Design and Analysis of a Community Size Solar Powered Reverse Osmosis Desalination Water System for Pakistan

By

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Abstract

Water crisis and global warming are two of the biggest challenge of the world. Around 1.1 billion people in the world do not have access to clean water whereas producing water by different purification methods required extensive amount of energy which is generated by burning fossil fuels impacting the environment. This thesis proposes a design of a solar powered reverse osmosis desalination system for a community in Pakistan, which would address the water issue problem for a community in Karachi Pakistan. The design and system sizing of the solar powered reverse osmosis system was done in HOMER Pro followed by techno-economic feasibility analysis of the complete system. The comprehensive dynamic modelling of the system was carried out using the bond graph modelling approach where multidisciplinary systems are modelled using a common bond graph language. 20sim simulation software was used for dynamic analysis of the system. Moreover, a detailed instrumentation system design and control system design was made. After finalization of instrumentation and control design a low-cost, open-source, internet-of-things (IOT) based SCADA system as design was made using field instrument devices and Node-Red. A comprehensive alert system was further integrated with the SCADA design to provide status and updates to the community. Local database was also generated and data was imported by Grafana data analytics tool for making data-driven decisions. A complete laboratory experimental setup was made to verify the SCADA based alert system. Lastly, conclusions are provided based on the research conducted in each section of this thesis, and areas for future research have been identified. This work will provide solution for clean drinking water for a community in Pakistan with robust supervisory control and data acquisition system.

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List of Abbreviations

IOT	Internet of Things
RTU	Remote Terminal Unit
MTU	Main Terminal Unit
DC	Direct Current
AC	Alternating Current
O&M	Operations and Maintenance
NPC	Net Present Cost
HOMER	Hybrid Optimization of Multiple Energy Resources
SOC	State Of Charge
MPPT	Maximum Power Point Tracking
PWM	Pulse Width Modulation
COE	Cost Of Energy
FID	Field Instrument Devices
TDS	Total Dissolved Solids
RO	Reverse Osmosis
SCADA	Supervisory Control and Data Acquisition
HMI	Human Machine Interface
PLC	Programmable Logic Controller
GSM	Global System for Mobile Communication
SMS	Short Message Service
DCS	Distributed Control System

CHAPTER 1: INTRODUCTION & LITERATURE REVIEW

1.1. Introduction

Pakistan economy mostly relies on agriculture and around 22.2% of that contributes to its overall GDP [1]. Approximately around 42.3% of the labor in Pakistan is employed from the total labor strength [2]. In 1950s Pakistan has the water capacity of around 5000 m3 per capita and it has decreased now to 1000 m3 per capita [2]. By 2025 the water shortfall is approximated to reach 150.8 Million acre – feet [1]. The scarcity of freshwater is a concern whole around the world. Approximately 1.1 billion population of the world have inadequate access to quality fresh water for drinking purpose.

With the advancement of technology and increase in world's population, the demand for the consumption of fresh water has increased overall worldwide. The most affected provinces of Pakistan are Sindh and Baluchistan when it comes to freshwater availability. United Nations World Water Development (UNWWD) published the report which elaborates that the demand for water consumption has increased from 2,961 to 3,420 m3 per cap from the year 2000–2005 respectively. According to Pakistan Water Partnership, there were 24 million acre feet of ground water and 153 million acre feet of surface water reserves. According to the United Nations Educational, Scientific and Cultural Organization report, Pakistan available water supply is just above 1000 m3 per capita which puts the country in the list of water stress countries [3]. According to estimates, the population of Pakistan will going to be nearly double in the next 25 years and this will further decrease the per capita availability of water. Approximately 36% of groundwater in Pakistan is considered as water that has high concentration of dissolved salts. Due to less or no availability of water in some parts of country and especially in the affected regions, people are now relying on pumping groundwater for their usage.

Overall worldwide, the countries that are facing difficulty in availability of freshwater are now relying on water desalination processes as this method allows to generate fresh water supply but at the cost of electricity consumption. According to an estimate it take 10,000 ton/yr of crude oil to produce 1000 m3/day of desalinated water from the process of thermal desalination [4]. This energy requirement is a big challenge as the world is already heading towards a big global climate change. Extracting this much amount of energy from the conventional thermal power plants would not only make the environment poor but would put the cost of production of water at a very higher rate. The renewable energy is the solution to that problem and solar powered reverse osmosis plants can be very beneficial when it comes to elimination of utilization of fossil fuels. Hence renewable technology based reverse osmosis systems can be a good source of sustainable fresh water production method [5].

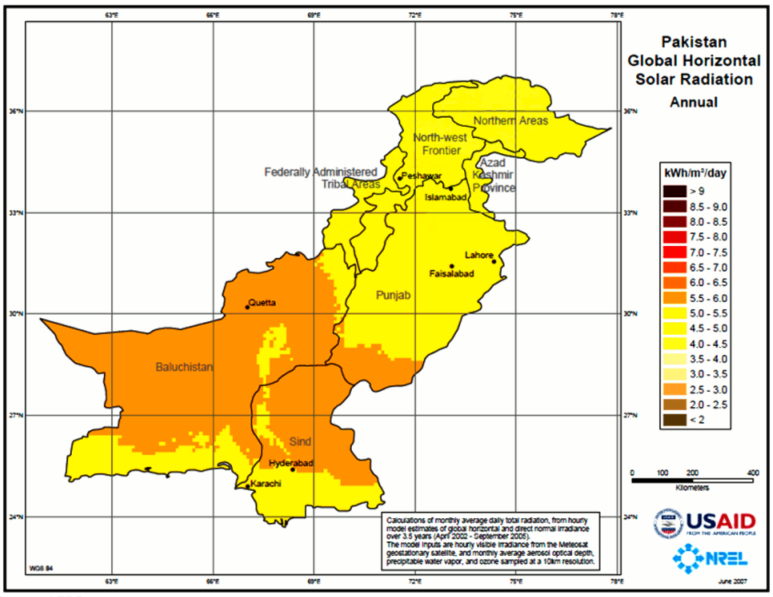
Pakistan is not a country that is rich in energy production although it has huge reserves. Thankfully, it lies on the region of good solar irradiance ranging from 5–7 kWh per m2 per day and sunshine hours of 1,500–3,000 [6] which can be used as an advantage for solar powered reverse osmosis systems. The desalination process now is used worldwide and its utilization trend has shown an increase in the recent years [7]. The Solar powered reverse osmosis is a unique idea for converting the saline or brackish water to fresh water as the water passes through membranes and remove approximately 98% - 99.5% salt from it [8].

With all of these factors being said and issues that Pakistan as a country has, powering a reverse osmosis system for extracting drinking water for a community in Pakistan using renewable energy sources makes a very favorable solution.

1.1.1. Pakistan Solar Potential

The location of Pakistan on map lies within latitude 23.45º to 36.75ºN and longitude 61º to

75.5ºE. The Renewable Energy Policy 2006 [9] of Alternative Energy Development Board (AEDB) Ministry of Energy and Power division Pakistan, explains that Pakistan is highly rich in terms of solar energy. The provinces of Baluchistan and Sindh receive the most solar irradiance in overall Pakistan which means that majority of southern Pakistan has the highest solar irradiance. The annual average horizontal solar radiation per day in these provinces is more than 5.48 kWh/m2 [9]. The National Renewable Energy Laboratory (NREL), Golden Colorado USA in collaboration with USAID, Pakistan Meteorology Department (PMD), and AEDB developed the Pakistan solar map based on the satellite data available from April 2002 to September 2005 and shown in below figure 1.



Source: AEDB

Figure 1: Pakistan Global Horizontal Solar Radiation [9].

From the Fig 1 it can be seen that majority of the country receives a solar radiation of more than 5.0 kWh/m2. The annual average solar radiation of Pakistan is about 5.5 kWh/m2. The Areas of Sindh and Baluchistan are even richer in terms of solar radiation excluding the coastal areas of these provinces. The AEDB report also recommends very large-scale solar power generation installation in the following areas:

(i) Baluchistan province,

(ii) Thal Desert and Cholistan area in Punjab province

(iii) Thar Desert in Sindh province

These areas have a huge amount of barren land available which is not good for other useful work such as agriculture and industries so this place would provide a perfect opportunity for capturing of renewable energy from the sun. The table 1 below shows global horizontal solar radiation captured from the website of NASA for 22 years period (July 1983 to June 2005).

Table 1: Province wise global horizontal solar radiation of Pakistan [9]

(Unit: kWh m^{-2} day^{-1})

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Sindh Province													
Average	4.09	4.84	5.57	6.36	6.70	6.60	5.82	5.55	5.53	4.99	4.22	3.80	5.34
Minimum	3.61	4.36	4.77	5.90	6.19	5.97	4.93	4.91	5.10	4.49	3.86	3.40	
Maximum	4.68	5.26	6.14	6.87	7.15	7.14	6.32	6.06	5.91	5.41	4.59	4.24	
Punjab Province													
Average	3.42	4.25	5.09	6.03	6.67	6.78	6.00	5.60	5.31	4.70	3.80	3.20	5.07
Minimum	2.84	3.80	4.37	5.41	5.96	5.90	5.38	5.09	4.75	4.08	3.46	2.83	
Maximum	3.95	4.81	5.89	6.70	7.24	7.37	6.78	6.31	5.85	5.19	4.15	3.67	
Islamabad Capital City													
Average	3.18	3.87	4.95	6.31	7.27	7.54	6.44	5.72	5.69	5.07	3.89	2.99	5.24
Minimum	2.58	3.33	3.91	5.36	6.47	6.64	5.28	4.80	4.67	4.01	3.46	2.57	
Maximum	3.78	4.61	6.29	7.32	7.71	7.92	7.60	6.81	6.37	5.53	4.20	3.68	

Source: NASA website

The table 2 shows the earth mean temperature values of three major areas of Pakistan which includes province Sindh, province Punjab and the Capital city of the country Islamabad.

Table 2: Earth Mean Temperature [9]

(Unit: ^{O}C)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Sindh Province													
Minimum	4.8	7.2	12.3	17.7	22.3	25.2	26.4	25.3	22.3	16.5	11.4	6.7	
Maximum	39.0	43.1	50.2	53.7	57.4	57.3	52.2	49.6	52.2	49.5	45.2	40.0	
Average	21.9	25.1	31.3	35.7	39.9	41.3	39.3	37.5	37.3	33.0	28.3	23.3	26.3
Punjab Province													
Minimum	-2.2	-0.5	3.7	9.2	13.6	16.9	18.1	17.2	13.7	7.9	3.8	0.1	
Maximum	30.7	35.0	44.0	50.6	55.2	56.9	50.4	44.8	46.1	45.2	38.7	32.6	
Average	14.3	17.3	23.9	29.9	34.4	36.9	34.3	31.0	29.9	26.6	21.2	16.3	29.6
Islamabad Capital City													
Minimum	1.5	3.4	7.6	13.1	17.7	21.1	21.4	20.4	17.1	11.9	7.5	3.4	
Maximum	17.1	20.1	27.2	36.6	42.5	44.4	37.5	34.4	34.1	32.0	26.7	20.2	
Average	9.3	11.7	17.4	24.9	30.1	32.8	29.5	27.4	25.6	22.0	17.1	11.8	21.4

Source: NASA website

It can be seen that the data gathered from the NASA website and the solar radiation map of the country both are almost the same hence the map can be used for further site selection and designing of solar powered reverse osmosis system for drinking purpose for a community in Pakistan.

1.1.2. Types of PV cells

There are different types of photovoltaic cells which can be used for powering up the reverse osmosis desalination system:

- Monocrystalline cell: These were the first ever commercially available solar cells. It was created from the extremely purest form of silicon. It has a continuous single lattices which was molded to form thin wafer and eventually formed the p-n junction. These cells are very efficient but expensive as their manufacturing process is very complex and slow as compared to other types [10]. The Figure 2 shows the physical appearance of monocrystalline cell.

Figure 2: Monocrystalline Panel [11]

- Polycrystalline cell: As its name says poly which means many, this type of cells is not formed from a single crystal rather it is formed using many small grains of crystals. It is formed by cutting silicon into thin plates. These cells are cheaper but less efficient compared to others and is used mostly worldwide [10]. The Figure 3 shows the physical appearance of polycrystalline cell.

Figure 3: Polycrystalline Panel [12]

- Thin Film cell: These are the type of cells which are most flexible and durable as these are produced by depositing thin layer of photovoltaic material over plastic metal or glass. These cells use very less amount of silicon in an unorganized manner and that is why they have the least efficiency. Due to less usage of silicon and easy manufacturing process these are the cheapest type of photovoltaic cell available in the market [10]. The Figure 4 shows the physical appearance of thin film cell.

Figure 4: Thin Film Panel [13]

1.1.3. Types of Water Desalination Systems

There are two main types of water desalination technologies used at commercial scales:

- Membrane Type
    - Reverse Osmosis
- Thermal Type
    - Multiple Effect distillation
    - Mechanical Vapor Compression
    - Multistage Flash Distillation

The Membrane type reverse osmosis uses the osmosis principle for the removal of impurities which includes salt etc. through a series of semi-permeable membranes whereas the Thermal type uses heat energy and applies the principle of evaporation on water for purification followed by condensation [14].

1.1.4. Comparison of Thermal Desalination with Reverse Osmosis

It was not until 1950s that the RO technology was developed and currently it is being used globally [14]. RO has a series of process to be done on impure water after which it can be purified. The major factors which are important in the selection of appropriate RO system includes:

- Source water quality
- Required water quality and quantity
- Pretreatment of water
- Total energy required
- Concentrate disposal

A normal osmosis process need water naturally disposing from the area of lower concentration to the region of higher concentration through a membrane. The Figure 5 show the normal osmosis process in which a dilute solution containing a high concentration of water molecules travel to concentrated solution containing a low concentration of water molecules.

