of the 24 values in the load table is the average electric demand for a single hour of the day. HOMER replicates this profile throughout the year unless you define different load profiles for different months or day types. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value.

Hold the pointer over an element or click Help for more information.

Label: Primary Load 1

Load type: ● AC ○ DC

Data source: ● Enter daily profile(s) ○ Import time series data file

Baseline data

Month: January

Day type: Weekday

Hour	Load (kW)
00:00 - 01:00	0.000
01:00 - 02:00	0.000
02:00 - 03:00	0.000
03:00 - 04:00	0.000
04:00 - 05:00	0.000
05:00 - 06:00	0.000
06:00 - 07:00	0.000
07:00 - 08:00	0.000
08:00 - 09:00	0.000
09:00 - 10:00	5.448
10:00 - 11:00	5.448
11:00 - 12:00	5.448

Random variability

Day-to-day: 0 %

Time-step-to-time-step: 0 %

Scaled annual average (kWh/d): 43.6 {..}

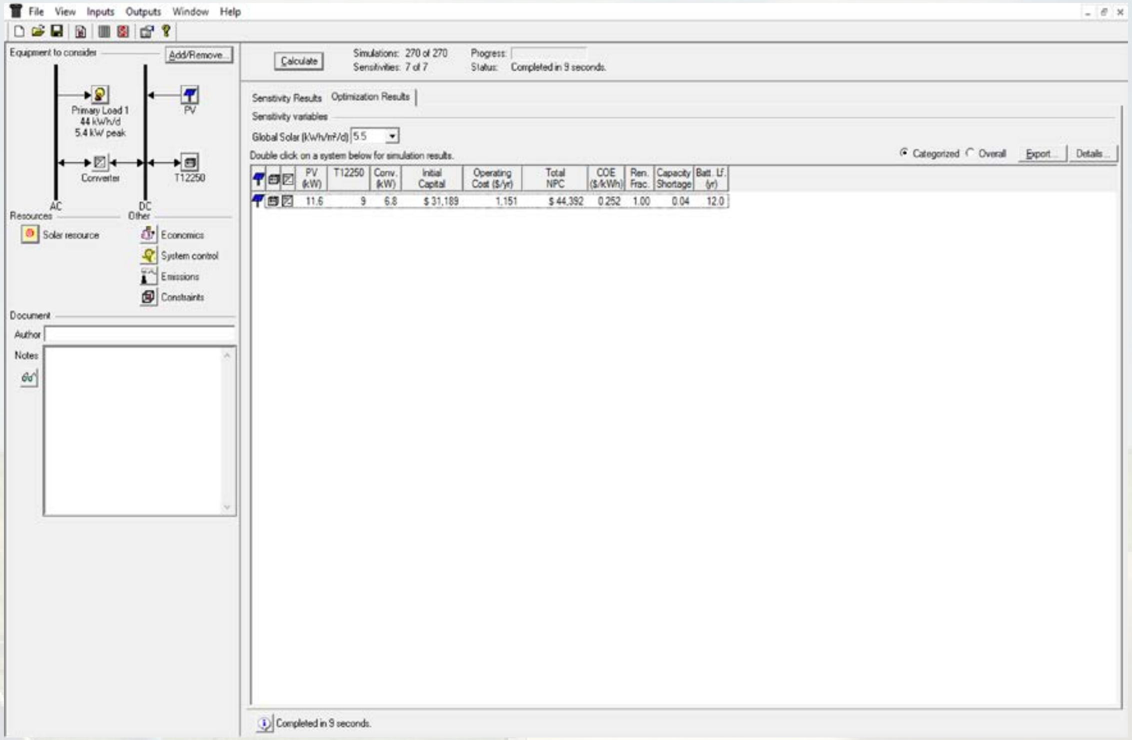
	Baseline	Scaled
Average (kWh/d)	43.6	43.6
Average (kW)	1.82	1.82
Peak (kW)	5.45	5.45
Load factor	0.333	0.333

Fig. 8: Screenshot for the load inputs.

System sizing

Solar PV, battery, converter sizing Homer software

Results:
11.6 kW (solar PV)
6.8 kW (converter)
9 (12 V 200Ah battery)



Simulations: 270 of 270
Sensitivities: 7 of 7
Progress:
Status: Completed in 9 seconds.

Sensitivity variables
Global Solar (kWh/m²/d) 5.5

Double click on a system below for simulation results.

PV (kW)	T12250	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Batt. Lf. (yr)
11.6	9	6.8	$ 31,189	1,151	$ 44,392	0.252	1.00	0.04	12.0

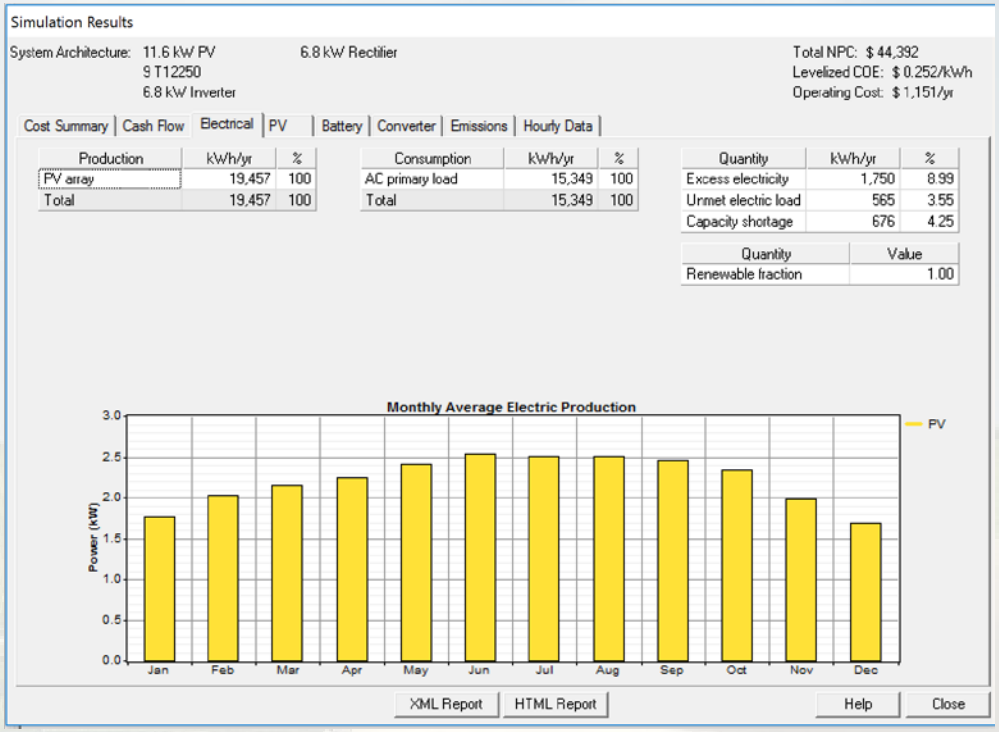
Completed in 9 seconds.

Fig. 9: Screenshot for the optimized system.

System sizing

Solar PV, battery, converter sizing Homer software

19,457 kWh/year (energy production)
15,349 kWh/year (load consumption)
8.9 % Excess electricity
100% Renewable source



Simulation Results

System Architecture: 11.6 kW PV
9 T12250
6.8 kW Inverter
6.8 kW Rectifier

Total NPC: $ 44,392
Levelized COE: $ 0.252/kWh
Operating Cost: $ 1,151/yr

Production	kWh/yr	%
PV array	19,457	100
Total	19,457	100

Consumption	kWh/yr	%
AC primary load	15,349	100
Total	15,349	100

Quantity	kWh/yr	%
Excess electricity	1,750	8.99
Unmet electric load	565	3.55
Capacity shortage	676	4.25

Quantity	Value
Renewable fraction	1.00

Fig. 10: Screenshot for simulation results.

