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Techno Economic Analysis of Directly Coupled Photovoltaic Water Pumping System Under Real Climatic Condition

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ABSTRACT: *Solar Photovoltaic (SPV) powered water pumping system is a cost-effective alternative to the conventional means of water pumping system. In coming days as cost of PV panels is decreasing, the energy efficient SPV based water pumping systems shall also become a popular technology particularly in remote areas. The focus of this paper is on designing of solar-powered pumping systems for drinking water in small villages where the water supply comes from a well or submersible pump. The performance analysis of SPV based water pumping system is carried out with the help of a detailed simulation model, taking the real climatic conditions into account. The economic analysis is also presented by generating results through simulation process employing PVSYST (version 5.63) software to estimate the losses at various level of this integrated system.*

Keywords: *PV panel; Pump; ; Direct Coupling; Performance; Economics*

I. INTRODUCTION

Among various technologies available from renewable energy sources, the solar photovoltaic technology (SPV) is considered well-suited technology particularly for distributed power generation. SPV technology is one of the first amongst the renewable that was adopted globally as well as in India for meeting basic electricity needs of rural areas that are not connected to the grid. The SPV systems increases the reliability of the entire network where they are connected, can also reduce transmission and distribution losses as they generate the electricity close to the point where it is consumed. A Distributed Generation (DG) is a relatively small power generation system, considered to cause significant impact on the distribution system by modifying parameters such as voltage, current and power flow. Optimal size and location of solar photovoltaic (SPV) based multiple location distributed generator (MLDG) in important in primary distribution system [5].

India being a tropical country receives adequate solar radiation for 300 days, amounting to 3,000 hours of sunshine equivalent to over 5,000 trillion kWh. Almost all the regions in India receive 4-7 kWh of solar radiation per sq meters depending upon the location. Even if 1% of this land is used to harness solar energy at an overall efficiency of 10%, as much as 429 × 109 kWh/year of electricity can be generated.

This generated energy can be effectively used for Photovoltaic pumping systems which provide a welcome alternative to grid power supply based water pumping systems or hand pumps. They provide the most water precisely when it is needed the most that is when the sun shines the brightest. The generation of solar electricity coincides with the normal peak demand during daylight hours in most places, thus justifying peak energy costs, brings total energy bills down, and obviates the need to build as much additional generation and transmission capacity as would be the case without PV Solar pumps. Advantages of using PV-powered pumps include low maintenance, ease of installation, reliability and scalability. A SPV water pumping system consist of a DC / AC surface mounted / submersible / floating motor pump set, electronics if any, interconnect cables, an on-off switch and a PV array mounted on a suitable structure with a provision of tracking. The discharge from the pump would vary with the intensity of the sunrays from morning till evening. The pumping of water for the purpose of drinking or irrigation during sunshine hours is a successful application of Solar Photovoltaic (SPV) System. The solar PV water pumping system has excellent performance in terms of productivity, reliability, and cost effectiveness. A number of ways have been developed to monitor the performance and reliability of each sub-system of pumping scheme for an extended period of time.

The pumping project is implemented in four steps - (i) Site selection (ii) System design (iii) System Installation and testing and (iv) system performance monitoring [11]. In case of deep well submersible pumps, a SPV water pumping system is expected to deliver a minimum of 65000 liters per day for a 900 watts panel and

135000 liters per day for an 1800 watts panel from a suction head of 7 meters and total head of 10 meters on a clear sunny day [8].J. S. Ramos et. al. [12] has shown that for a well depth of 100 m, pumping of water costs about 1.07 €/m^3 where the required pump power is of 154 W and a solar array of 195 Watt peak (Wp) is used. When a 720 Wp PV array is connected to a permanent magnet DC (PMDC) motor coupled with centrifugal pump for 5–8m water head, 20 to 140 liter/minute can be pumped depending on the solar intensity. Thus 38000 liters volume of water can be pumped at the water head of 5 m with 9 hr of operation [13]. S. Lal et al. [9] in their study replaces 100% fossil fuel system by pv pumping system and saved CO_2 by 14977.57 kg/year in economical way. In [14-15] authors mentioned that pv pumping system is able to lift water as far as 1,400 meters horizontally with total head 218.34 meters using 3,200 Wp solar panel to operate 2 submersible pumps with total head of 250 meters. The flow rate of water produced is about 0.4 – 0.9 liters/second to cater daily live. SPV technology advances to maintain different control objectives such as settling time, peak overshoot of the responses. Authors [2-3] proposed a small-signal model of PV pumping system without battery and dc–dc converter employed with PI controllers. Through this approach the optimum operating frequency can be found to drive the induction motor at maximum power point (MPP) by the analysis of short circuit current of pv panels. S. Jain et al. [4] presented a single-stage solution for PV pumping system using an integrated control algorithm, which includes MPPT, the *V/f* control, and the sample-averaged zero-sequence elimination pulse width modulation technique with dual-inverter fed open-end winding induction motor drive to avoid large string of PV modules. This system helps in reducing the voltage rating of the capacitors and semiconductor devices used in the system at reduced cost. Several types of pumps and motors based on PV Pumping technology are available in the market.