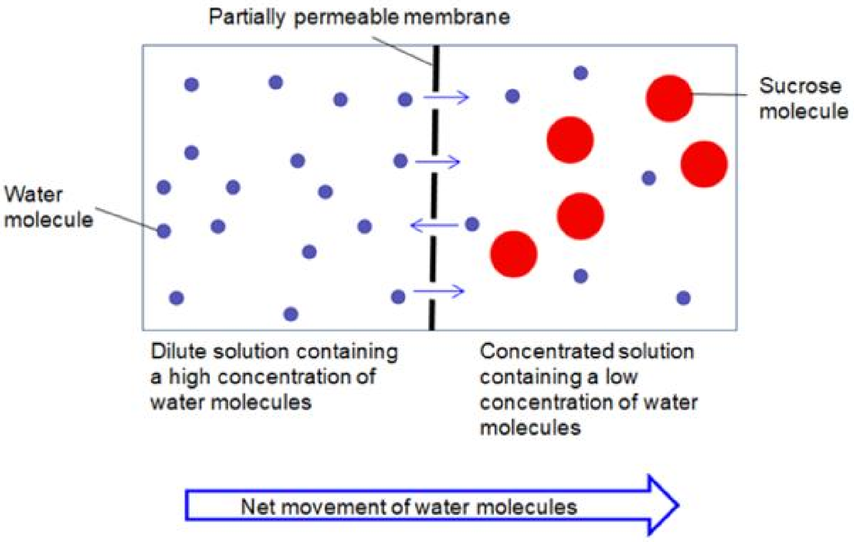


Figure 5: Normal Osmosis Process [15]

Similarly, if we apply external pressure in opposite direction to this natural flow then it is called reverse osmosis. Hence, if pressure is applied to seawater or ground water and it is passed through the membrane then all of the salt containing water will accumulate to the high pressure side of cell whereas all the clean water will be captured in the low pressure region [14]. The Figure 6 show the explanation of process of reverse osmosis.

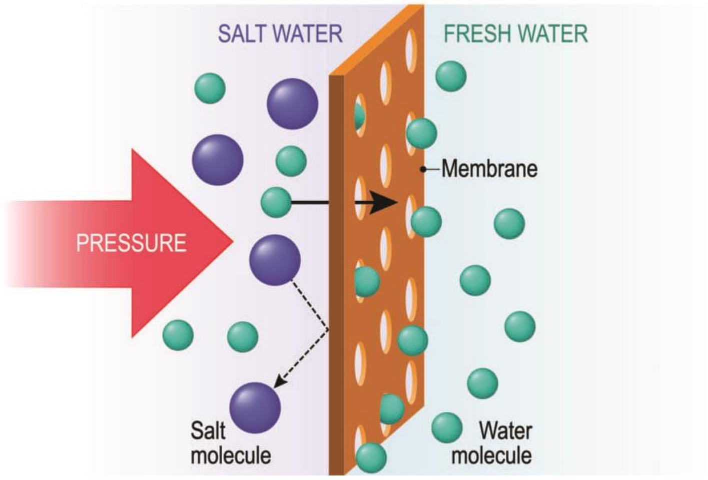


Figure 6: Reverse Osmosis [16]

On the other hand, Thermal desalination is a very natural process in which water evaporates from the ocean and then gets accumulated in the air. It is then released by either in the form of rain or snow and then it is collected. Since the most important part in thermal desalination process is the availability of heat for evaporation, hence some thermal desalinations are often used in power plants and oil refineries where there is excessive heat energy available to be reused for such processes [14].

1.1.5 Reverse Osmosis

Reverse osmosis convert unfiltered feed water to clean water when feed water is pressurized and passed through a membrane as shown in Figure 6. The water flows through the membrane and more contaminants are accumulated to the more concentrated side of the membrane whereas clean drinking water is accumulated to less concentrated side of the membrane. Normally we call the unfiltered water as feed water, the clean water as permeate and the concentrated contaminated water as the waste or brine. A membrane is an equipment that has small pores that allow water molecules to pass through but stop contaminants. In normal osmosis, on both sides of membrane equilibrium is obtained but in the process of reverse osmosis a constant pressure is being applied to feed water which ensures that brine and permeate are not mixed and collected separately.

At the first step, sediments and chlorine is removed from feed water using a pre filter which has a sediment and carbon filter. This process will ensure that membrane is not damaged and it will increase its lifetime. Then the water is pressurized and sent to the membrane for the removal of dissolved contaminants. This is the most important step during the whole RO process as in this step dissolved particles of the smallest size are separated by the help of membrane. It removes dissolved solids like arsenic and fluoride through the RO membrane. The following below are removed from water as a result of reverse osmosis process:

- Fluoride's
- Salt
- Sediments
- Chlorine
- Arsenic
- Volatile Organic Compounds VOCs
- Herbicides and pesticides
- Bad taste and odor

Once clean water is collected from the membrane it is then polished i.e. passed through a post carbon filter so that it is safe for drinking purpose. The cleaned water is then stored in a storage tank and usually the system is designed in a way that when the storage tank is full the RO system shut downs automatically. The storage tank provide a buffer for the consumption and production of clean water. The brine water is drained as a water waste. Normally four gallon of water exits as a brine for every one gallon of fresh water being produced from the system [17]. The brine water can be used for dishwashing and other cleaning purpose so that it is not wasted and utilized for increasing efficiency of the system. Also, if another pump is installed, this brine water can be sent back to the feed water loop for extracting more fresh water out of it but depends upon system design and efficiency requirements of user. The Figure 7 shows the flow diagram of reverse osmosis process with all major steps involved.

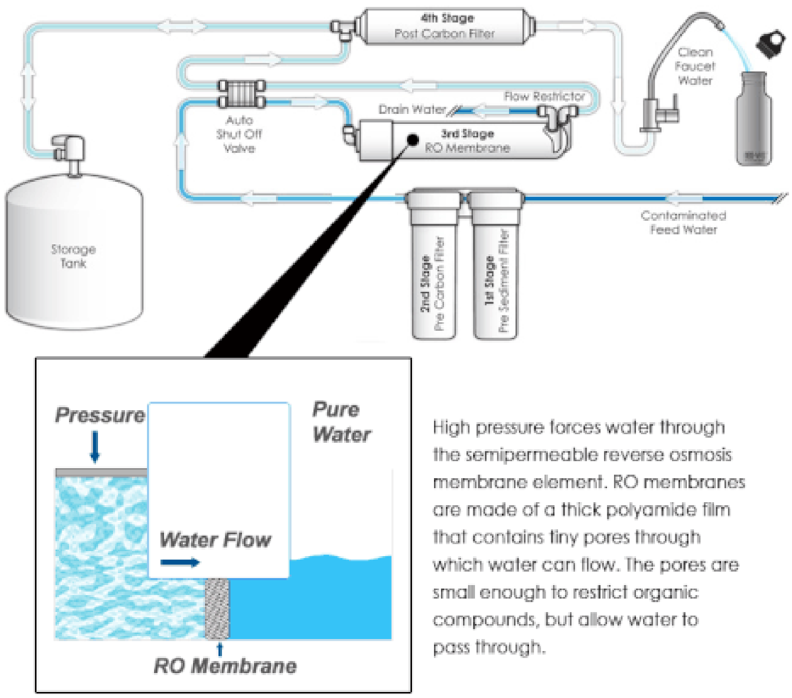


Figure 7: Reverse Osmosis Plant Flow Diagram [17]

1.1.6 Karachi Water Supply

The current population of Karachi is approximately 14.9 million [18]. The city is the backbone of country economy as most of the industries and important financial centers are located in the city as it contributes approximately 12 – 15 percent to the national gross domestic product [19]. The supply of water to Karachi relies on surface water sources and ground water sources. The ground water major source are the Dumlottee well-fields but the supply from these wells are very limited and provide only 1.4 million gallon per day (MGD) water only after rainy season [20]. The major three surface water sources of Karachi includes:

- Haleji Lake (Shown in Figure 8)

Figure 8: Haleji Lake [21]

- Keenjhar Lake (Shown in Figure 9)

Figure 9: Keenjhar Lake [21]

- Hub Dam (Shown in Figure 10)

Figure 10: Hub Dam [21]

The board responsible for providing water to Karachi is called Karachi Water and Sewerage Board (KWSB) that provide approximately 665 MGD water to Karachi [21]. The water demand of Karachi is 820 to 1200 MGD and hence there is always a shortfall of 155 to 535 MGD of water [22]. This is not just the only issue which is faced by Karachi, approximately 210 MGD of water supplied to Karachi is not even filtered rather it's just raw lake or ground water [21]. The city has a very poor and old supply system and no major investments have been done to make it more efficient. The system is at least 40 to 45 years old [22]. Due to the old and inefficient system, around 35 percent of the supplied water is lost in the transmission lines hence the total amount of water reaching Karachi results to 433 MGD of water [23]. Unfortunately the consumption of water in Karachi is also not recorded as almost none of the retails customers have a metered supply connection. For industries and commercial customers only 25 percent have metered supply of water [19].

To cater the needs of the city and its people, regulated and unregulated water hydrants are spread across the city. There is a tanker system in the whole city. Water tankers fill their tanks from these hydrants and supply water to the consumer at higher prices. These unregulated water hydrants were a big issues as they tap water supply from main lines resulting in lesser water being available to consumer from the government. In 2009 around 948 unregulated water hydrants were closed in the city but still many are operational till today [19] [22].

1.1.7 Drinking Water Quality Standards

Every living organism need water for its survival and living life. All human beings need water for their living. There should be no harmful contaminants in the water that should effect the life of a human being. Drinking water quality standards describe the quality parameters set for the drinking water. Unfortunately, there has been no such universally recognized and accepted international standard for drinking water [24]. The world health organization (WHO) provides detailed guidelines on the drinking water quality standards but it is up to every region/country to define their own set of drinking water quality standards. Following are the drinking water quality standards used by the countries themselves:

- Europe: European Drinking Water Directive [25]
- United States: Safe Drinking Water Act [26]
- China: GB3838-2002 (Type II) [27]

The Table 3 below shows date for different types of parameters in comparison to what is suggested by world health organization and what levels are defined in Europe, United States, China and Canada

Table 3: Comparison of Water quality standards across the globe [28]

Parameter	Table	WHO	European Union	United States	China	Can ada

Arsenic	As	10µg/l	10 µg/l	10µg/l	50µg/l	10.0 µg/l
Cadmium	Cd	3 µg/l	5 µg/l	5 µg/l	5 µg/l	5.00 µg/l
Chromium	Cr	50µg/l	50 µg/l	0.1 mg/L	50 µg/l (Cr6)	0.050 mg/L
Copper	Cu	50µg/l	2.0 mg/l	1.3 mg/l*	1 mg/l	1.00 mg/L
Iron	Fe	N/A	0,2 mg/l	N/A	N/A	0.300 mg /L
Lead	Pb	N/A	10 µg/l	15 µg/l*	10 µg/l	10.0 µg/l
Mercury	Hg	6 µg/l	1 µg/l	2 µg/l	0.05 µg/l	1.00 µg/l
Nitrate	Nt	50 mg/l	50 mg/l	10 mg/ L (as N)	10 mg/ L (as N)	10mg/L
pH						6.5 to 8.5

Legend:

"Indicates that no standard has been identified by editors of this article

Ns or N/A indicates that no standard exists

µg/l indicates Micro grams per liter

mg/L indicates 1 ppm or 1000 µg/l

* Action level; not a concentration standard. A public water system exceeding the action level must implement "treatment techniques" which are enforceable procedures.

1.1.8 Pakistan Drinking Water Quality

The major quality parameters includes physical, biological and chemical factors in drinking water quality as these factors if disturbed can cause affects to human health. The biggest problem in drinking water in Pakistan is the amount of contaminations which includes microbiological and chemical contaminants. The Table 4 below compares biological standard values of Pakistan with the guidelines of WHO.

Table 4: Comparison of Pakistan standard with WHO for Biological Parameters [29]

Parameter	**Standard Value for Pakistan**	**WHO Standards**
All water intended for drinking measuring E coli or thermo tolerant coliform bacterial	Must not be detectable in any 100 ml Sample	Must not be detectable in any 100 ml Sample
Treated water entering the distribution system (E. coli or thermo tolerant coliform and total coliform bacteria)	Must not be detectable in any 100 ml Sample	Must not be detectable in any 100 ml Sample
Treated water in the distribution system (E. coli or thermo tolerant coliform and total coliform bacteria)	Must not be detectable in any 100 mL sample In case of large supplies, where sufficient samples are examined, it must not be present in 95% of the samples taken throughout any 12-month period	Must not be detectable in any 100 mL sample In case of large supplies, where sufficient samples are examined, it must not be present in 95% of the samples taken throughout any 12-month period

The Table 5 below compares physical standard values of Pakistan with the guidelines of WHO.

Table 5: Comparison of Pakistan standard with WHO for Physical Parameters [29]

Parameter	**Standard Value for Pakistan**	**WHO Standards**
Color	≤15 TCU	≤15 TCU
Taste	None	None
Odor	None	None
Turbidity	<5 NTU	<5 NTU
Total hardness as CaCO3	<500 mg/L	-
TDS	<1000	<1000
pH	6.5-8.5	6.5-8.5

The Table 6 below compares chemical standard values of Pakistan with the guidelines of WHO.