System sizing

Solar PV, battery, converter sizing Homer software

9 batteries (12 V 200Ah)

Voltage bus level: 108V

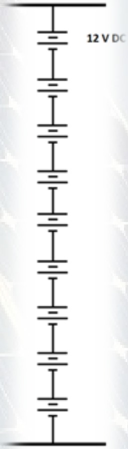
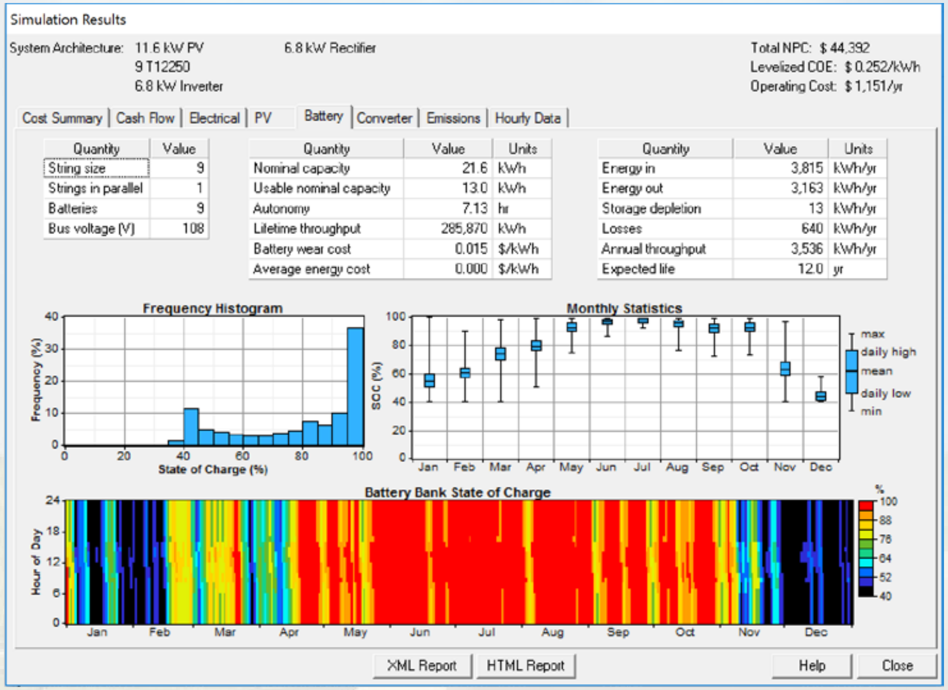


Fig. 11: Schematic diagram of batteries connection.



Simulation Results

System Architecture: 11.6 kW PV
9 T12250
6.8 kW Inverter
6.8 kW Rectifier

Total NPC: $ 44,392
Levelized COE: $ 0.252/kWh
Operating Cost: $ 1,151/yr

Quantity	Value
String size	9
Strings in parallel	1
Batteries	9
Bus voltage (V)	108

Quantity	Value	Units
Nominal capacity	21.6	kWh
Usable nominal capacity	13.0	kWh
Autonomy	7.13	hr
Lifetime throughput	285,870	kWh
Battery wear cost	0.015	$/kWh
Average energy cost	0.000	$/kWh

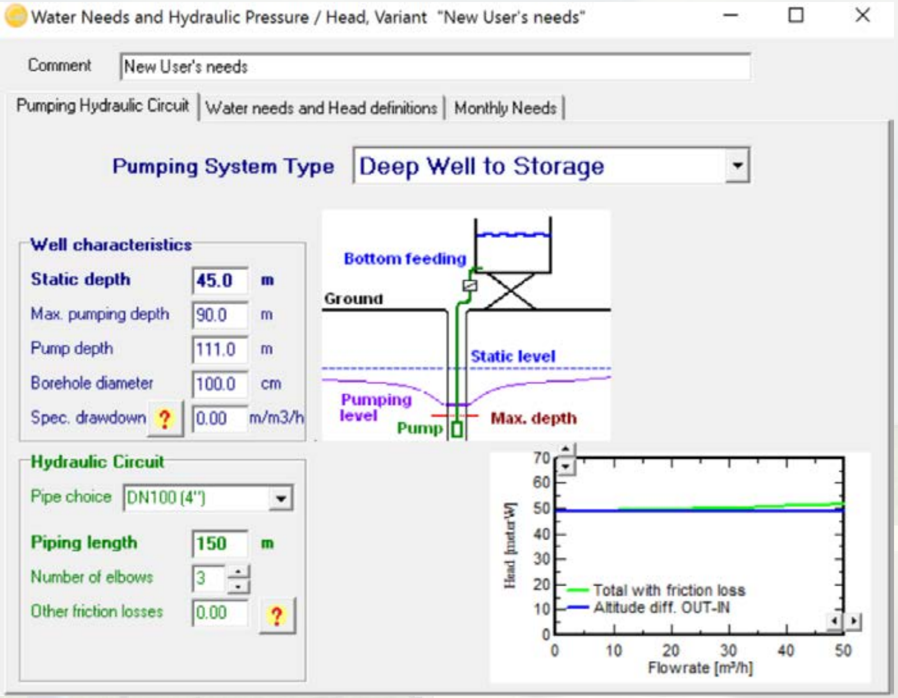
Quantity	Value	Units
Energy in	3,815	kWh/yr
Energy out	3,163	kWh/yr
Storage depletion	13	kWh/yr
Losses	640	kWh/yr
Annual throughput	3,536	kWh/yr
Expected life	12.0	yr

Fig. 12: Screenshot for simulation results (batteries).

System sizing

Solar PV, converter, tank size PVsyst software

TDH parameters in PVsyst:
Same inputs of pump size calculation



Water Needs and Hydraulic Pressure / Head, Variant "New User's needs"

Comment: New User's needs

Pumping System Type: Deep Well to Storage

Well characteristics

Static depth	45.0	m
Max. pumping depth	90.0	m
Pump depth	111.0	m
Borehole diameter	100.0	cm
Spec. drawdown	0.00	m/m3/h

Hydraulic Circuit

Pipe choice	DN100 (4")	
Piping length	150	m
Number of elbows	3	
Other friction losses	0.00	

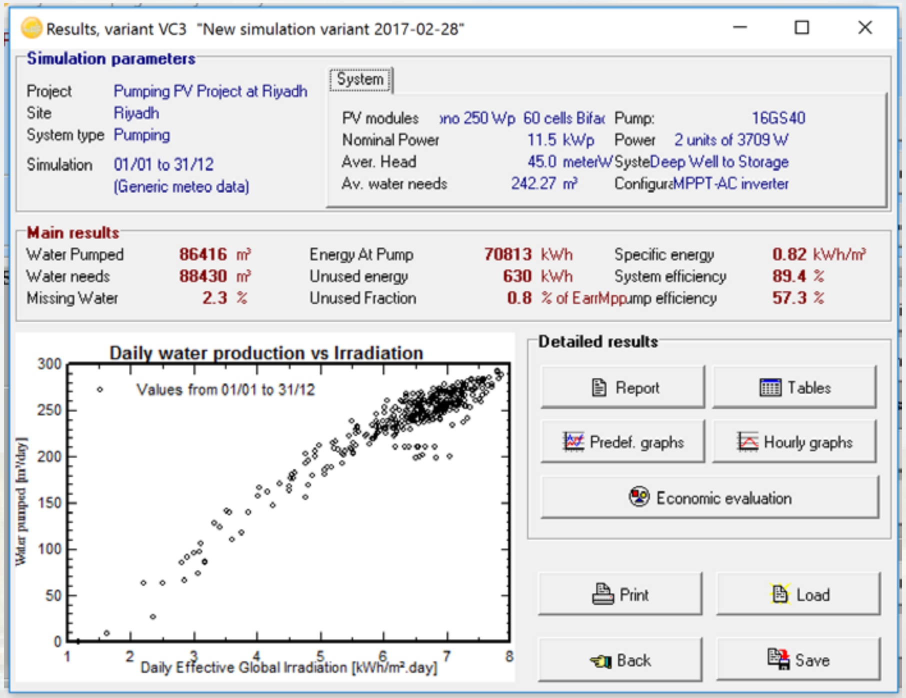
Fig. 13: Screenshot for simulation TDH parameters (PVsyst).