A comprehensive literature review of solar pumping technology, economic viability, research gaps and impediments in the widespread propagation of solar water pumping systems and technology is presented in [1]. The study focuses on update on solar water pumping technology, performance analysis, optimum sizing, degradation of PV generator supplying power to pump, economic and environmental aspects and advances in PV materials and efficiency improvements. An update on the current state of research and utilization of solar water pumping technology is also presented. Solar water pumping is found to be economically viable in comparison to electricity or diesel based systems for irrigation and water supplies in rural, urban and remote regions. The investment payback for some PV water pumping systems is found to be 4 –6 years [8].

In the proposed study here, a positive displacement pump with direct coupling configuration is used to supply water nearly at a constant water flow rate and independent of head. Permanent Magnet Brushless DC (PMBLDC) motor with appropriate electronic control and conversion system is suggested for SPV based pumping system.

The proposed system is analysed technically by measuring output of system components, loss diagram, performance ratio, and the economics related to this pumping system is also discussed. Section II of the paper present flow rate and power flow equations, pumping head equations used for the proposed study, Section III describes SPV pumping system design and modeling. Results and Discussions are presented in Section IV. In the end conclusion followed by references are presented.

II. FACTORS AND CONSIDERATIONS

The technical factors that govern selection of the site for SPV pumping are the solar radiation availability, water head, the amount of water required, pressure of well and the water storage system as shown in fig. no. 1. An understanding of the well requires information regarding the casing diameter, the static and the dynamic water depths with dynamic drawdown characteristics. These parameters are used to calculate pumping time, pump size, and power demand in the pump which in turn are used to determine the size of PV system & accessories. The total amount of water required depends on the specific application. In case of irrigation, the water requirement is in gallons of water per minute. To avoid pumping inadequacies as the characteristic of pump is highly non – linear, the capacity of the pump should not exceed the designed limits.

2.1. Flow rate and power flow equations

Pump sizing estimation

$$P_w = \rho * g * Q * H / \eta_p \qquad (1)$$

where P_w is the pump size in watts,
g= acceleration due to gravity meter/sec^2,
Q is flow rate in m^3 per hour,
H is total head in meter,
η_p is efficiency of pump and
ρ is the density of water in kg/m^3.
Based on hydraulic properties

$$W_p = E_h / (S * F_m * F_t * \eta_e) \qquad (2)$$

where W_p is solar array power required in watt,

$E_h = \rho *g*Q*H$;
S is peak solar irradiation in kwh/m² ;
F_m is array mismatch factor = 0.9 ;
F_t is temperature derating factor = 0.8;
η_e is engine efficiency