Table 6: Comparison of Pakistan standard with WHO for Chemical Parameters [29]

Parameter	**Standard Value for Pakistan**	**WHO Standards**
Aluminum (Al) mg/L	≤0.2	0.2
Antimony (Sb)	≤0.005 (P)	0.02
Arsenic (As)	≤0.05 (P)	0.01
Barium (Ba)	0.7	0.7
Boron (B)	0.3	0.3
Cadmium (Cd)	0.01	0.003
Chloride (Cl)	<250	250
Chromium (Cr)	≤0.05	0.05

Copper (Cu)	2	2
Cyanide (CN)	≤0.05	0.07
Lead (Pb)	≤0.05	0.01
Manganese (Mn)	≤0.5	0.5
Mercury (Hg)	≤0.001	0.001

Drinking water quality of Islamabad was analyzed and it showed that 66.66% of the water sample was contaminated with fecal microbes and not fit for drinking purposes [30]. Islamabad water quality revealed that about [31] 77% of the water samples were biologically contaminated. The physicochemical analysis of Faisalabad city deduced that the turbidity, hardness, pH, and TDS are within safe limits but the microbial analysis showed that all samples were contaminated with total coliforms and E. coli [32]. In Punjab drinking water quality revealed that the Total dissolved solids (TDS) are in allowable range in Sargodha, Sheikhupura, Kasur, Faisalabad, and Rawalpindi [33]. In Peshawar analysis of drinking water quality revealed that just 13% of the samples were negative for bacterial contamination whereas 47% of the samples were found to be highly contaminated with E. coli and remainder were fine [34]. In Peshawar and Mardan more than 38% and 67% of samples were contaminated with iron, respectively [33]. Baluchistan water analysis also did not provide any satisfactory results as half of the samples obtained from Ziarat were highly contaminated [33]. Sindh ground water was tested for drinking and irrigation purposes and it was revealed that all samples were above the WHO guidelines and water was not fit for use in both purpose [35]. Furthermore, ground water in various districts in Sindh provided good result for pH but turbidity and most chemical parameters were way above limits set by WHO [36]. Major cities of Sindh including Sukkur, Hyderabad, and Karachi were analyzed and found that the drinking water quality is very poor in Sindh as compared to other provinces. About 67-93% of the samples in these cities were declared unfit for drinking purpose [33].

1.1.9 Karachi Water Quality

According to the analysis of Karachi it was revealed that around 88% samples had very high levels of lead in most of the surface or ground water of Karachi than the benchmark of WHO [21]. The water supply system is very old and contaminated hence the supplied water gets contaminated also resulting in around 30,000, mostly children that die per year due to its consumption [37]. One of the water supply to Karachi is from Keenjhar Lake, located in Thatta, Sindh where it was found that its pH of water in lake is within limits but the color is dark brown which is not fit for drinking purposes. Study and water analysis of Orangi town in Karachi revealed the presence of microbial contamination in water [38]. The water quality in Gulshan e Iqbal Town of Karachi was also assessed and found that all major parameters were within range except in three samples where contamination occurred due to water leakages [39].

1.2. Literature Review

In this section several papers were reviewed related to the photovoltaic based reverse osmosis system and their conclusions are discussed. A simulation based RO design system was used to find the performance of solar powered RO system. Three cities of Pakistan were assessed which includes Lahore, Hasil Pur and Faisalabad [40]. According to WHO quality requirements the TDS concentrations for these three cities was reduced from 1495 to 295.44, 2190 to 237.69 and 7683 to 241.98 respectively [40]. The drinking water production was kept fixed at 0.80 m3 /h for all three cities. Total pumping power requirement is 200, 300, and 1000W for Lahore, Hasil Pur, and Faisalabad, respectively [40]. The required energy turns out to be 60, 95, and 311 kWh/month for Lahore, Hasil Pur, and Faisalabad respectively. The paper used PVsyst software for solar calculation and deduced that 19, 15 and 40 PV panels will be used by Lahore, Hasil Pur, and Faisalabad respectively [40]. Another study was conducted for photovoltaic based reverse osmosis system in which 500 L/hr system was designed using 2KW PV system with a 5KVA hybrid inverter. The Analysis includes no tracking and three point manual PV tracking modes. Also, analysis and comparison on cooling and no-cooling of PV system was also carried out. It was concluded that around 18% more daily PV energy was utilized using the tracking system and also 10% more PV energy was used when the panels were cooled [41]. AbdelKareem [42] analysis was based on capturing desalination water using solar, wind and geothermal energy. His conclusion defined that good designing is very important when off grid PV systems are designed. He further concluded that solar tracking and cooling of PV cells eventually makes the process overall efficient. Ali et al. [43] did a different analysis of combining reverse osmosis and adsorption desalination system. He further used MATLAB for simulations of different scenarios. His work concludes that if both are run together the permeate salinity is slightly decreased which will make the process more efficient. Charcosset [44] also carried out his analysis on the same topic. His research work revolve around merging renewable energy with different designs and mathematical models for achieving best economical solution. It was concluded in his work that PV based RO plants are most efficient in terms of energy consumption when utilized for a small scale. Ahmad and Schmid [45] studies water desalination in Egypt desert using PV system for energy. Gocht et al. [46] carried out his study for reverse osmosis using photovoltaic as energy source in Jordan. Richards and Schafer [47] worked on PV based desalination plant for remote communities in Australia. Tzen et al. [48], kalogirou [49] also carried out analysis for same systems. Goosen et al. [50] work was slightly different from others as he studies and compare the challenges in renewable based desalination system. Liu et al. [51] suggested ways on how to improve the energetic efficiency of complete desalination system. He worked on the nano filtration system and did analysis the losses in the system. His work concluded that most portion of energy loss in sin the membrane section of the system. Dimitriou et al. [52] worked on modelling of reverse osmosis membrane where he concluded that water flux drop when pressurized water is passed through it. Ghermandi and Messalem [53] concluded in their work that photovoltaic based reverse osmosis is a good technology which has a potential to reach to 2-3 US$ per m3. Eke and Senturk [54] concluded that solar trackers can increase around 30% of energy in Turkey if implemented and similar was the conclusion of Babelli [55]. Lastly Bentaher et al. [56] suggested to utilize the maximum potential of solar tracking system during the day time.

1.3 Motivation and Research Objectives

Clean Drinking water is the need of every human being worldwide. Accessibility to clean drinking water not only promotes a healthier lifestyle but also provide mental relief for the community. It decreases the load on hospitals as fewer diseases are spread because of contaminations in drinking water. On the other hand we cannot just simply install desalination systems which are energy intensive units. Pakistan has been struggling for the past decade to fulfill its electricity requirements. As the country is rich in solar energy, this strengthens the case for solar powered reverse osmosis drinking water systems to be implemented in the country. This approach of renewable energy based reverse osmosis desalination system will target and provide solution to drinking water issue of Pakistan by keeping in line the following sustainable development goals of the United Nations:

- Goal 3: Good Health and Well-being
- Goal 6: Clean Water and Sanitation
- Goal 7: Affordable and Clean Energy
- Goal 13: Climate Action

The research objectives for this thesis were to

- Design a solar powered reverse osmosis system for a community in Pakistan for drinking water using HOMER, which can be taken as a case study for future scenarios.
- Perform dynamic analysis for the designed system 20Sim simulation software and

applying bond graph modelling to validate the designed system.

- Design a comprehensive instrumentation and control system strategy for the solar powered reverse osmosis desalination system
- Design a supervisory control and data acquisition (SCADA) System with secured database, data analytics provision and embedded alert system to the community.

1.4 Structure of Thesis

The first chapter of thesis talks about the introduction of the problem in Pakistan and conducts the extensive literature review which includes understanding of reverse osmosis process, understanding of Pakistan solar potential, understanding of Pakistan water quality and WHO recommendations etc.

In the second chapter, the design and analysis of a solar based reverse osmosis system in HOMER is discussed, including designing and site selection of solar based reverse osmosis system to evaluate ratings of different components. It also includes a detailed cost analysis of the overall proposed system solution.

The third chapter is about dynamic modeling of the proposed solar based reverse osmosis system in 20Sim Simulation Software. Detailed dynamic modeling and analysis of the solar based reverse osmosis system is performed using the bond graph language to analyze the system response to dynamically changing conditions.

The fourth chapter discusses a comprehensive instrumentation system design and control strategy for the execution of the solar powered reverse osmosis desalination system.

In the fifth chapter, a low-cost, open-source, internet-of-things based SCADA system is designed for the complete system with the provision of data security as local server is created. Furthermore data analytics tools are used for data visualization with an elaborative alert system for the community.

The sixth chapter discusses concluding remarks, research contributions and improvements that can be incorporated in the already designed solar based reverse osmosis system to make the overall system better.

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CHAPTER 2: SYSTEM DESIGN AND ECONOMIC ANALYSIS OF A SOLAR POWERED DRINKING WATER REVERSE OSMOSIS DESALINATION SYSTEM FOR A COMMUNITY IN PAKISTAN

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Abstract

With the advancement of technology and increase in world's population, the demand for the consumption of fresh drinking water has increased worldwide. The world is also facing climate change due to excessive emissions in the atmosphere from the conventional power generating stations. Utilization of clean energy sources for purification of water is the need of today's world. This paper focuses on explaining the water shortage situation in Pakistan and elaborates a design for a solar powered drinking water reverse osmosis system for a community in Pakistan using the HOMER Pro software. It further utilizes the optimization feature of HOMER Pro software to carry out economic analysis of the system to provide the most economical system design.

Keywords

Solar, Reverse Osmosis, Water Desalination, HOMER Pro Software, Economic Analysis

2.1. Introduction

Pakistan economy mostly relies on agriculture and around 22.2% of that contributes to its overall gross domestic product (GDP) [1]. Approximately around 42.3% of the labor in Pakistan is employed from the total labor strength [2]. In 1950s Pakistan has the water capacity of around 5000 m3 per capita and it has decreased now to 1000 m3 per capita [2]. The most affected provinces of Pakistan are Sindh and Baluchistan when it comes to freshwater availability. According to the United Nations Educational, Scientific and Cultural Organization report, Pakistan available water supply is just above 1000 m3 per capita which puts the country in the list of water stress countries [3]. According to estimates, the population of Pakistan will going to be nearly double in the next 25 years and this will further decrease the per capita availability of water. Overall worldwide, the countries that are facing difficulty in availability of freshwater are now relying on water desalination processes using ground water as this method allows to generate fresh water supply but at the cost of electricity consumption. According to an estimate it take 10,000 ton/yr. of crude oil to produce 1000 m3/day of desalinated water from the process of thermal desalination [4]. This energy requirement is a big challenge as the world is already heading towards a big global climate change. Extracting this much amount of energy from the conventional thermal power plants would not only make the environment poor but would put the cost of production of water at a very higher rate. The renewable energy is the solution to that problem and solar powered reverse osmosis plants can be very beneficial when it comes to elimination of utilization of fossil fuels. Hence renewable technology based reverse osmosis (RO) systems can be a good source of sustainable fresh water production method [5]. Pakistan is not a country that is rich in energy production although it has huge reserves of fossil fuels. Thankfully, it lies on the region of good solar irradiance ranging from 5–7 kWh per m2 per day and sunshine hours of 1,500–3,000 [6] which can be used as an advantage for solar powered RO systems. The desalination process now is used worldwide and its utilization trend has shown an increase in the recent years [7]. The Solar powered reverse osmosis is a unique idea for converting the saline or brackish water to fresh water as the water passes through membranes and remove approximately 98% - 99.5% salt from it [8]. With all of these factors being said and issues that Pakistan as a country has, powering a reverse osmosis system for extracting drinking water for a community in Pakistan using renewable energy sources makes a very favorable solution.

2.2 Literature Review

In this section several papers were reviewed related to the photovoltaic (PV) based reverse osmosis system and their conclusions are discussed. A simulation based RO design system was used to find the performance of solar powered RO system in three cities of Pakistan which includes Lahore, Hasil Pur and Faisalabad [9]. The paper used PVsyst software for solar calculation and deduced that 19, 15 and 40 PV panels will be used by Lahore, Hasil Pur, and Faisalabad respectively [9]. Another study was conducted for photovoltaic based reverse osmosis system in which 500 L/hr. system was designed using 2 KW PV system with a 5 KVA hybrid inverter. It was concluded that around 18% more daily PV energy was utilized using the tracking system and also 10% more PV energy was used when the panels were cooled [10]. Abdel Kareem [11] analysis was based on capturing desalination water using solar, wind and geothermal energy. He concluded that solar tracking and cooling of PV cells eventually makes the process overall efficient. Liu et al. [12] suggested ways on how to improve the energetic efficiency of complete desalination system. He worked on the nano filtration system and did analysis the losses in the system. His work concluded that most portion of energy loss is in the membrane section of the system. Dimitriou et al. [13] worked on modelling of reverse osmosis membrane where he concluded that water flux drop when pressurized water is passed through it. Ghermandi and Messalem [14] concluded in their work that photovoltaic based reverse osmosis is a good technology which has a potential to reach to 2-3 US$ per m3. Eke and

Senturk [15] concluded that solar trackers can increase around 30% of energy in Turkey if implemented and similar was the conclusion of Babelli [16]. Lastly Bentaher et al. [17] suggested to utilize the maximum potential of solar tracking system during the day time for increasing system efficiency.

2.3 Reverse Osmosis Desalination System

Reverse osmosis convert unfiltered feed water to clean water when feed water is pressurized and passed through a membrane. The water flows through the membrane and more contaminants are accumulated to the more concentrated side of the membrane whereas clean drinking water is accumulated to less concentrated side of the membrane. A membrane is an equipment that has small pores that allow water molecules to pass through but stop contaminants. At the first step, sediments and chlorine is removed from feed water using a pre filter which has a sediment and carbon filter. This process will ensure that membrane is not damaged and it will increase its lifetime. Then the water is pressurized and sent to the membrane for the removal of dissolved contaminants. This is the most important step during the whole RO process as in this step dissolved particles of the smallest size are separated by the help of membrane. It removes dissolved solids like arsenic and fluoride through the RO membrane. Once clean water is collected from the membrane it is then polished i.e. passed through a post carbon filter so that it is safe for drinking purpose. The cleaned water is then stored in a storage tank and usually the system is designed in a way that when the storage tank is full the RO system shut downs automatically. The storage tank provide a buffer for the consumption and production of clean water. The brine water is drained as a water waste. Normally four gallon of water exits as a brine for every one gallon of fresh water being produced from the system [18]. The brine water can be used for dishwashing and other cleaning purpose so that it is not wasted and utilized for increasing efficiency of the system.