System sizing

Solar PV, converter, tank size PVsyst software

Simulation parameters and results:

- 11.5 kW PV
- 2 X 3.7 KW pumps
- Average water needs 242 m3/day
- 89.4 % System efficiency



Results, variant VC3 "New simulation variant 2017-02-28"

Simulation parameters

Project	Pumping PV Project at Riyadh
Site	Riyadh
System type	Pumping
Simulation	01/01 to 31/12 (Generic meteo data)

System

PV modules	ɔno 250 Wp 60 cells Bifa	Pump:	16GS40
Nominal Power	11.5 kWp	Power	2 units of 3709 W
Aver. Head	45.0 meterW	Syste	Deep Well to Storage
Av. water needs	242.27 m³	Configura	MPPT-AC inverter

Main results

Water Pumped	86416 m³	Energy At Pump	70813 kWh	Specific energy	0.82 kWh/m³
Water needs	88430 m³	Unused energy	630 kWh	System efficiency	89.4 %
Missing Water	2.3 %	Unused Fraction	0.8 % of EarrMpp	pump efficiency	57.3 %

Fig. 14: Screenshot for the main simulation results (PVsyst).

System sizing

Solar PV, converter, tank size PVsyst software

Simulation results:

- Water demand varies along with solar irradiation.
- Average missing water is 2.3%
- Average pumping water is 236.8 m3/day

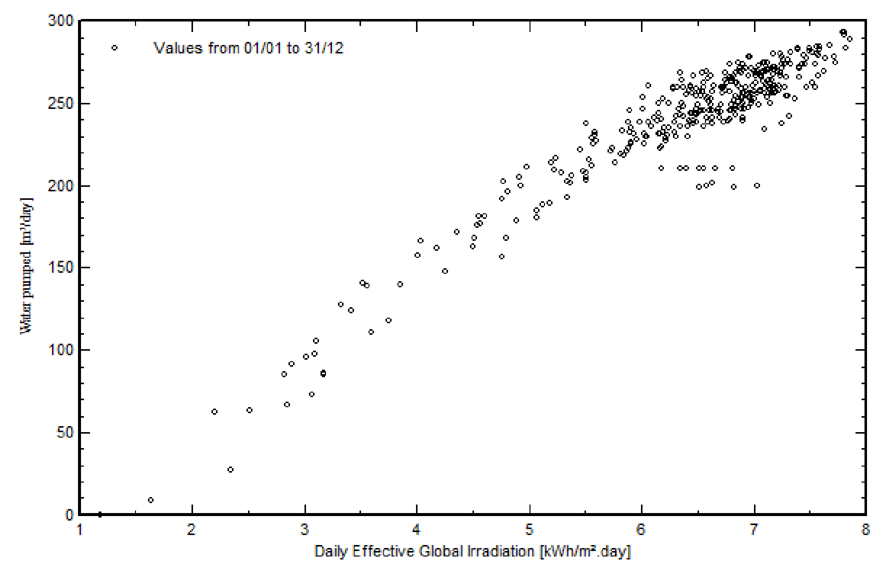
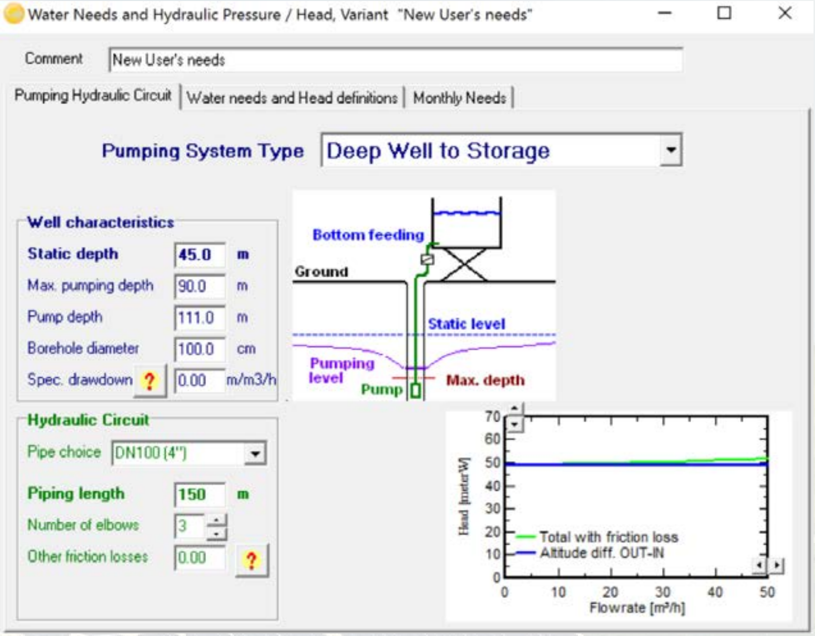


Fig. 15: Daily water production vs Irradiation (PVsyst).

Results

Comparing the results of both HOMER and PVsyst

TDH parameters in PVsyst:



Water Needs and Hydraulic Pressure / Head, Variant "New User's needs"

Comment: New User's needs

Pumping System Type: Deep Well to Storage

Well characteristics

Static depth: 45.0 m
Max. pumping depth: 90.0 m
Pump depth: 111.0 m
Borehole diameter: 100.0 cm
Spec. drawdown: 0.00 m/m3/h

Hydraulic Circuit

Pipe choice: DN100 (4")
Piping length: 150 m
Number of elbows: 3
Other friction losses: 0.00

Fig. 16: Screenshot for simulation TDH parameters (PVsyst).

TDH estimation for HOMER:

TDH = 111 m (vertical) + [(1.8 x 3 elbows) + 20 m] x 20% + 4 m (vertical) = 120.08 ~ 120 m