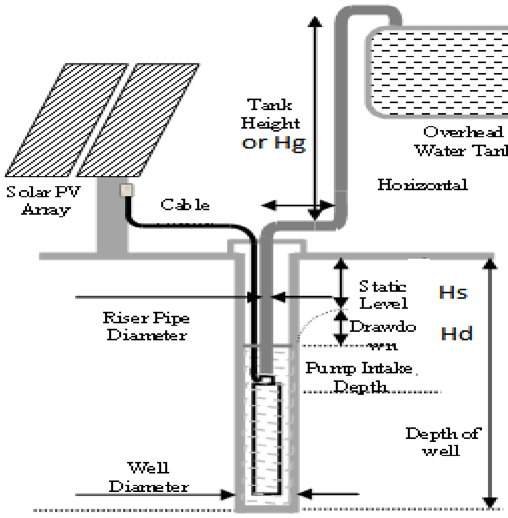


Fig. 1 Layout for the proposed system

2.2. Pumping Head equation

Pumping head is defined as

$$H_{Tot} = H_G + H_S + H_D \quad (3)$$

where:
H_{Tot} is the total height in meters.
H_G is height of the outlet pipe above the ground in meters.
H_S is static head of the water level in the well, in absence of any pumping in meters.
H_D is dynamic head in a borehole well as the water level is dynamically lowered by the extraction of water flow in meter [7].

III. SPV PUMPING SYSTEM DESIGN AND MODELLING

The aim is to design a water pumping system from underground at a head of 28 meter where daily requirement of water is assumed 27.3 m³. At the proposed site the panel tilt angel is fixed at $30^0$and azimuthal angle is 0^0. The investigation is based on available practical data taken from data logger using RS – 232 serial port.

3.1. Pre - Sizing of the system

Pre-sizing of a SPV system is done by a simplified simulation that employs meteorological data as input. This simulation is repeated with different number of solar panel pump size arrangements until it match the requirement of user. Pre-sizing tool is a quick sizing and evaluation process to determine the size of PV array, pump size and tank volume that are necessary to meet water demand requirements. It also provides a rough estimation of the costs.

After knowing the pre – sizing of the pv system, next step is establishment of a general model describing the electrical and hydraulic behavior of a pump. Data considered here is the real time data collected from the weather station installed on the top of the roof of the building under study as shown in fig. no. 2. The model considered is taking the environmental conditions into account during general simulation process. Here deep well borehole pumping model with dynamic drawdown characteristics according to pumped flow rate is also taken under consideration.

3.2. Final Design of SPV pumping system

With the help of preliminary design, the main components (solar pump, PV module, controller and accessories) are first specified. The system components are selected as per the installed PV module and solar pump details taken from manufacturer ‘All Power’. Controller is used in between solar module and pump to control the main switching function,overload protection of motor etc. The controller through a sensor stops action or operation if the tank is full of water. In case of direct coupling, three componentsPV module, solar pump and controller along with a water tank is sufficient for simulation purpose as shown in Fig. 3. For the estimation of rating of the system component as per the requirement with the help from presizing data , PVSyst software is used as shown in Fig. 4.