2.4 Pakistan Data Analysis

The location of Pakistan on map lies within latitude 23.45º to 36.75ºN and longitude 61º to 75.5ºE. The Renewable Energy Policy 2006 [19] of Alternative Energy Development Board (AEDB) Ministry of Energy and Power division Pakistan, explains that Pakistan is highly rich in terms of solar energy. The provinces of Baluchistan and Sindh receive the most solar irradiance in overall Pakistan which means that majority of southern Pakistan has the highest solar irradiance.. The annual average solar radiation of Pakistan is about 5.5 kWh/m2. The Areas of Sindh and Baluchistan are even richer in terms of solar radiation excluding the coastal areas of these provinces.

2.5 Materials and Method

In order to achieve the best possible design, all aspects of the system are to be analyzed. The following framework has been considered in this paper for an accurate evaluation of the system:

- Karachi water supply system
- Characteristics of the selected site.
- Water system configuration.
- Load demand data.
- Solar radiation data
- System components.

2.5.1 Karachi Water Supply System

The current population of Karachi is approximately 14.9 million [20]. The city is the backbone of country economy as it contributes approximately 12 – 15 percent to the national gross domestic product [21]. The supply of water to Karachi relies on surface water sources and ground water sources. The major three surface water sources of Karachi are Haleji Lake, Keenjhar Lake and Hub Dam. The board responsible for providing water to Karachi is called

Karachi Water and Sewerage Board (KWSB) that provide approximately 665 million gallons per day (MGD) water to Karachi [22]. The water demand of Karachi is 820 to 1200 MGD and hence there is always a shortfall of 155 to 535 MGD of water [23]. Also, approximately 210 MGD of water supplied to Karachi is not even filtered rather it's just raw lake or ground water [22]. Due to the old and inefficient system [23], around 35 percent of the supplied water is lost in the transmission lines hence the total amount of water reaching Karachi results to 433 MGD of water [24]. To cater the needs of the city and its people, regulated and unregulated water hydrants are spread across the city. There is a tanker system in the whole city. Water tankers fill their tanks from these hydrants and supply water to the consumer at higher prices. These unregulated water hydrants were a big issues as they tap water supply from main lines resulting in lesser water being available to consumer from the government supply lines. In 2009 around 948 unregulated water hydrants were closed in the city but still many are operational till today [21] [23].

2.5.2 Characteristic of the Selected Site

Karachi is situated in the south of Pakistan and faces severe population migration, water crisis and pollution issues in the last few years. Qasim Town as the selected location for this study is a slum area in Karachi city, Sindh Province, Pakistan (24°49'37.2"N 67°15'08.1"E). This is a Slum community with families having very low income to support their living. This area is currently relying on water tanker system and unscheduled limited supply of contaminated water from the government water supply lines. The cost of water tanker is very high and it became highly unfeasible for such low income community to purchase expensive water for drinking purpose. The figure 11 shows the google earth image of the selected site.

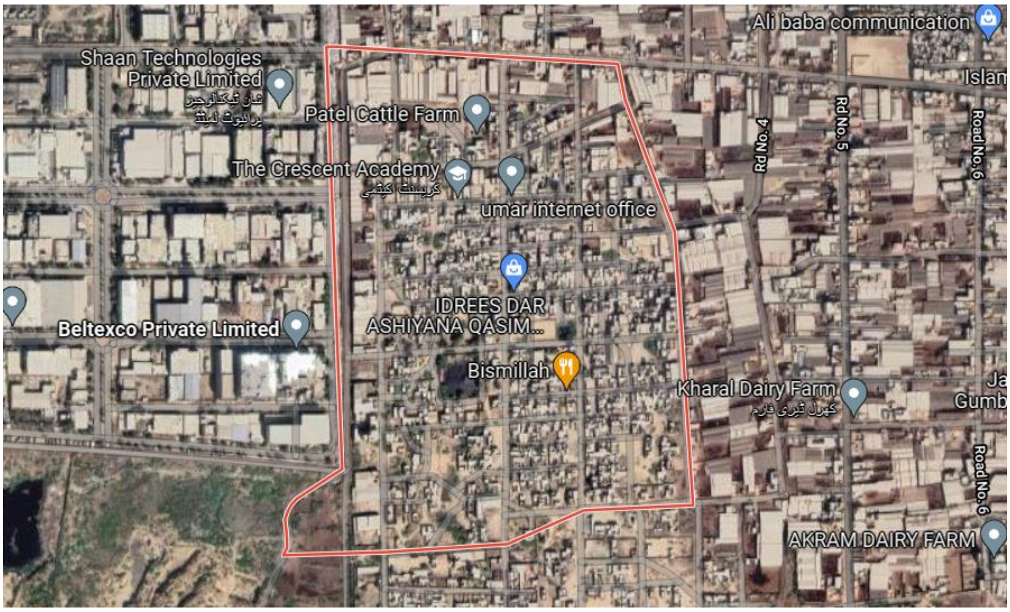


Figure 11: Google Image of Selected Site

This selected community has around 223 houses with a total population of approximately 780 persons. The availability of ground water was explored by the nearby company Beltexco Private Limited as seen in figure 6 for their utilization of water. According to that company report, ground water was found at 300 feet below the surface. The total dissolved solids (TDS) was found to be 1612 mg/L and hardness was found as 518.49 mg/L.

2.5.3 Water System Configuration

A submersible pump is installed to extract the brackish ground water from a depth of 300 feet's. On average, drinking water consumption by a person in one day is 3.7 liters. In order to feed the complete community of 780 persons around 2964 liter of water is required per day. A brackish water tank is used that has a capacity of 4000 liters so that sufficient quantity of brackish water is stored once pumped from the ground. A pressure pump is utilized to increase the tank's brackish water pressure and then passed through the reverse osmosis (RO) system before it leaves to the drinking water storage tank and finally is available for community utilization from the common header. The figure 12 shows the complete water system configuration adopted.

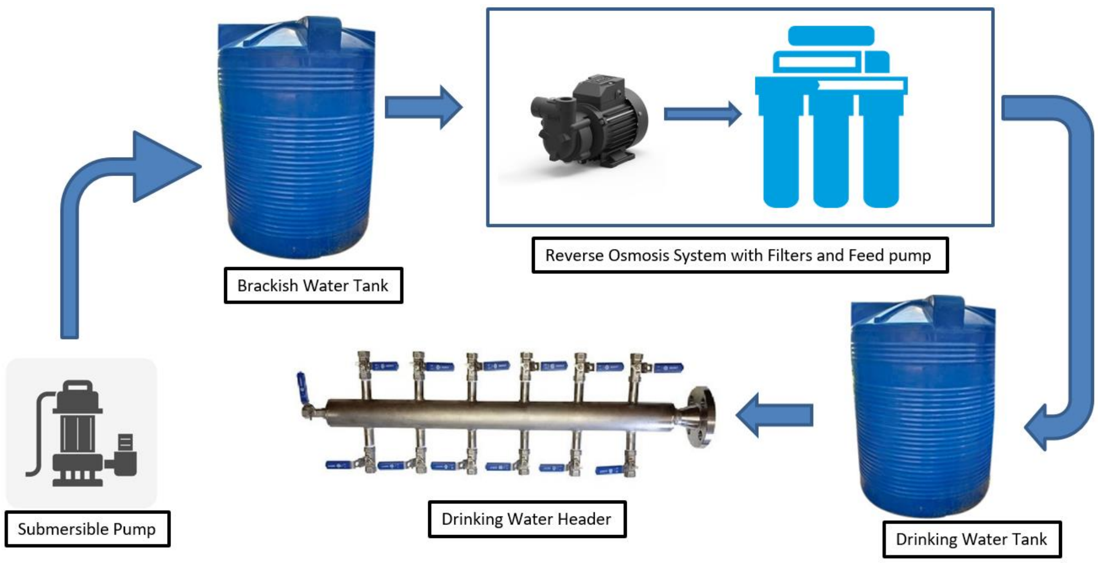


Figure 12: Water System Configuration

2.5.4 Electrical Load Requirement

The major components of load in the system are submersible pump motor, complete RO system load and miscellaneous load. The complete system will run for 06 hours in a day to produce sufficient drinking water for the complete community. Based on the total dynamic head of 320 feet's, liquid flow rate of 2.175 gallons per minute and pump efficiency of 50%, a 1.5 horsepower single phase induction motor is selected to be coupled with the submersible pump. The complete RO system for producing 2.175 gallons per minute has a power requirement of 0.5 kilowatt. Some miscellaneous energy that will be required which includes area lightning, control equipment etc. would require a maximum of 0.3 kilowatt. Hence the total energy required will be approximately 2.0 kilowatt for running the system smoothly at a production rate of more than 2.175 gallons per minute. The table 7 summarizes the Electrical load requirement for the complete system.

Table 7: Electrical Load Summary

Component	Load (KW)
Submersible pump motor	1.2
Reverse Osmosis System including feed pump	0.5
Miscellaneous	0.3
Total Load	2.0

2.5.5 Solar Radiation Data

The selected location has significant solar irradiance because of its favorable location. Based on the database, which is downloaded from NASA's prediction of worldwide energy resources, the monthly radiation and clearness index is depicted in figure 13. The average annual solar irradiance in this region is 5.45 kWh/m2/day, while the maximum and minimum irradiance occurs in May and December, respectively.

Figure 13: Solar Radiation and Clearness Index

2.5.6 System Component

2.5.6.1 PV Module

The PV module used in this analysis is a fixed tracking system with an efficiency of around 17.49%. The nominal maximum DC output power of 340 W is produced when the PV module is exposed directly to the sunlight. The module is of Max Power Company.

2.5.6.2 Battery

The lead acid battery of Trojan Company whose model number is SCS-200 is selected for the analysis. The battery has maximum capacity of 116 Ah under the nominal voltage of 12 V. The DC bus voltage is set to 48 V in this study to reduce the DC bus current. The minimum state of charge (SOC) is 20% in the design.

2.5.6.3 Inverter

The inverter's main responsibility is to convert the PV module's DC output power to AC to feed the load. A 6 kilowatt inverter of Max Power Company is selected. The model number is Suntronic 6KW with a battery nominal voltage of 48 VDC. The solar inverter has 96% efficiency and a 10 years lifetime is selected for analysis.

2.6 System Design in HOMER Pro

Hybrid optimization of multiple energy resources (HOMER) software from the National Renewable Energy Laboratory (NREL) is an enhanced software for simulation of micro grids. This software allows to use various components including conventional generator, extensive renewable and storage resources. The optimization feature of this software enables a designer to evaluate a stand-alone hybrid PV system with cost effective solutions, incorporating the highest percentage of renewable energy for grid stability and considering environmental concerns i.e. to reduce carbon dioxide emissions.

In this paper, proposed electrical system is designed to power a submersible pump and RO desalination system simultaneously. The HOMER Pro software is used for the techno-economic analysis to optimize the system and introduce the most feasible solution. The system design includes a PV array, lead acid battery and inverter feeding the load. The system has a daily energy requirement of 12 kilowatt hour with peak load of 3.63 kilowatt. The PV has 4.8 kilowatt of maximum power and uses a 6.0 kilowatt of inverter. Result of Homer Pro with optimization suggest 20 12-volt batteries with 4 batteries in each string to keep the DC bus voltage at 48 volts. The system configuration in HOMER software is shown in figure 14.

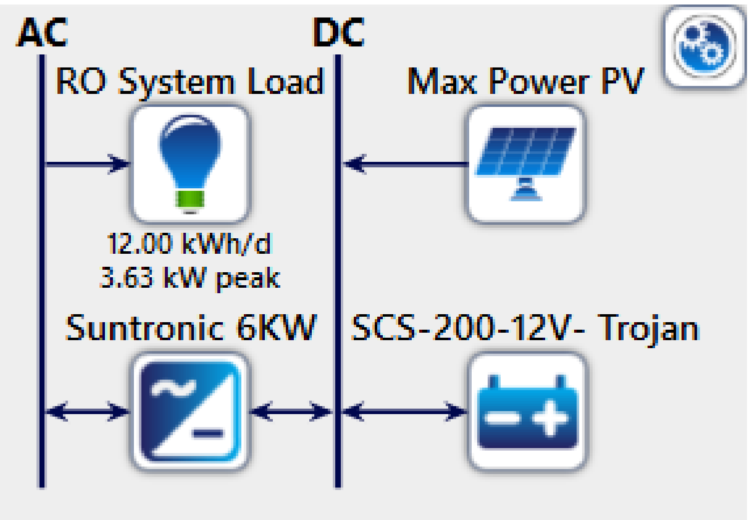


Figure 14: System Configuration on HOMER Pro

2.7 Results

2.7.1 Electrical Design Results

The results were analyzed and electrical parameters were derived. The figure 15 shows monthly analysis of maximum PV power generation. It can be seen that at least 0.5 Mega Watt hr. of energy is generated with lowest in the month of July and maximum in the month of March.

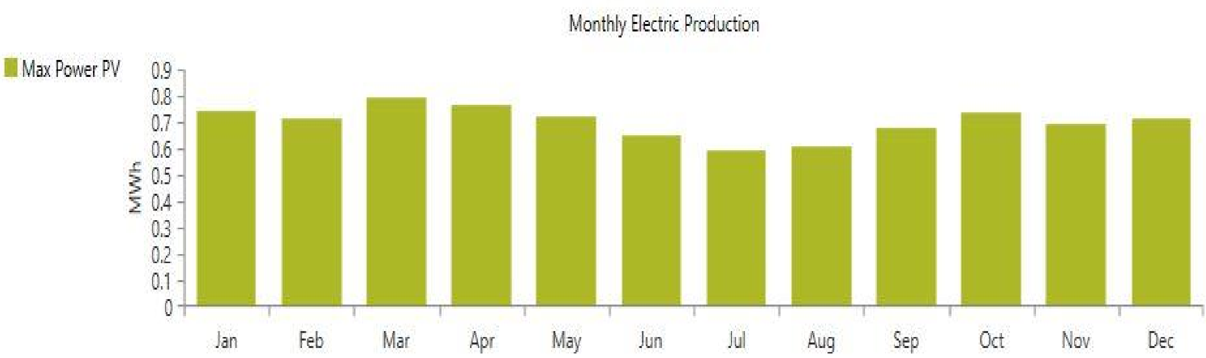


Figure 15: Monthly Electric Power Generation

The figure 16 shows monthly analysis of state of charge for battery. It can be seen that the highest deviation in state of charge (SOC) is in the month of August whereas the minimum deviation is in April.