Results

Comparing the results of both HOMER and PVsyst

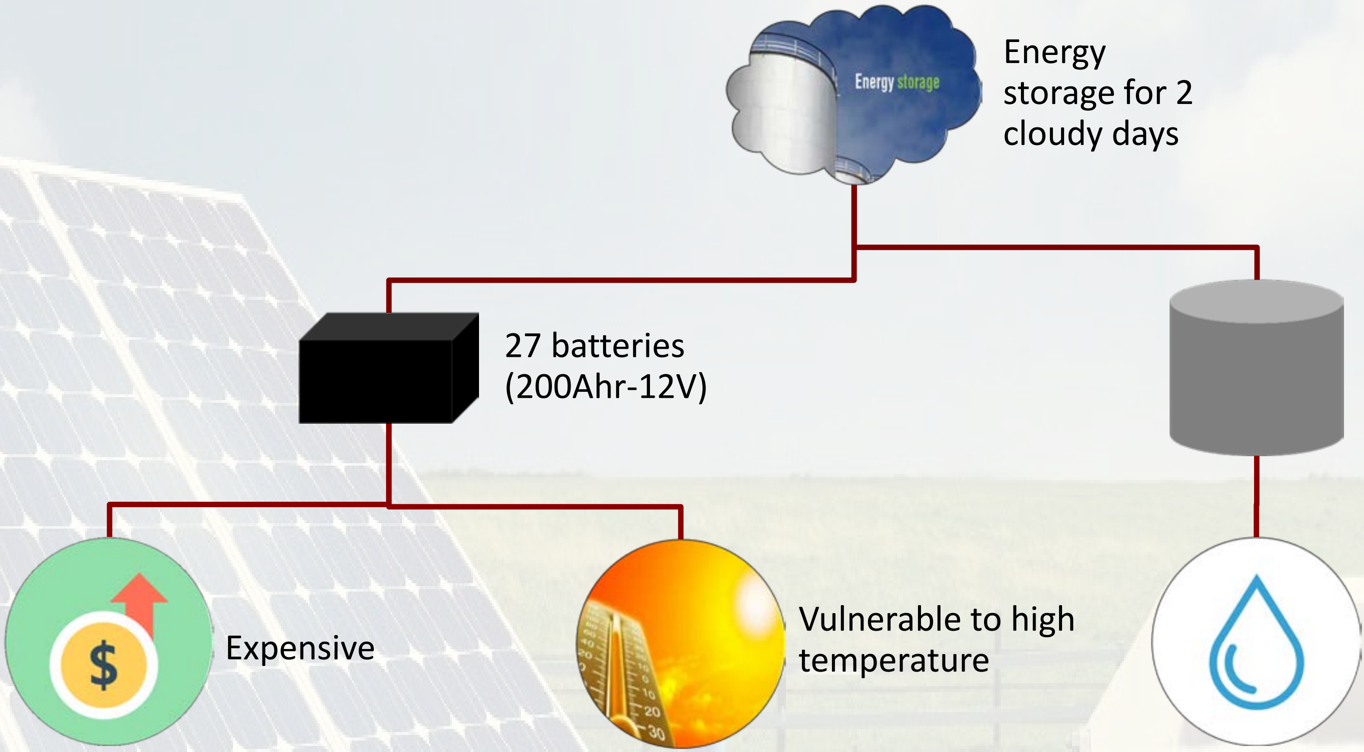
Main results of such system:

- The batteries can be replaced by a storage tank.
- The system cost includes installations, cable, and wiring.
- Water cost are equal due to the missing water in PVsyst sizing since there is no batteries to substitute the voltage drop.

Table 1: The main results of both HOMER and PVsyst.

	HOMER	PVsyst
Pump size	5.4 kW w/ eff. 65%	2 x 3.2 kW w/ eff. 57.3%
PV	11.6 kW	11.5 kW
Batteries	9 (4 hrs)	0
system cost	38,905 USD	36,200 USD
Water cost	0.04 USD/m3	0.04 USD/m3

Possible energy storage methods



Energy storage for 2 cloudy days

27 batteries (200Ahr-12V)

Water storage tank (490 m3)

Expensive

Vulnerable to high temperature

Water leakage or evaporation

Proposed system

System description

- A standalone PV system.
- 11.5 Kw (50 modules, 230 W)
- Designed with 9 batteries (200 A-12V)
- DC coupled
- Two stages DC-DC boost converter.

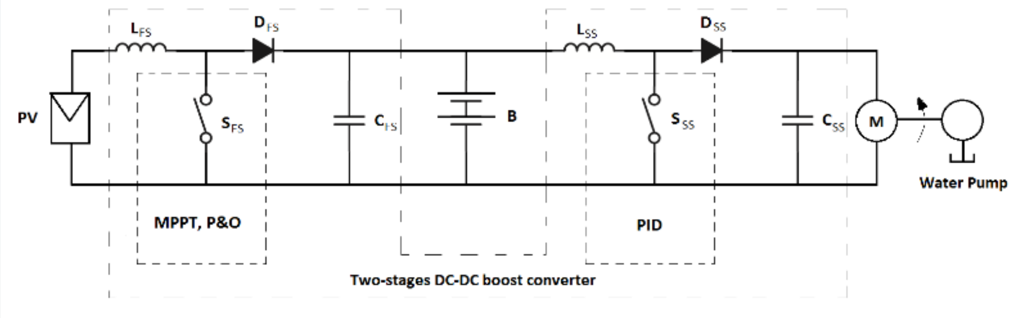


Fig. 17: The block diagram of the proposed system.

System modelling

PV modelling

Peak Power W	230
Max power voltage Vmp	29.23
Max power current Imp	7.88
Open circuit voltage Voc	36.54
Short circuit current Isc	8.38
Module efficiency %	14
Ns	2
Np	25

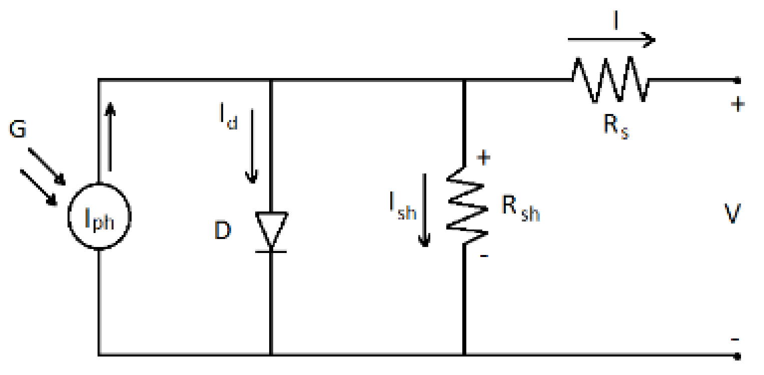


Fig. 4: The equivalent circuit of solar cell.

System modelling

PV modelling

$$V_t = \frac{KT_{op}}{q} \qquad (3)$$

$$I_{rs} = \frac{I_{sc}}{[e^{\frac{V_{oc}\,q}{KCT_{op}\,n}}]} \qquad (4)$$

$$I_{sh} = \frac{V+I_{rs}}{Rp} \qquad (5)$$

$$I_d = [e^{\frac{(V+I_{rs})}{(NV_tCNs)}} - 1]I_sN_p \qquad (6)$$

$$I = I_{ph}N_p - I_d - I_{sh} \qquad (7)$$

$$V_{oc} = V_t \ln\left(\frac{I_{ph}}{I_s}\right) \qquad (8)$$

$$I_{ph} = G_k[I_{sc} + K1(T_{op} - T_{ref})] \qquad (9)$$

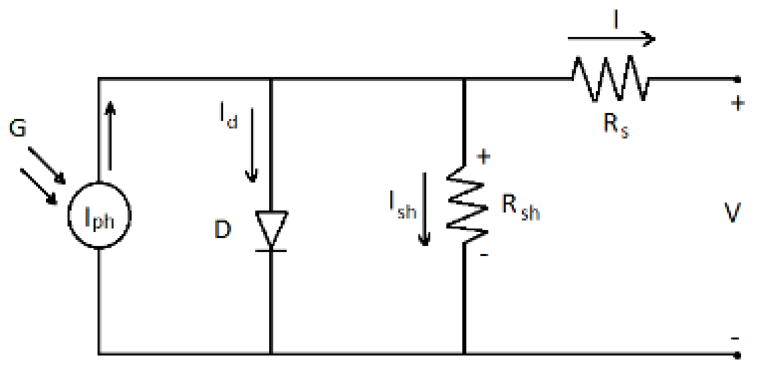


Fig. 4: The equivalent circuit of solar cell.