Fig. 2 Figure showing roof top SPV pumping system employed in this paper

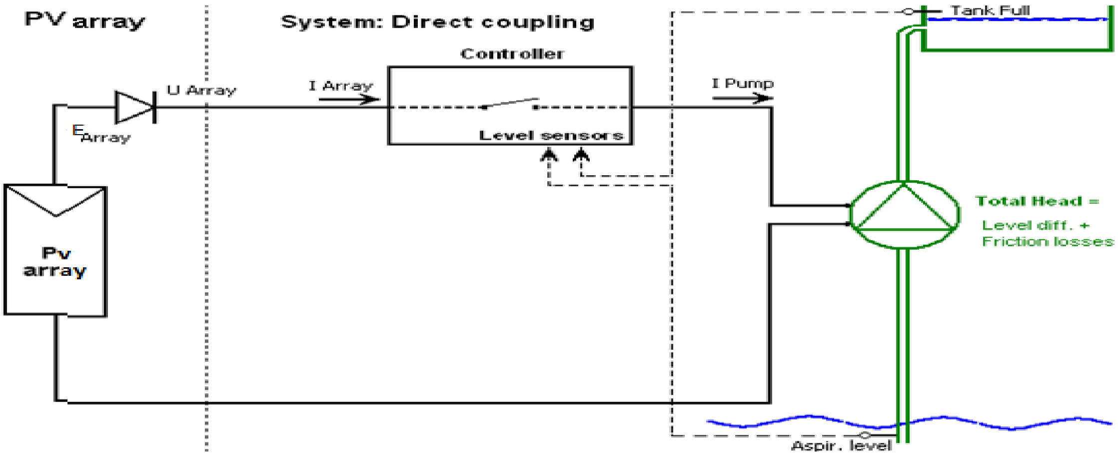
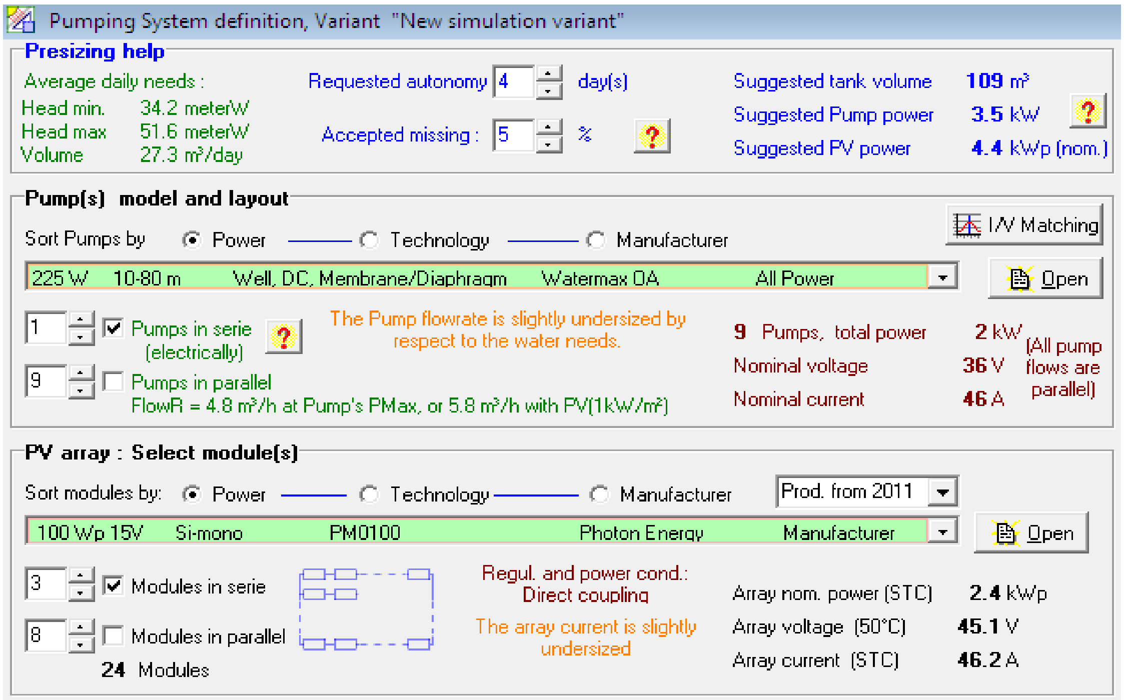


Fig. 3 Basic model of directly coupled PV pumping system



Pumping System definition, Variant "New simulation variant"

Presizing help

Average daily needs :
Head min. 34.2 meterW
Head max 51.6 meterW
Volume 27.3 m³/day

Requested autonomy 4 day(s)
Accepted missing : 5 %

Suggested tank volume 109 m³
Suggested Pump power 3.5 kW
Suggested PV power 4.4 kWp (nom.)

Pump(s) model and layout

Sort Pumps by ● Power ○ Technology ○ Manufacturer

225 W 10-80 m Well, DC, Membrane/Diaphragm Watermax OA All Power

1 ☑ Pumps in serie (electrically)
9 ☐ Pumps in parallel
FlowR = 4.8 m³/h at Pump's PMax, or 5.8 m³/h with PV(1kW/m²)

The Pump flowrate is slightly undersized by respect to the water needs.

9 Pumps, total power 2 kW
Nominal voltage 36 V
Nominal current 46 A
(All pump flows are parallel)

PV array : Select module(s)

Sort modules by: ● Power ○ Technology ○ Manufacturer Prod. from 2011

100 Wp 15V Si-mono PM0100 Photon Energy Manufacturer

3 ☑ Modules in serie
8 ☐ Modules in parallel
24 Modules

Regul. and power cond.: Direct coupling
The array current is slightly undersized

Array nom. power (STC) 2.4 kWp
Array voltage (50°C) 45.1 V
Array current (STC) 46.2 A

Fig. 4 Pumping system component design through simulation

IV. RESULTS AND DISCUSSION

For the proposed system, results are obtained using PVsyst software for the power generated from the solar panels and energy supplied to the pumping set. Amount of water pumped during different months of a year are presented in table 1.