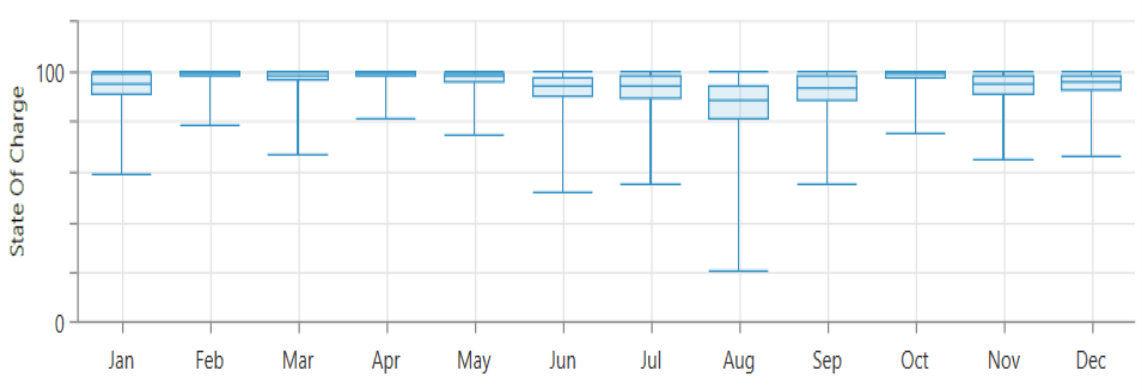


Figure 16: Monthly SOC battery

The figure 17 shows comparison of total electrical load served, PV Panel Power output and battery input power for three consecutive days in the month of May

.

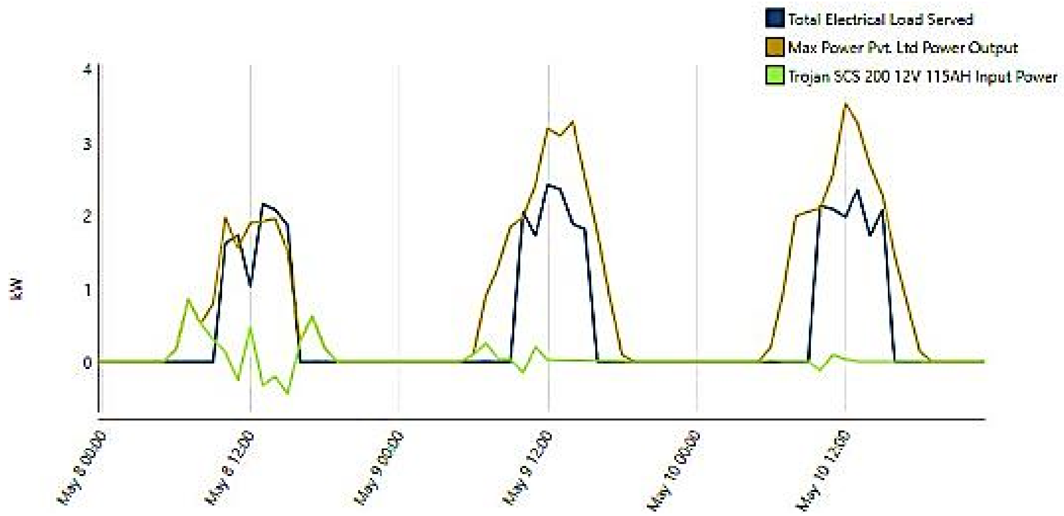


Figure 17: Comparison of total electrical load served, PV Panel Power output and battery input power

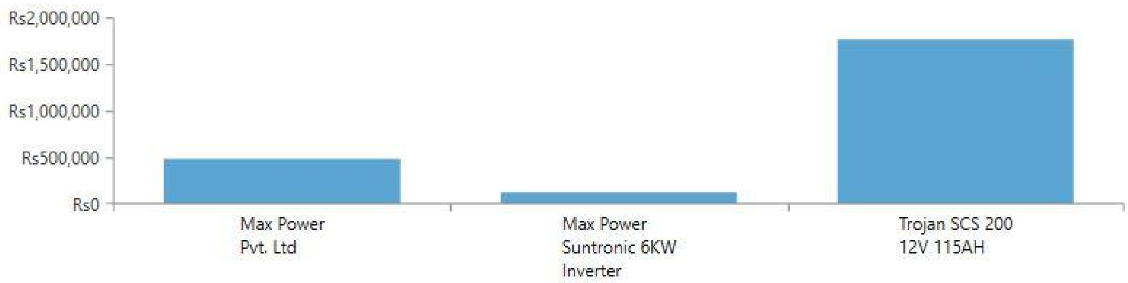
The table 8 below summarizes all important electrical parameters of PV, battery and inverter.

Table 8: Summary of Electrical Parameters

Parameter	**Value**
PV Maximum Power	4.80 KW
Number of Batteries Required	20; 5 set of 4 strings
Inverter	4.30 KW
Renewable Energy Fraction	100%
PV Maximum Production	8418 KWH/Year
Battery Autonomy	44.6 hours
Battery Annual throughput	480 KWH/Year
Battery Nominal Capacity	27.9 KWH
Battery Usable Nominal Capacity	22.3 KWH
Inverter Mean Output	0.500 KW

2.7.2 Economic Analysis Results

The results were analyzed and cost analysis was carried out. The figure 18 shows show cost summary of the system. The highest cost is of lead acid batteries.



Component	Capital (Rs)	Replacement (Rs)	O&M (Rs)	Fuel (Rs)	Salvage (Rs)	Total (Rs)
Max Power Pvt. Ltd	Rs278,401.04	Rs245,949.95	Rs0.00	Rs0.00	-Rs33,346.58	Rs491,004.42
Max Power Suntronic 6KW Inverter	Rs73,149.34	Rs64,622.88	Rs0.00	Rs0.00	-Rs8,761.75	Rs129,010.47
Trojan SCS 200 12V 115AH	Rs530,000.00	Rs0.00	Rs1,292,751.65	Rs0.00	-Rs64,058.78	Rs1,758,692.88
System	Rs881,550.38	Rs310,572.83	Rs1,292,751.65	Rs0.00	-Rs106,167.10	Rs2,378,707.77

Figure 18: Cost Summary

The figure 19 shows cash flow analysis for a period of 25 years according to the type of cost including replacement, salvage, operating and capital.

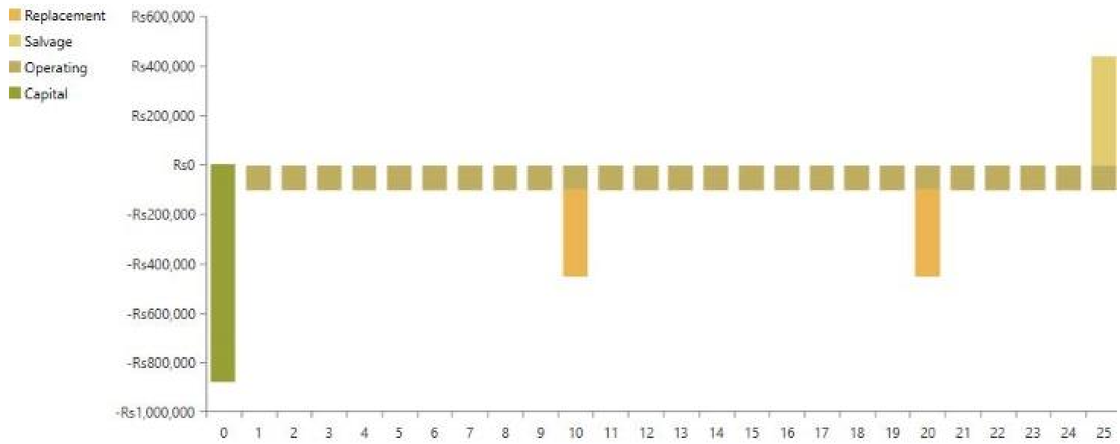


Figure 19: Cash Flow

The table 9 below summarizes all important economic parameters which indicates that the initial capital of PKR 881,550 is required for this system.

Table 9: Summary of Economic Parameter

Parameter	**Value (PKR)**
Net Present Cost	2.38 Million
Cost of Energy	42.04
Operating Cost	115,812/year
Initial Capital	881,550
PV Panel Capital Cost	278,401

2.8 Conclusion

Based on the results drawn using the optimization feature of the HOMER Pro Software, a most economical design of a solar powered based drinking water reverse osmosis system is designed which will provide sufficient amount of drinking water to the complete community. The system is totally based on solar power which means that there is no carbon dioxide emission in the environment. The results depicts that with 4.8 KW of maximum power from the solar panels and battery arrangement of 5 sets of 4 strings will be sufficient for smooth operation of the system. There is an initial investment cost as summarized in table 6 but considering the advantages of system and the need of the residents of the community it turns out to be the most feasible solution for providing drinking water to the whole community.

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CHAPTER 3: DYNAMIC MODELING AND ANALYSIS OF A SOLAR POWERED REVERSE OSMOSIS DESALINATION SYSTEM USING THE BOND GRAPH MODEL

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A version of the manuscript in this chapter has been presented as a conference paper in the 2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), Toronto, Canada. As the primary author in this paper, Sheikh Usman carried out the research under the supervision of Dr. Geoff Rideout as the co-author. The MEng candidate performed the literature review and was involved in dynamic system modelling using the bond graph method. Moreover, he prepared the first draft of the paper. The co-author supervised the research by actualizing the research ideas, reviewing and correcting the manuscript.

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Published Reference Link: https://ieeexplore.ieee.org/document/9795742

Abstract

With the advancement of technology and increase in world's population, the demand for the consumption of fresh drinking water has increased worldwide. Utilization of clean energy sources for purification of water is the need of today's world. This paper focuses on modelling the solar powered reverse osmosis system using the bond graph modelling technique which is very effective for multidisciplinary systems. The model contains electrical, mechanical and hydraulic domains merged together using the bond graph language. It further utilizes the 20-Sim software to implement the dynamic model and simulate the system. The paper eventually provides a detailed analysis on how the system will respond to the changing system parameters.

Keywords

Solar, Reverse Osmosis, Bond Graph, Dynamic Modelling, Simulation, 20sim Software

3.1. Introduction

Pakistan economy mostly relies on agriculture and around 22.2% of that contributes to its overall gross domestic product (GDP) [1]. Approximately 42.3% of the labor in Pakistan is employed from the total labor strength [2]. In 1950s Pakistan has the water capacity of around 5000 m^3 per capita and it has decreased now to 1000 m^3 per capita [2]. According to the United Nations Educational, Scientific and Cultural Organization report, Pakistan available water supply is just above 1000 m^3 per capita which puts the country in the list of water stress countries [3]. Overall worldwide, the countries that are facing difficulty in availability of freshwater are now relying on water desalination processes using ground water as this method allows to generate fresh water supply but at the cost of electricity consumption. According to an estimate it take 10,000 ton/yr. of crude oil to produce 1000 m^3/day of desalinated water from the process of thermal desalination [4]. This energy requirement is a big challenge as the world is already heading towards a big global climate change. The renewable energy is the solution to that problem and solar powered reverse osmosis plants can be very beneficial when it comes to elimination of utilization of fossil fuels. Hence renewable technology based reverse osmosis (RO) systems can be a good source of sustainable fresh water [5]. Thankfully, Pakistan lies on the region of good solar irradiance ranging from 5–7 kWh per m^2 per day and sunshine hours of 1,500–3,000 [6] which can be used as an advantage for solar powered RO systems. The desalination process now is used worldwide and its utilization trend has shown an increase in the recent years [7]. The Solar powered reverse osmosis is a unique idea for converting the saline or brackish water to fresh water as the water passes through membranes and remove approximately 98% - 99.5% salt from it [8]. With all of these factors being said and issues that Pakistan as a country has, powering a reverse osmosis system for extracting drinking water for a community in Pakistan using renewable energy sources makes a very favorable solution. Modelling of such multi-disciplinary systems which involves electrical, mechanical and hydraulic domains require complex modelling techniques. This paper utilizes the bond graph modelling approach which facilitates different domains using the explicitly graphical power flow paths among interconnected system elements, and leverage analogies among different energy domains such as thermal, fluid, mechanical, and electrical. This modelling technique is then utilized to understand the behavior of desired outputs in relationship to the changing parameters of the system.

3.2. Literature Review

In this section several papers were reviewed related to the photovoltaic (PV) based reverse osmosis system and their conclusions are discussed. S. Sobana and Rames C. Panda [9] have reviewed more than 65 literatures for identifying different process parameters, dynamic modelling and control of desalination system. Their work mainly gives an account of two types of phenomenological models of desalination processes, namely, mechanistic model or membrane transport model and lumped parameter model. Many researchers have presented identified transfer functions from input – output data of reverse osmosis process. Alatiqi et al. (1989) [10] used system identification techniques to estimate a MIMO structure of RO plant at Doha. Assef et al. (1995), Riverol and Pilipovic (2005), and Robertson et al. (1996) [11] [12] [13] also developed multivariable transfer function models from the plant's input – output data. Zilouchian (2001) [14] worked and find the reverse osmosis desalination system transfer function and also in steady state matrix form using recursive least square method. Ramaswamy et al. (1995) [15] implemented connected multilayer feed forward neural network using the back propagation algorithm to identify the nonlinear multivariable multistage flash desalination plant. Fkirin et al. (1997) [16] presented an algorithms which focus on optimal identification for the timevarying dynamic process based on linear combination of the recursive least square method. Saengrung et al. (2002) [17] modeled two reverse osmosis plants using system identification. Gambier et al. (2007) [18] derived a lumped parameter dynamic MIMO model from first principle laws and used it in carrying out diagnostics of system and even in finding faults in system. Ahmad et al. (2007) [19] developed and simulated a membrane transport model suitable for the multiple solutes system in reverse osmosis for unsteady-state condition. Chaaben et al. (2008) [20] developed a MIMO model relating input and output variable for a small photovoltaic reverse osmosis desalination unit. All these research approach provides a great insight on how to model the reverse osmosis system.