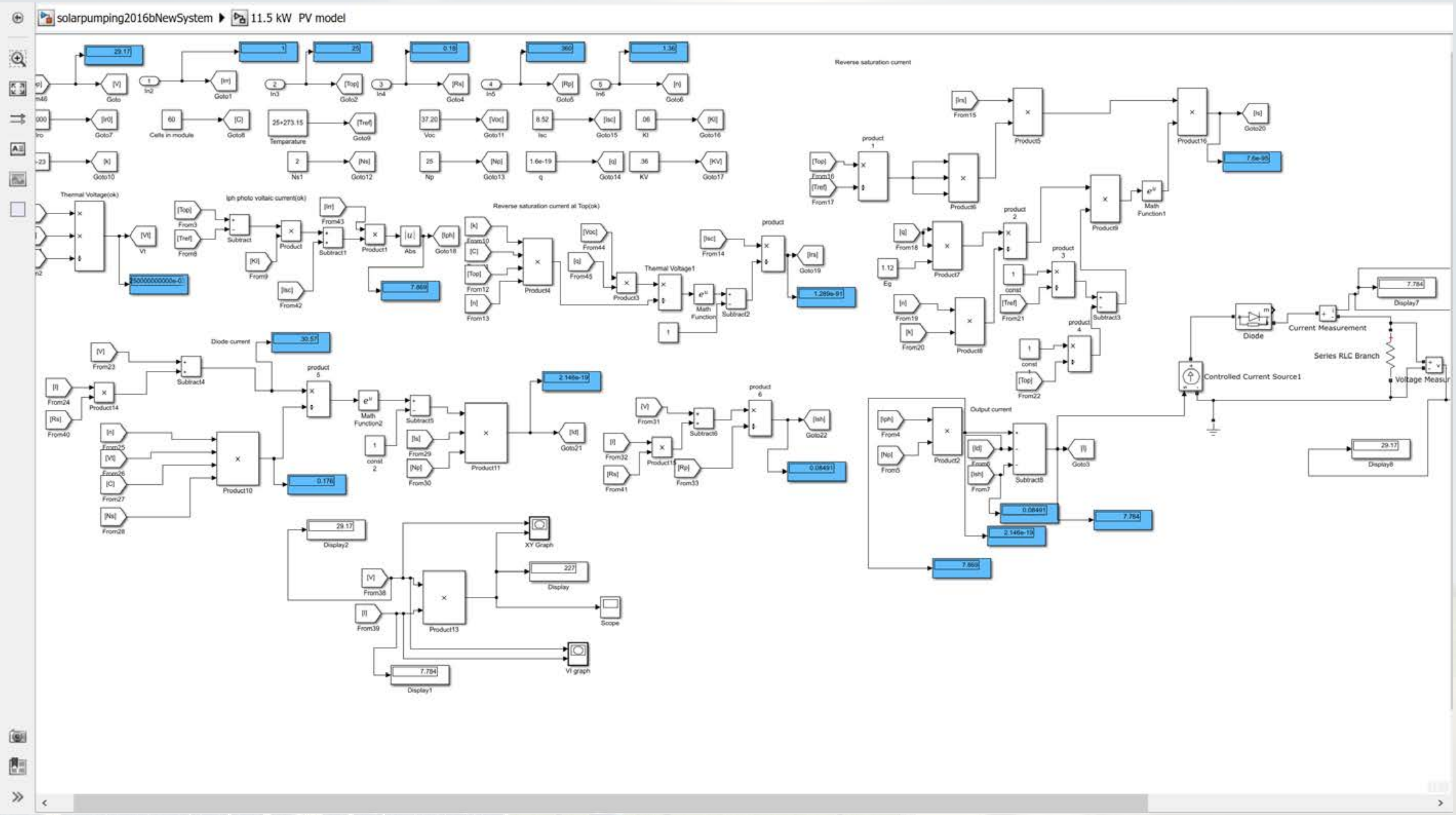


Fig. 19: Overview of the solar array modeled in Simulink

System modelling

Modeling of two stages dc-dc boost converter

TABLE 2. THE PARAMETERS OF DC-DC BOOST CONVERTER.

First stage (FS)		Second stage (SS)	
V_{in}	58V	V_{in}	110V
V_{out}	110V	V_{out}	380V
f_S	25kHz	f_S	40kHz
η	90%	η	90%

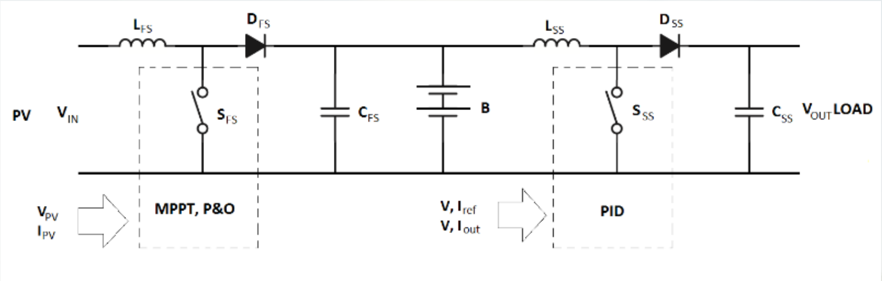


Fig. 20: The block diagram of two stages DC-DC boost converter.

System modelling

Modeling of two stages dc-dc boost converter

A. Duty cycle:

The maximum duty cycle for both can be obtained from this expression:

$$D = 1 - \frac{V_{IN(MIN)}\times\eta}{V_{OUT}} \qquad (10)$$

$V_{IN(MIN)}$: minimum input voltage
V_{OUT} : output voltage
η : converter efficiency

$$D_{FS} = 1 - \frac{58\ \times 0.9}{110} = 53\%$$

$$D_{SS} = 1 - \frac{110\ \times 0.9}{380} = 73\%$$

B. Inductor selection:

$$L = \frac{V_{IN}\times(V_{OUT}-V_{IN})}{\Delta I_L\times f_S\times V_{OUT}} \qquad (11)$$

$$L_{FS} = \frac{58\times(110-58)}{9.51\times 25000\times 110} = 115.25\ \mu H$$

$$L_{SS} = \frac{110\times(380-110)}{10.88\times 40000\times 380} = 179.64\ \mu H$$

System modelling

Modeling of two stages dc-dc boost converter

Two methods of controllers have been used:

MPPT with P&O algorithm.

Efficiency improver

charging controller

2. PID controller.

Pump voltage level meeting

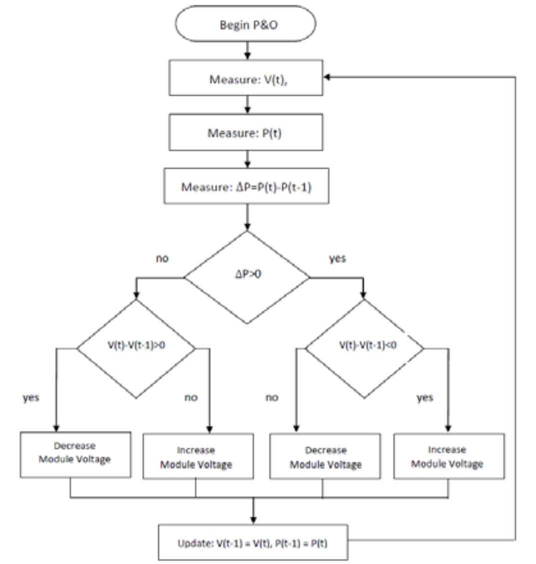


Fig. 21: Perturbation and observation method algorithm.