Column 1 of Table I present the month wise available global solar radiation recorded from the weather station installed on the proposed site. For the month of January average effective radiation is found 110.3kWh/m². Array collects energy virtually at maximum power point is 233 kWh for the same month of January as shown in column 2 of table 1. Pump receives energy 119.6 kWh from the available solar radiation considering all the losses during the processing of energy transfer as presented in column 3of table1. The lost power during the process of transfer from pv panels to pumping set is shown in the loss diagram shown in figure 6 and it has been tabulated also. From this generated power from pv system, the DC drive is able to pump 13.34 m³ water in a single day of January, which is less than 27.3 m³/day, the assumed water requirement of a day. However during winters per day water requirement also reduces and this pumped water quantity during the month may be considered sufficient to cater our needs. As summer approaches, the water requirement also increases. Results show that pumping water also increases during summer season. In the month of August, pumped water is found 25.41 m^3/day as shown in table1.

Table I: Main results for direct coupling

	Global Effective radiation (kWh/m^2)	Array Energy available at MPP (kWh)	Pump output Energy (kWh)	Pump head (Meter)	Amounts of the pumped water (m^3/day)
January	110.3	233.0	119.6	41.81	13.34
February	98.0	203.3	98.7	41.20	12.13
March	123.2	247.5	127.9	41.73	14.31
April	138.2	267.4	153.6	41.19	17.79
May	193.4	359.0	251.8	42.21	28.17
June	168.1	314.5	212.4	41.45	24.40
July	174.2	333.0	216.2	41.61	24.09
August	174.1	328.0	226.5	42.30	25.41
September	134.3	258.1	147.0	41.43	16.89
October	123.5	244.5	119.5	40.83	13.39
November	118.6	238.4	137.2	41.86	15.85
December	94.3	197.2	104.4	42.13	11.68
Year	1650.1	3223.8	1941.9	41.68	18.16

4.1. Performance Analysis

The performance of the system is analyzed from the performance ratio obtained after simulation. Performance ratio is calculated as Y_f/Y_r, where Y_f is energy reach at pump and Y_r is reference incident energy. This performance ratio is calculated for each month individually in the proposed study. The month of December explains least performance whereas the month of May shows best performance as shown in fig. 5. Average Overall performance ratio is counted as 46. 9%.