3.3. Bond Graph Language

Due to the increasing number of sophisticated and interdisciplinary systems, multidisciplinary techniques are becoming increasingly crucial in the modelling process. Bond graph approach establishes a common vocabulary for understanding relationships and similarities among various modelling methodologies. It provides a uniform domain-independent graphical representation of multidisciplinary models [21]. Bond graph provides a clear graphical representation from which other representations can be derived, e.g. linearized state equations, system transfer functions, or differential equations. The bond graph is a modelling technique that is based on energy transfer between system components. Bonds connect the component ports, demonstrating how power is transferred between them. A half-arrow on one end of the bond indicates the direction of power transfer. In a bond graph, there are two variables: effort (e) and flow (f). The system, which is composed of many energy domains such as mechanical, electrical, and hydraulic, is turned into a single model in order to simplify the system's analysis. The figure 20 shows analogies of different bond graph variables utilized in different domains [22].

Energy Domain	Effort (e)	Flow (f)	Generalized Momentum	Generalized Displacement
Translational Mechanics	Force	Velocity	Momentum	Displacement
Rotational Mechanics	Torque	Angular Velocity	Angular Momentum	Angle
Electro-magnetic	Voltage	Current	Flux Linkage	Charge
	Magneto-motive Force	Magnetic Flux Rate	------	Magnetic Flux
Hydraulic	Total Pressure	Volume Flow	Pressure Momentum	Volume
Thermodynamic	Temperature	Entropy Flow	------	Entropy
Chemical	Chemical Potential	Molar Flow	------	Molar Mass

Figure 20: Analogies of different bond graph variables utilized in different domains [22]

3.4. System Description

The overall system will comprise of an electrical, mechanical and hydraulic system. The figure 21 below shows the complete block diagram of the system.

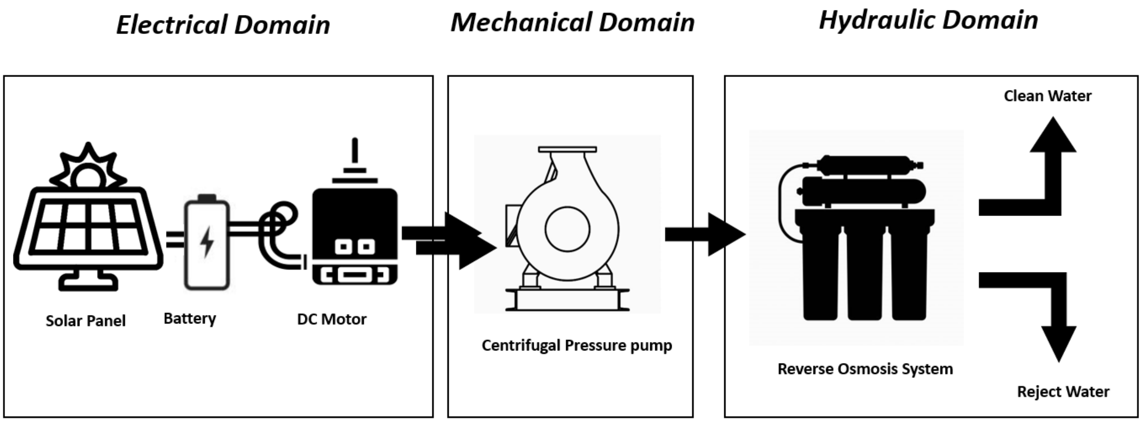

Figure 21: Block Diagram of Complete System

3.4.1 Electrical System

The electrical system will use the energy of the sun and by using the photovoltaic cell convert that energy to electrical direct current form. This energy will be fed to the batteries through charge controllers so that it can be used to provide power to the reverse osmosis system. The major load of reverse osmosis system is the dc motors that is coupled with the centrifugal pressure pump to run the hydraulic system. The block diagram for a solar powered dc motor is shown in figure 22 [23].

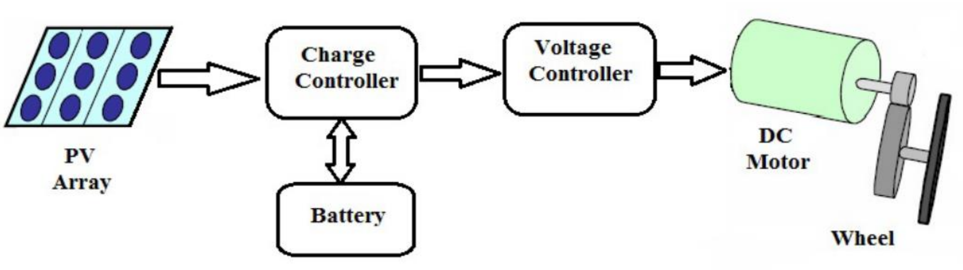

Figure 22: Block Diagram of Solar Powered DC motor [23]

3.4.2 Reverse Osmosis Desalination System

Reverse osmosis system converts unfiltered feed water to clean water when feed water is pressurized and passed through a membrane. The water flows through the membrane and more contaminants are accumulated to the more concentrated side of the membrane whereas clean drinking water is accumulated to less concentrated side of the membrane. The cleaned water is then stored in a storage tank and usually the system is designed in a way that when the storage tank is full the RO system shut downs automatically. The brine water is drained as a water waste [24]. The brine water can be used for dishwashing and other cleaning purpose so that system efficiency is increased. The basic components of a RO process are: pre-treatment system used for cleaning brackish water, High-Pressure Centrifugal (HP) pump used to provide required pressure to membrane, and post-treatment system for smell and odor removal [25]. The overall block diagram of reverse osmosis system is shown in figure 23.

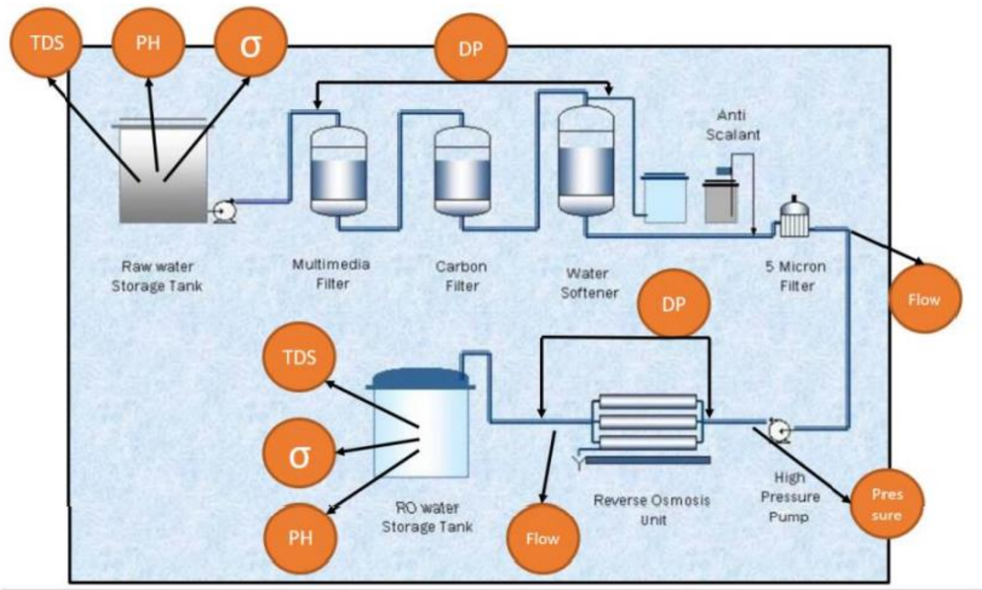

Figure 23: Block Diagram of Reverse Osmosis System

3.5 System Modelling

3.5.1 Generalized bond graph model of system

The generalized interrelation of multidisciplinary system can be seen in figure 24. The distinct systems are connected with the power variable defined as effort and flow. Electrical domain output of motor torque and motor speed is used as the input to the mechanical domain. The mechanical domain outputs the Pump Pressure and pump flow rate that is used as the input to the hydraulic domain and eventually producing clean and reject water.

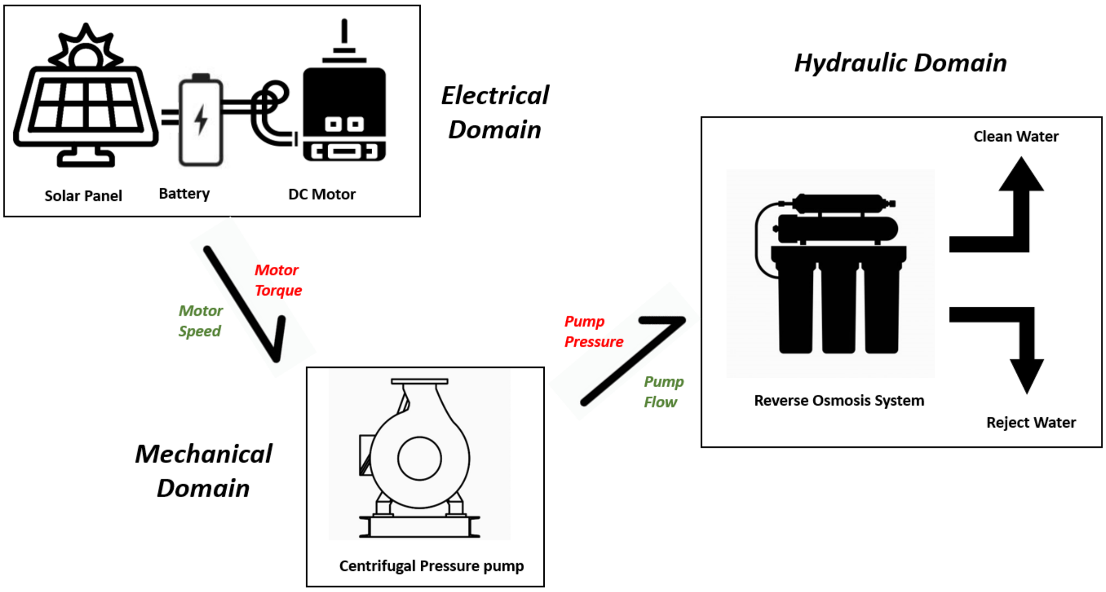

Figure 24: Generalized Bond Graph Model of System

3.5.2 Detailed system based bond graph modelling

3.5.2.1 Electrical system bond graph modelling

In order to reduce the complexity of the system, the solar panel and battery are modelled as a voltage source. The rated voltage of battery is 24V DC. The DC motor model is created in which motor resistance and inductance are modelled as R-element and I-element respectively. The conversion from electrical domain to mechanical domain is executed with the help of gyrator that relates effort to flow with the motor constant (K_m). The selected parameters of the model are shown in table 10. The bond graph model of the system is shown in figure 25.

Table 10: Electrical Model Parameters

Element	**Description**	**Value**	**Unit**
Se	Voltage Source	24.0	V
R	Winding Resistance	5.0	Ohm
I	Winding Inductance	0.03	H
GY	Motor constant	0.02848	Nm/A

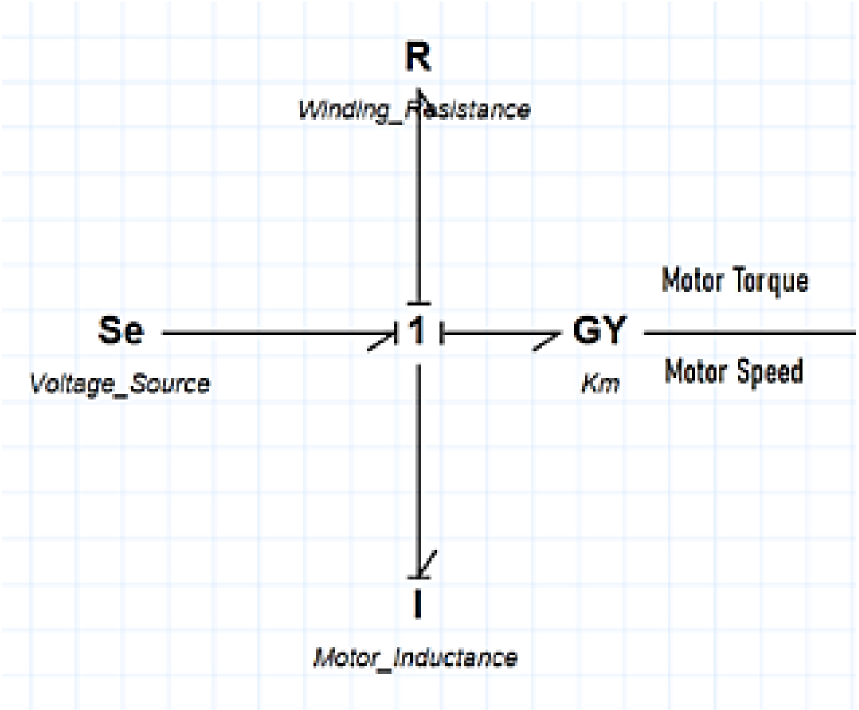

Figure 25: Bond Graph Model of Electrical System

3.5.2.2 Pressure pump bond graph modelling

The pump is defined as a machine used to generate a pressure differential in order to propel liquid through a piping system from one location to another. An electric motor rotates an impeller in a centrifugal pump that adds energy to the water after it is directed into the core of the rotating impeller. The pump is coupled directly to the motor and the load of the pump is modelled using the equations (1) and (2) [26] [27].

$$T_l = (K_1 . \omega - K_2 . Q) . Q \quad (1)$$

$$P = (K_1 . \omega - K_2 . Q) . \omega \quad (2)$$

Where:

T_l is the load torque of the pump

P is the pressure of the fluid

ω is the rotational speed of the machine

Q is the flow rate of the pump

$K_1 and\ K_2$ are the pump parameters

The modelling of a single stage pump is done in the bond graph by the help of the gyrator element whereas R-element represent losses due to impeller/diffuser wear and fluid disk friction, I-(inertia) element models the rotating fluid of the pump and another R-element represents the pipe loss when water is transmitted from pump discharge to the reverse osmosis system inlet. The selected parameters for the model are shown in table 11. The bond graph model of the system is shown in figure 26.