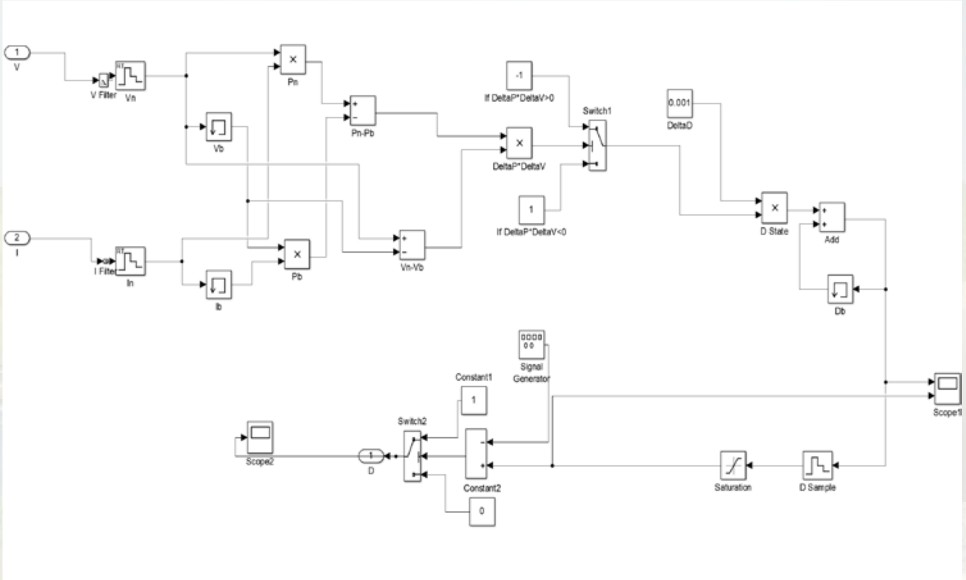


Fig. 22: P&O algorithm implementation.

System Modelling

Modeling dc shunt motor and centrifugal pump

Load 5.5 kW DC shunt motor connected to a centrifugal pump

TABLE 3. MOTOR AND PUMP SPECIFICATIONS.

DC PUMP SPECIFICATIONS						
Model	Impeller	voltage (V)	Pump Power (W)	Max Flow (M3/H)	Max Head (M)	Outlet (IN)
4ZPC14/148-D380/5.5	Centrifugal (SS)	DC380	5500	10	120	4
DC SHUNT MOTOR SPECIFICATIONS						
Rated voltage (V)	Rated speed (RPM)	Rated current (A)	Rated torque (N.M)	Rotor inertia(Kg.cm^2)		
380	1700	15	14.5	0.01		

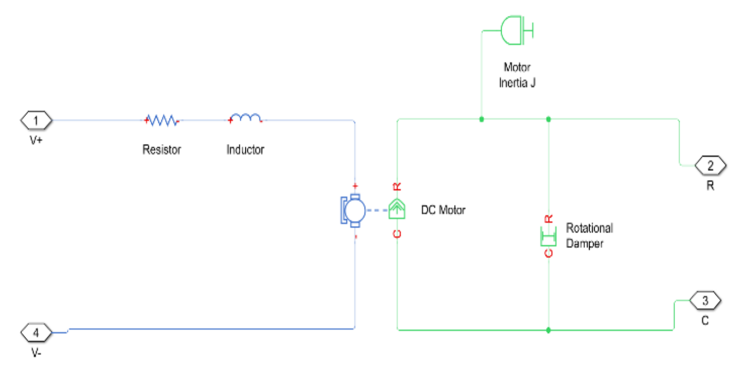


Fig. 23: DC shunt motor simulation in Simulink.

Simulation results and discussions

The final designed circuit in Simulink/Matlab

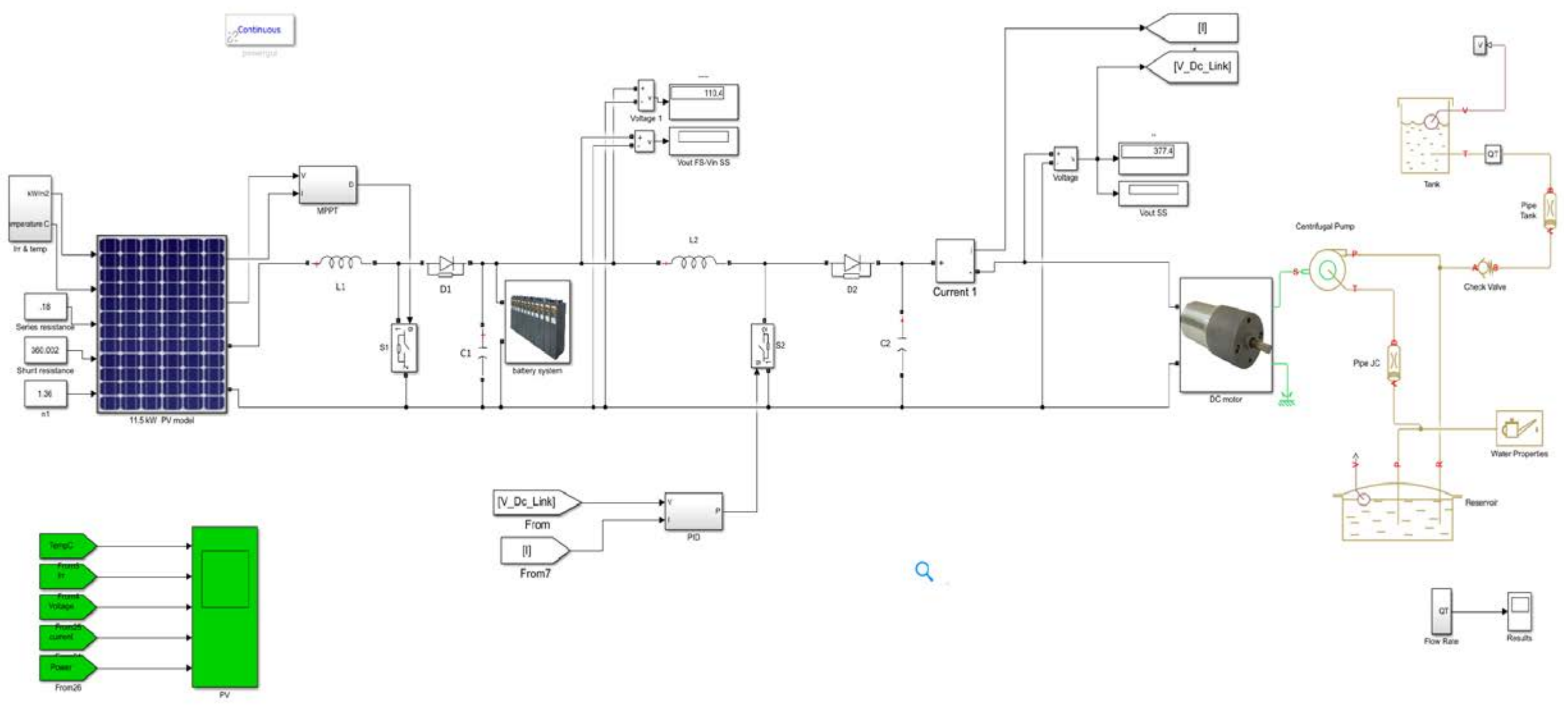


Fig. 24: The proposed system model in Simulink.