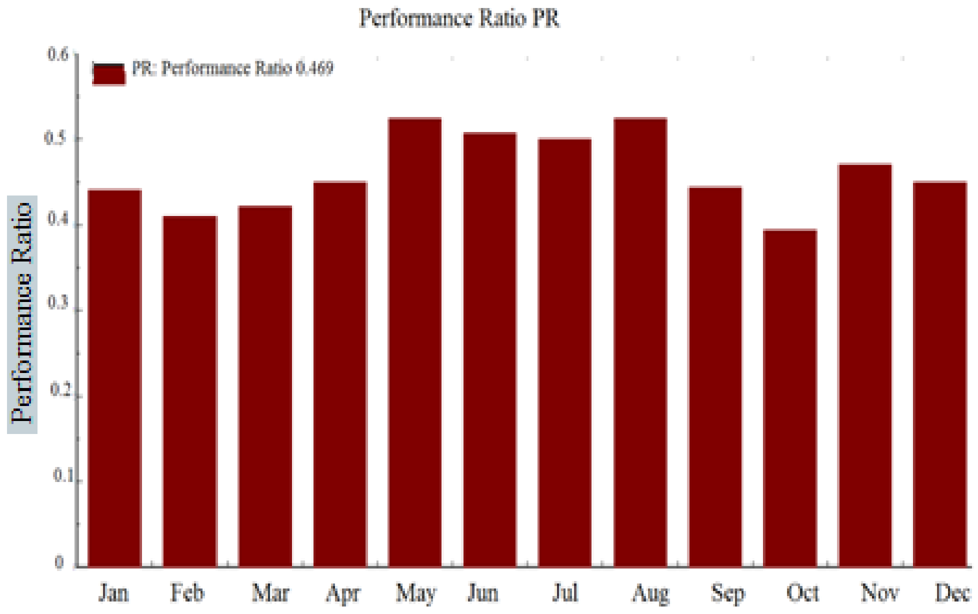


Fig. 5 Performance Ratio graph

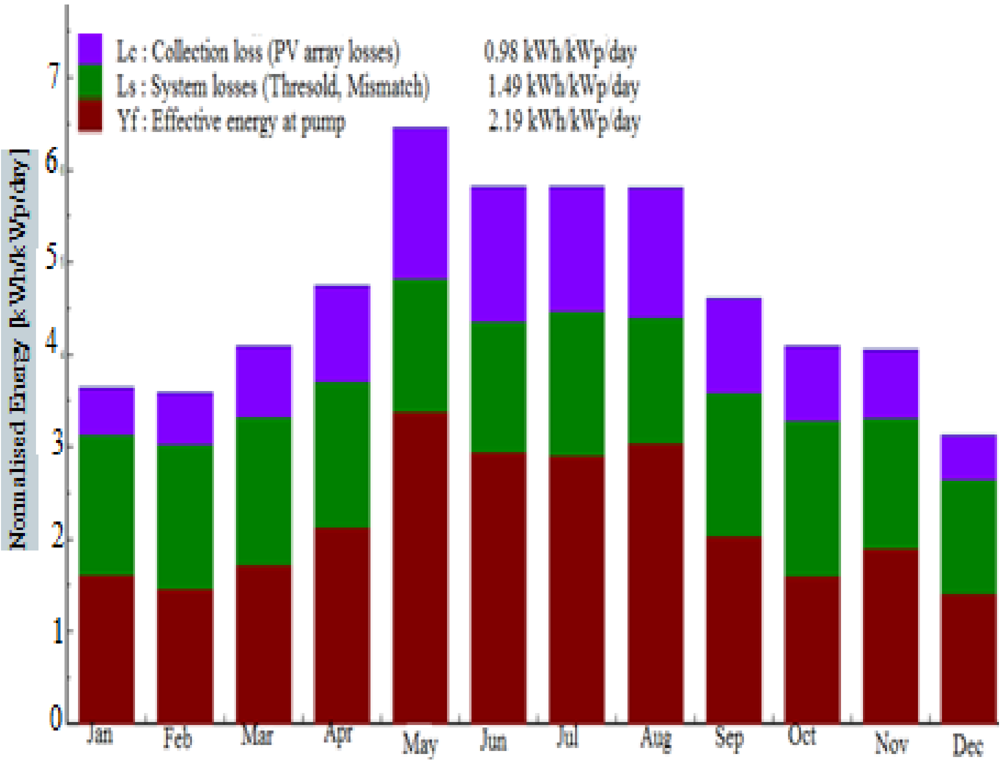


Fig. 6 Normalised Production Graph

Fig. 6 briefly describes about the generalization of model output at different stages electrical and hydraulic system. In this pedagogic graph three main parameters Collection Loss (L$_c$), system losses (L$_s$) and reaching of effective energy at pump (Y$_f$) are given in normalization with the energy available in kWh/kWp/day from simulation results. It can be observed easily that in the month of May L$_c$, L$_s$, Y$_f$ each of the parameter are highest and due to availability of highest energy at pump maximum water is unearthed. L$_c$ normalized as 0.98kWh/kWp/day includes the losses for temperature, module quality, array mismatch and resistance of the array which is exactly equal to 18.1% of array nominal energy at STC effective as can be shown from loss diagram referred to fig. 7. After normalization L$_s$ is calculated as 1.49kWh/kWp/day (from normalized production graph) i.e. again exactly equal to (40.6% of array virtual energy at MPP from loss diagram) this is system losses comprising of mismatch of array, array threshold limit and overload. Y$_f$ is the energy available to pump out the water from underneath.