Table 11: Pump Model Parameters

Element	Description	Value	Unit
GY	Centrifugal Pump Equations Modelled	Pressure & Flow rate	Bar & GPM
R	Impeller Loss	0.05	Bar
R	Pipe Loss	0.0005	Bar
I	Rotating Fluid Inertia	0.125	kgm^2

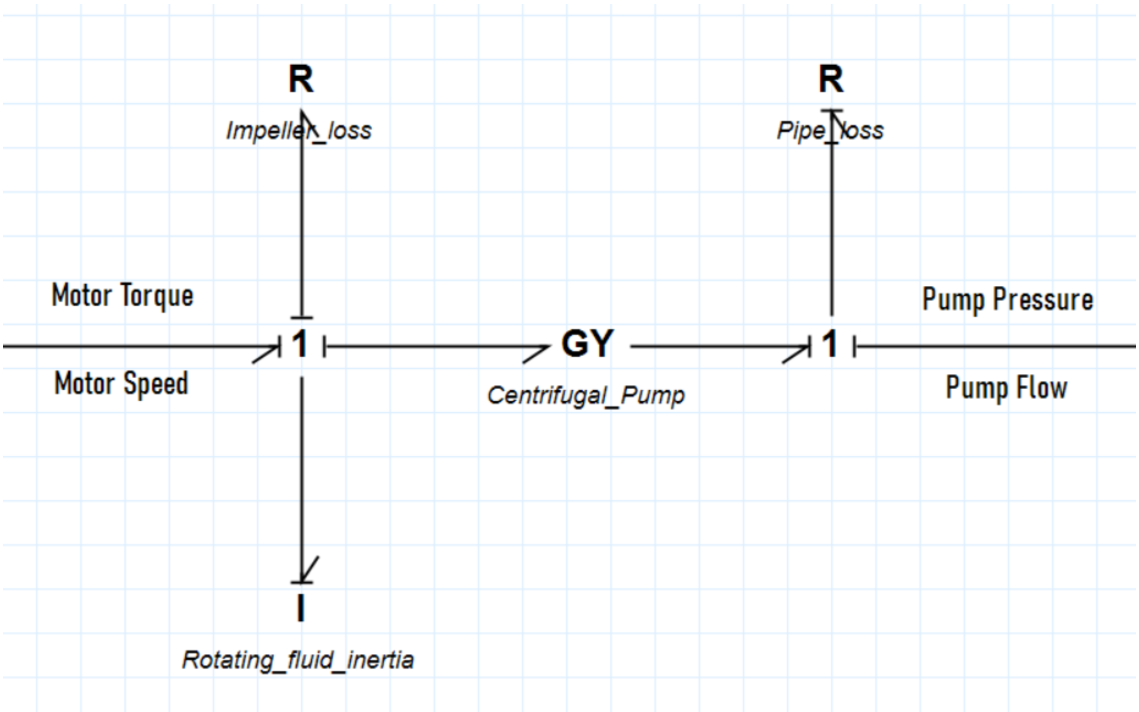

Figure 26: Bond Graph Model of Centrifugal Pump

3.5.2.3 Membrane bond graph modelling

The reverse osmosis system works opposite to the phenomena of osmosis system. By applying the external pressure which is from the centrifugal pump clean water and dirty water are separated. The feed water pressure from the pump must be large enough to overcome the osmotic pressure and the membrane resistance, as well [28] [29]. The flow inside the membrane is cross in nature resulting in clean water being diffused to the other side of membrane and all brine (dirty) water being collected on the other side. Figure 27 shows the water flow inside the membrane [30].

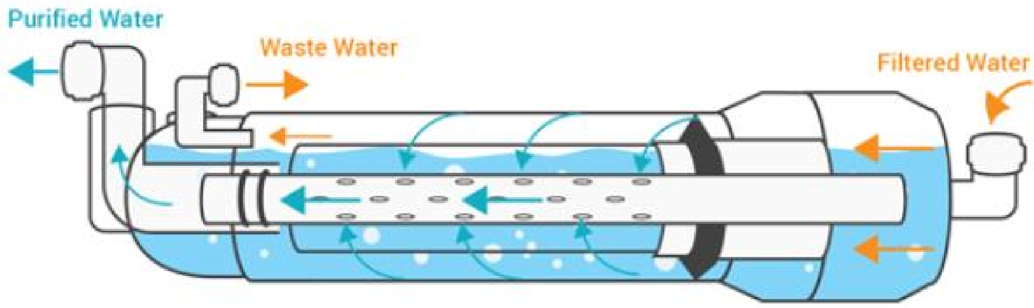

Figure 27: Water flow inside reverse osmosis membrane [30]

Therefore, a quantity of the feed water permeates through the membrane reducing strongly the water salt concentration to get the fresh water (purified water), and the remaining feed water becomes very concentrated brine (waste/dirty) water. It can be seen that the feed water flow is used by both the clean water and rejected water. To reduce this complex modelling the system is converted to complete hydraulic system. The system is modelled using a C-element that represent the water storage under pressure inside the membrane. The membrane is considered as a tank which has radius 0.025 meters with water density of 1000 kg/m^3. The area was calculated using equation (3) and used to calculate the value of capacitance using equation (4).

$$A = \pi . r^2 \quad (3)$$

$$C = \frac{A}{\rho . g} \quad (4)$$

Where A is the area in m^2, π is the constant with value of 3.142, r is the radius of the membrane, C is the capacitance value of the tank, ρ is the density of water and g is the acceleration due to gravity. Two R-elements are used to model the hydraulic membrane resistance on the clean water side and on dirty water side which depends highly on the membrane temperature and conductivity. To control the pressure of reject water, a non-linear valve is modelled using the R-element. The valve is modelled using the valve law equation (5) [31].

$$Q = \frac{P^2.\rho}{2.(C_d.A_0)^2} \quad \text{....(5)}$$

Where:

Q is the flow rate of the valve

P is the pressure across valve

ρ is the density of the water

C_d is the discharge coefficient of the valve

A_0 is the nominal area of the valve

The clean water pressure, hydraulic load losses and osmotic pressure are all modelled using the Se-element with its summation. In order to keep the dirty water at required pressure Se-element is also used to model that. The selected parameters for the model are shown in table 12. The generalized bond graph model of the system can be seen in figure 28.

Table 12: Reverse Osmosis System Parameters

Element	Description	Value	Unit
C	Membrane Water Storage	2.0e-07	m^3/bar
R	Clean water resistance	1.0	bar
R	Reject water resistance	0.0005	bar
R	Reject water valve	Eq. (7)	bar
Se	Clean water	5.0	bar
Se	Reject water	2.0	bar

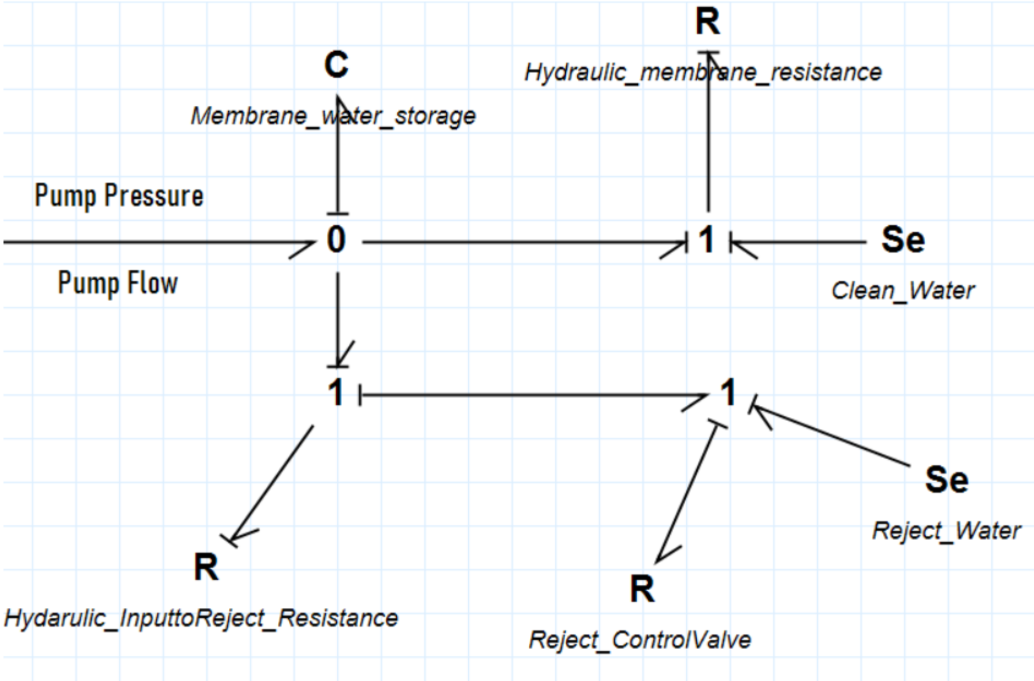

Figure 28: Bond Graph Model of Reverse Osmosis System

3.5.3 Complete system model

After combining all the individual systems, the complete bond graph is established as shown in figure. The multi-disciplinary systems (electrical, mechanical and hydraulic) are all combined with their effort to flow relationship as shown in figure 29.

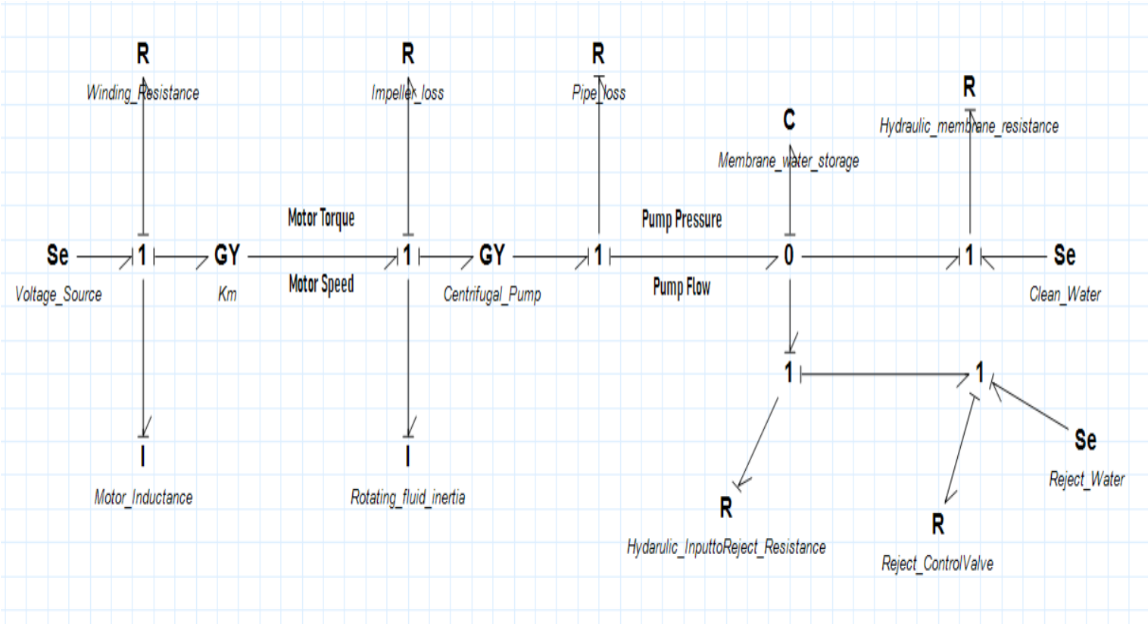

Figure 29: Complete System Bond Graph Model

3.6 Analysis and Results

The system was modelled in 20sim software and using the simulation feature, dynamic response was analyzed after which system reaches the steady state response. The normal response of the system was shown in the first part. The comparative results are shown later. In comparative parts the dark color line represents the system response based on changing the system parameter whereas the light color line represents the normal system response.

3.6.1 Normal System Dynamic Response

Figure 30 shows that the source voltage is stabilized at 24V DC and the current reaches the maximum value of 5 Ampere. Figure 31 shows that the motor torque is stabilized at 1.13Nm and the motor angular speed reaches a value of 1.25 rad/s. Figure 32 shows that at the start the pump pressure becomes negative and the flow rate is also disturbed but once the pump reaches its capacity a pressure of 0.15 bar is achieved and flow rate of 5 GPM is stabilized. Figure 33 and 34 shows that the pressure of clean and reject water is maintained at 5 bar and 2 bar where as the flow rate reaches a value of 5.2 GPM and 0.0004 GPM respectively which is optimum condition as there is minimum dirty water and the system is operating at the most efficient point.