Simulation results

PV inputs and outputs

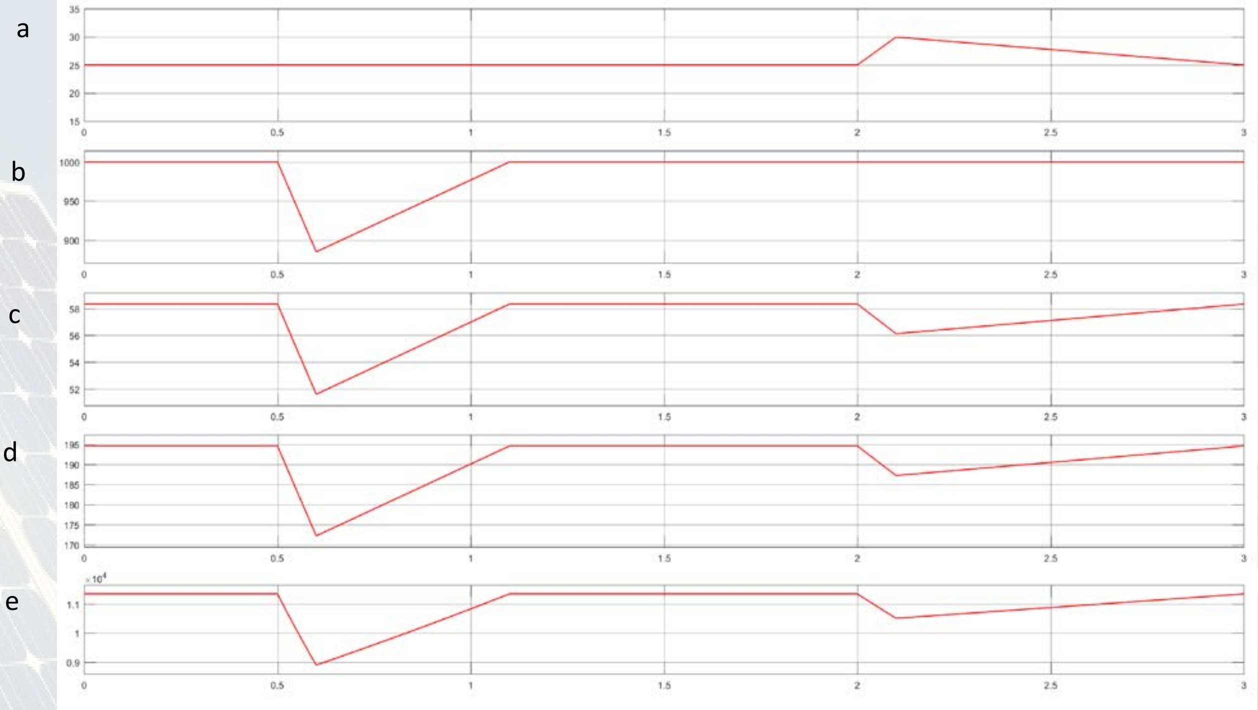


Fig. 25: (a) Temperature °C. (b) Solar Irradiation W/m (c) PV output voltage, V. (d) PV output current, A. (e) PV output power, kW.

Simulation results

Results

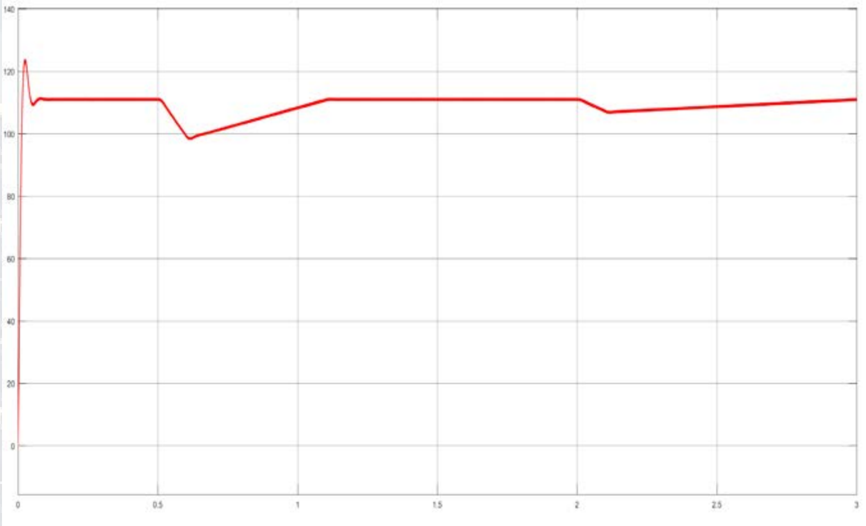


Fig. 26: Output voltage of fixed DC-DC converter controller by a MPPT algorithm.

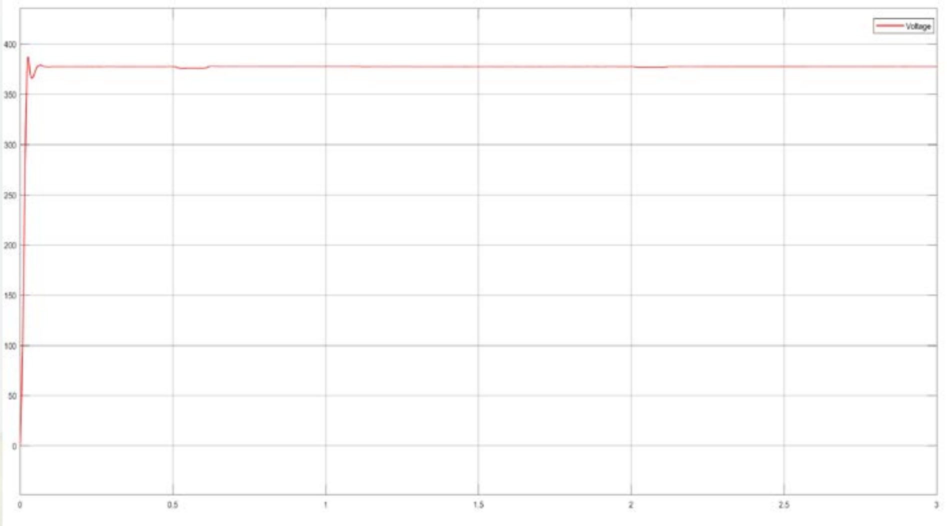


Fig. 27: Output voltage of the second DC-DC converter stage.

Simulation results

Results

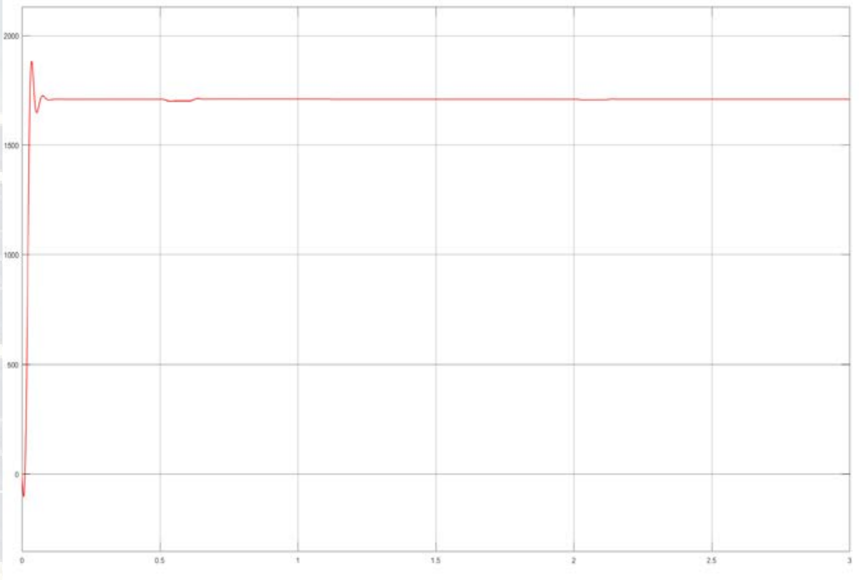


Fig. 28: Motor load speed, 1700 rpm.