4.2. Loss Diagram

For the proposed direct coupling control strategy, the loss flow chart is prepared in Fig. 7 for the whole of year through simulation process. This flow chart depicts total horizontal global irradiation available for a year. Effective irradiance incident up to 1650 kWh/m^2 is achieved as shown in loss flow chart by considering two environmental factors one positive global incidence (5.2%) and one negative IAM factor [The incidence effect (the designated term is IAM, for "Incidence Angle Modifier") corresponds to the decrease of the irradiance really reaching the PV cell's] (3%). Area of the array is 21 m^2 which is able to collect nominal energy at STC effective around 3934 kWh after considering PV cells efficiency 11.45%. Out of 3934 kWh only around 1915 kWh energy at pump for operation is received because of two consecutively high losses in PV array (18.1 % of array nominal energy) and System (40.6% of array virtual energy). PV losses include the losses for temperature, module quality, resistance of the array and system losses comprise of mismatch of array, array threshold limit and overload. In this study two parameters are considered as no loss component one is energy under dynamic drawdown limit and the energy under tank full condition as there is no occurrence of tank full situation is observed throughout the year except of month of May. After conversion in pumping mechanism, available hydraulic energy can pump 6671m^3 of water considering 41 meter of head and 6629 m^3 of water considering 41.7 m of water head which results around 3294m^3 of missing water. This loss diagram which is a result of simulation shows how losses are occurring at different stages of this integrated system.