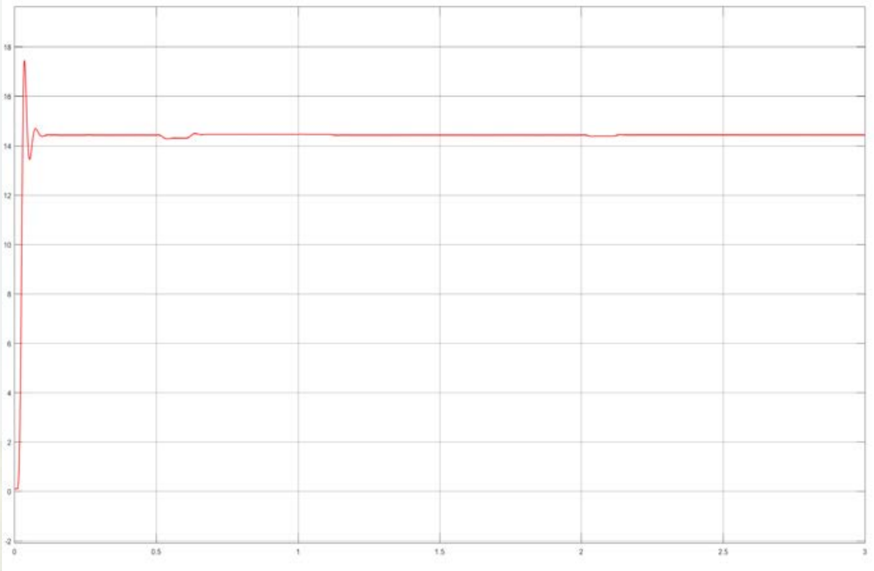


Fig. 29: Motor torque, 14.5 N.m

Simulation results

Results

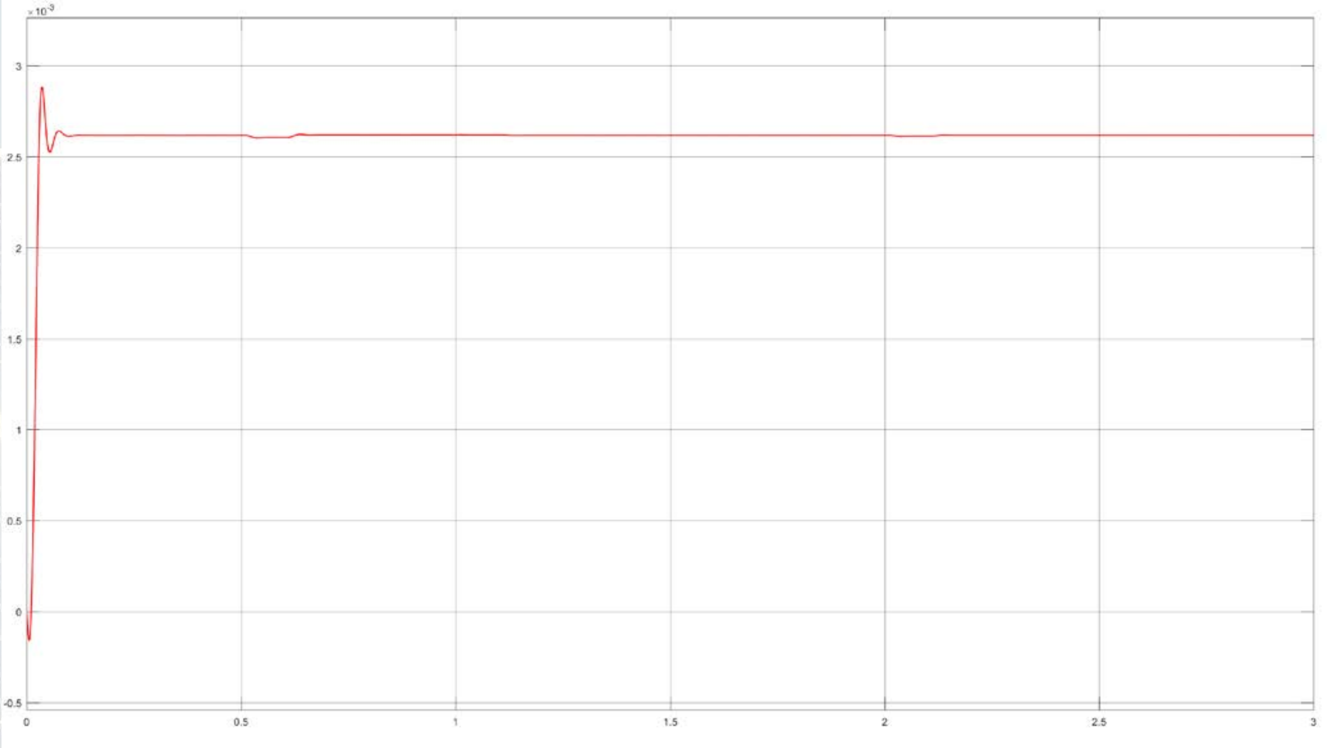


Fig. 30: Flow rate, 0.0027 m^3/s.

Conclusions & Recommendations

- **Conclusion:**
- Comparable results were attained from the use of both Homer and PVsyst. A PV system rated at 11.6 kW was used for Homer, while a 11.5 kW system was used for PVsyst.
- Sizing PVWPS has been carried out and economically analyzed; helping to understand the whole concept of using renewable energy over conventional energy.
- Exploiting such systems in a place like Saudi Arabia yields, to some extent, the lowest water extraction cost with $0.04 for each m3.
- It was compared to a diesel generator system(DSG); resulting in a quite difference in the cost of energy (COE) with 1.88 USD/kWh for the DGS, while the PVWPS (HOMER, PVsyst) is (0.25, 0.18 USD/kWh respectively).

Conclusions & Recommendations

- The dynamic modeling of a large scale solar powered water pumping system has been carried out successfully using Matlab/Simulink .
- Simulation results that have been obtained show satisfactory outcomes.
- Dynamic results indicate that using:

MPPT algorithm for the first DC-DC stage & PID controller for the second DC-DC stage

↙

Able to achieve the objective for a variation in the input temperature and input solar irradiance.

Conclusions & Recommendations..cont.

Recommendations

- Using a water storage tank over batteries is highly recommended ;costing 25% of the batteries expenses on the course of 20 years.
- Drip irrigation which is considered the best method for water distribution. It has been compared to other irrigation methods and comes as the most efficient way with 85% efficiency.

Future work:

- It will be related to the modeling and controlling of the system.
- Developing an experimental work and comparing the performance of both approaches.
- the data logging system should be developed based on experimental work such as writing cods for Arduino and configuring the monitoring system.

Conclusions & Recommendations..cont.

A list of resulting publications:

1. Abdulhamid Alshamani, Tariq M. I qbal, “Sizing and Modelling of a large deep water Solar Water Pumping System for irrigation in Saudi Arabia” presented at IEEE NECEC 2016 conference, St. John’s, Canada.

2. Abdulhamid Alshamani, Tariq M. I qbal, “Feasibility of using a Large Deep Water PV Water Pumping System A case study for an average farm in Riyadh, Saudi Arabia” presented at IEEE IEMCON 2017 conference, Vancouver, Canada.

3. Abdulhamid Alshamani, Tariq M. I qbal, “Modelling of a large-scale Solar Powered Water Pumping System for irrigation in Saudi Arabia” presented at IEEE IEMCON 2017 conference, Vancouver, Canada.

Thank You for Your Attention ☺

Q & A