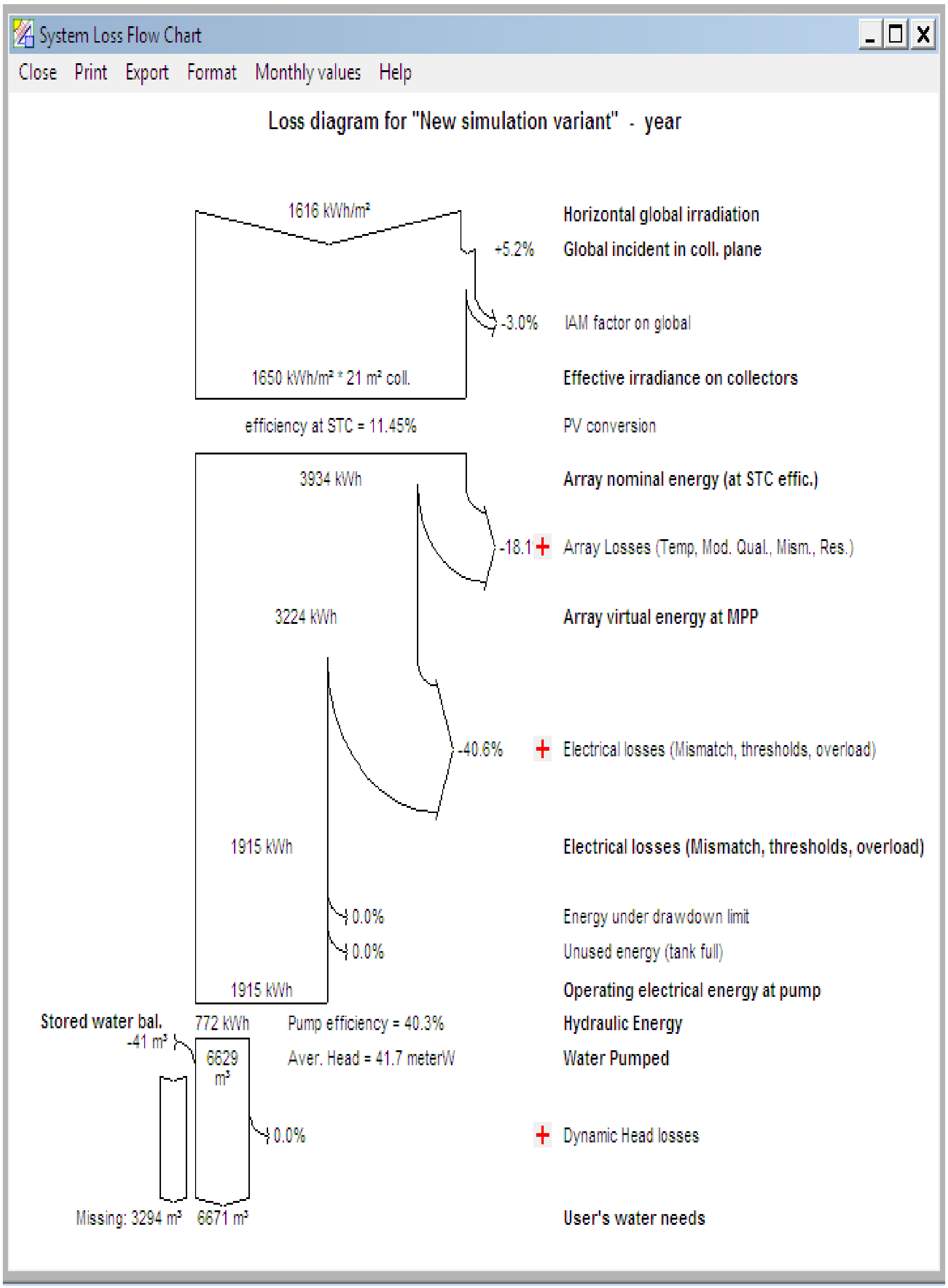


Fig. 7 Loss Diagram for Direct coupling

4.3. Economical Evaluation

An economical analysis for 2 kW directly coupled pv pumping system is presented in this section of the paper. The system is considered as a deep well to storage tank. Basic head of the pumping system is taken as 34.2 meter. Water requirement is 27.3 m^3. Total nine pumps (make Watermax /All power) are connected to meet the requirements. Twenty four pv modules (3 in series x 8 in parallel) (manufacturer Photon Energy) each of 100 watts are connected to get the total array power output of 2400 Wp.

Table 2 depicts about the economical assessment. The costs are considered as per the bill of materials of SBD logistics/All Power for this integrated system [19-20]. The gross investment as per our requirement is Rs. 8,40,000 considering cost of pv module & its support integration , pumps, controller, setting & wiring, masonry, data logger, transport & assembly etc. Taking all the financing and loan details into account the yearly investment now stands at Rs. 1,09,126. Life of pump is considered as 10 years whereas the life of other equipment is considered 20 years. Pumped water costs from our study came around Rs. 16.5 per m^3 of water.

Table 2 Economical Evaluation

Investment			
PV module (Pnom = 100 Wp)	24 units	9300 INR/Unit	223200 INR
Supports / Integration		7000 INR/ module	168000 INR
Pumps (Pnom =225W)	9 units	16000 INR/unit	144000 INR
Controller			84000 INR
Settings/ Wiring			36000 INR
Masonry			52800 INR
Data Logger			88800 INR
Transport and Assembly			84000 INR
Engineering			19200 INR
Substitution Underworth			- 0 INR
Gross Investment without taxes			**840000** INR
Financing			
Gross investment without taxes			840000 INR
Taxes on Investment	Rate 12.5%		105000 INR
Gross Investment (Including Vat)			945000 INR
Subsidies			- 96000 INR
Net Investment (Including taxes)			**849000** INR
Annuities	Loan 5 % over 20 years		68126 INR/Year
Maintenance			15000 INR/Year
Insurance, Annual Taxes			13000 INR/Year
Provision for Pump Replacement	Life time 10 Years		13000 INR/Year
Total Yearly Cost			**109126** INR/Year
Water & Energy Cost			
Energy used for Pumping			1915 kWh/Year
Excess energy (tank full)			0.0 kWh/Year
Water Pumped			6629 m^3
Cost of Pumped water			**16.5** INR/m^3

The cost of conventional fuel is increasing day by day and the operating cost of a diesel engine will also be increasing. Further carrying diesel to work station is a cumbersome process. Since at remote areas where there is no grid supply, solar pumping set is a cost effective and feasible option. In small villages, where population is less, high investment on transmission system is not worth as revenue collection from the village due to a small size of population and generally poor people also is hardly possible. In such circumstances solar based pv systems are best and economically feasible option.

V. CONCLUSION

In this paper design, modeling, simulation and economic analysis of SPV based water pumping set are presented. Real time data of solar radiation collected from weather station installed on roof top of the building considered for study is used. For simulation, PVsyst software is used. It is found that average water pumped during the whole year is 18.13 m^3 per day, which is sufficient to cater the needs and cost of the pumped water is 16.5 INR/m^3 which is also highly economical. The overall system has the performance ratio of 46.9%, which may be considered technically quite good.

The installation cost of pv based water pumping system can be recovered within 4-7 years. So, the pv based pumping system will supply the needs at free of cost for next 13-16 years that will be a huge saving. In the proposed study power backup is not considered that will make system costly. The directly coupled SPV based water pumping system is a simplest, economical, technically viable and efficient option for water pumping in remote areas.

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