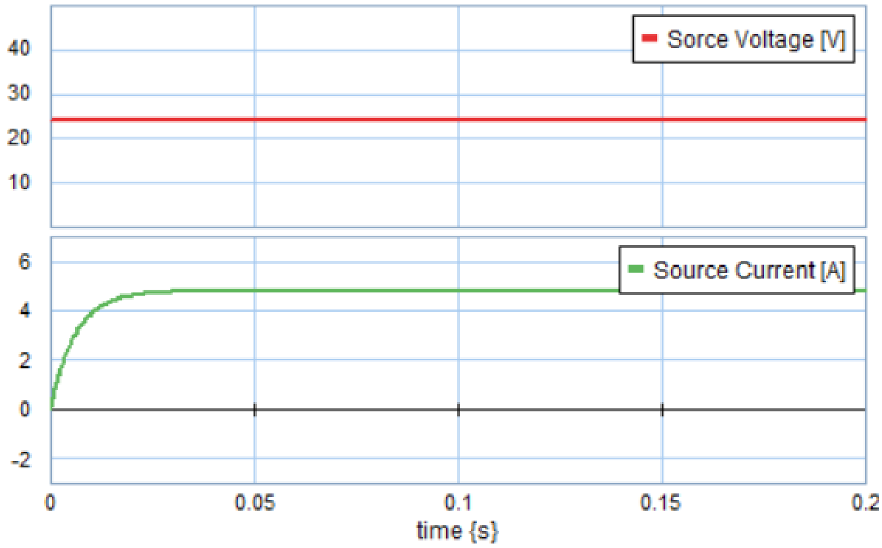

Figure 30: Source Voltage and Current Response

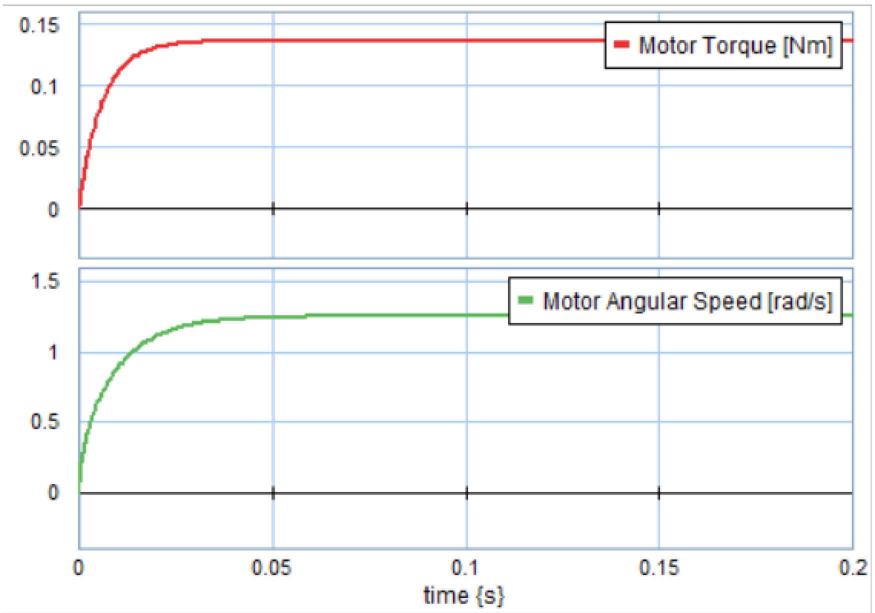

Figure 31: DC Motor Torque and Angular Speed Response

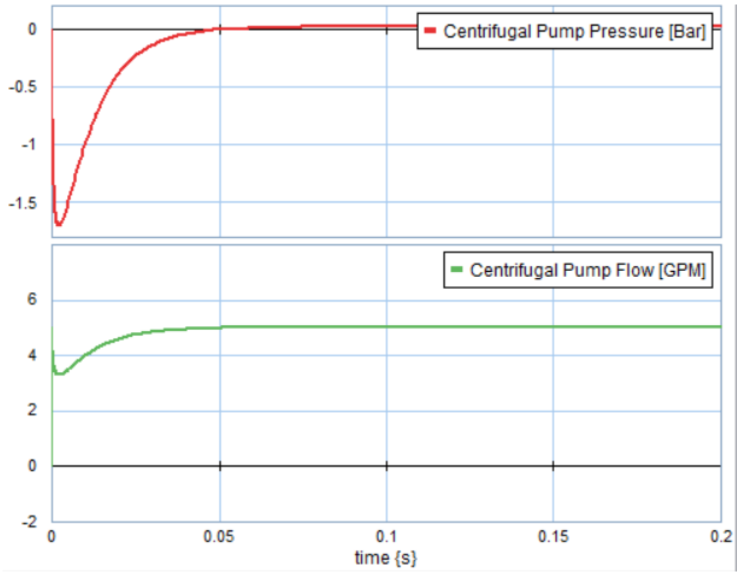

Figure 32: Centrifugal Pump Pressure and Flow rate Response

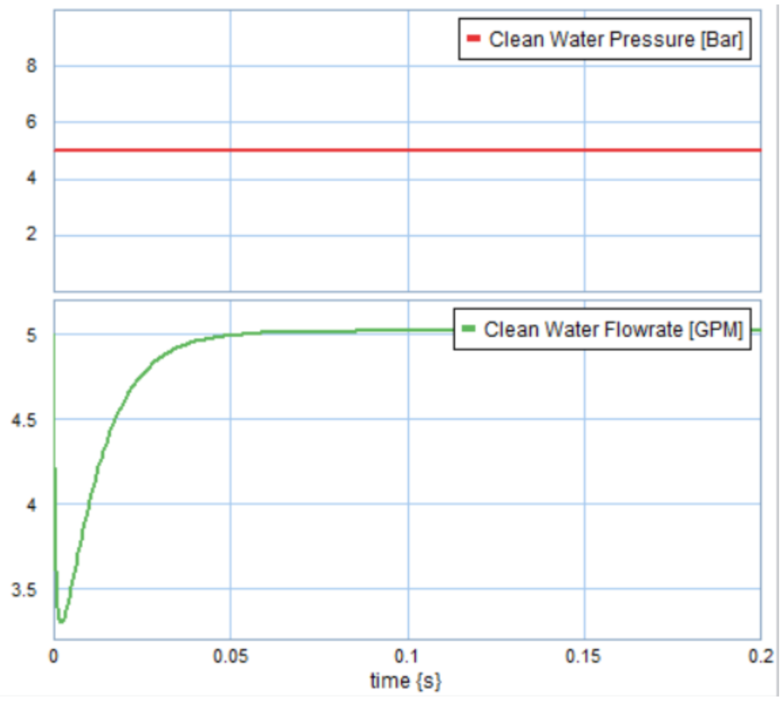

Figure 33: Clean Water Pressure and Flow rate Response

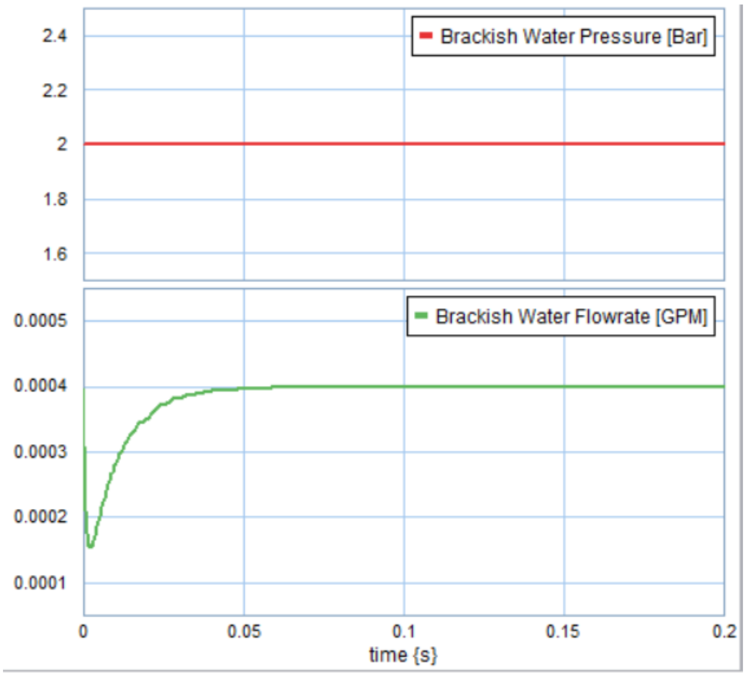

Figure 34: Dirty Water Pressure and Flow rate Response

3.6.2 Voltage reduced due to intermittent solar sources (comparison with normal response)

The voltage source is now reduced and dynamic response is analyzed compared to the actual dynamic response of the system. This happens because the state of charge of battery is not fixed and dependent on the charging and discharging of battery which in turn depends on the availability of solar energy and conversion efficiency of the photovoltaic system. Figure 35 showed that now the voltage is reduced to 20V DC and the current is also reduced. Figure 36 verifies that torque of motor is dependent on the voltage and it can be seen that torque is reduced whereas the angular speed of the motor is still the same.

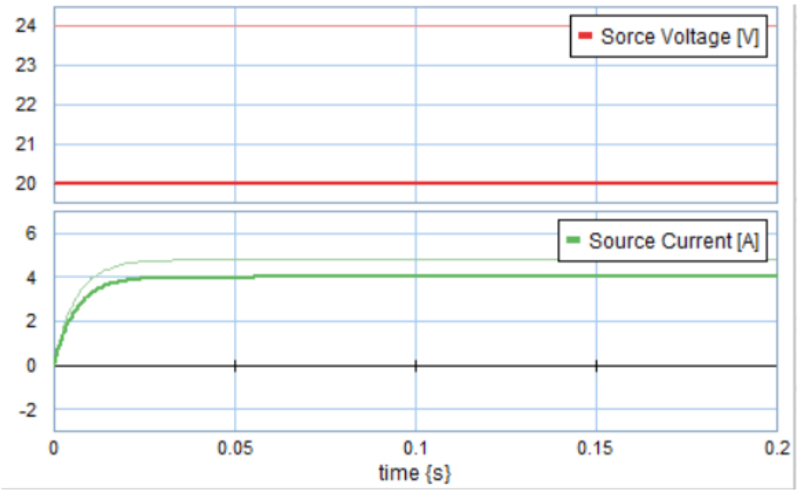

Figure 35: Source Voltage and Current Response

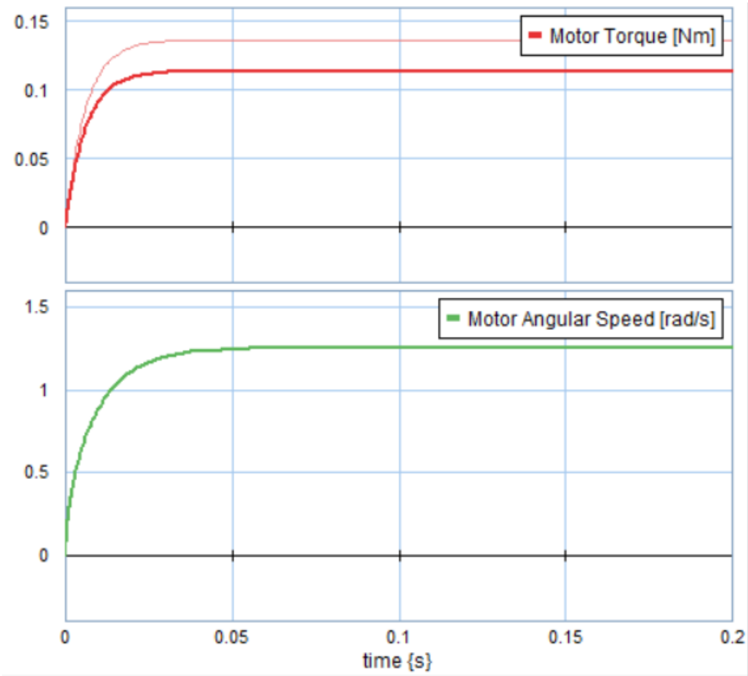

Figure 36: DC Motor Torque and Angular Speed Response

3.6.3 Increased clean water side hydraulic resistance (comparison with normal response)

The clean water side hydraulic resistance is increased and the dynamic responses are analyzed as shown in fig 37, 38, 39 and 40. It can be seen that the motor speed has drastically reduced because of the load on the impeller. Also the pump now has low negative pressure and reaches the stability quickly but due to high hydraulic resistance the flow rate of pump is now reduced significantly resulting in very low flow rate of clean water and same flow rate of dirty water.

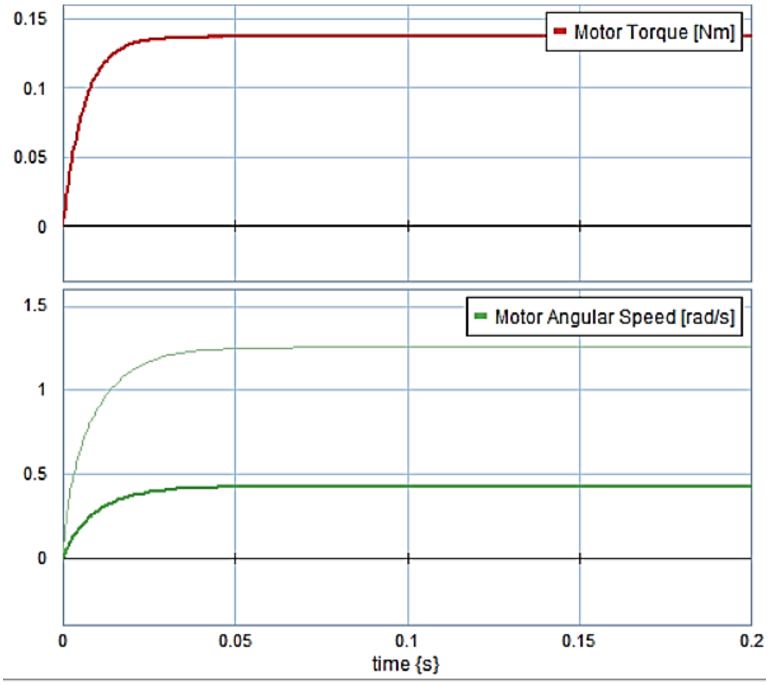

Figure 37: DC Motor Torque and Angular Speed Response

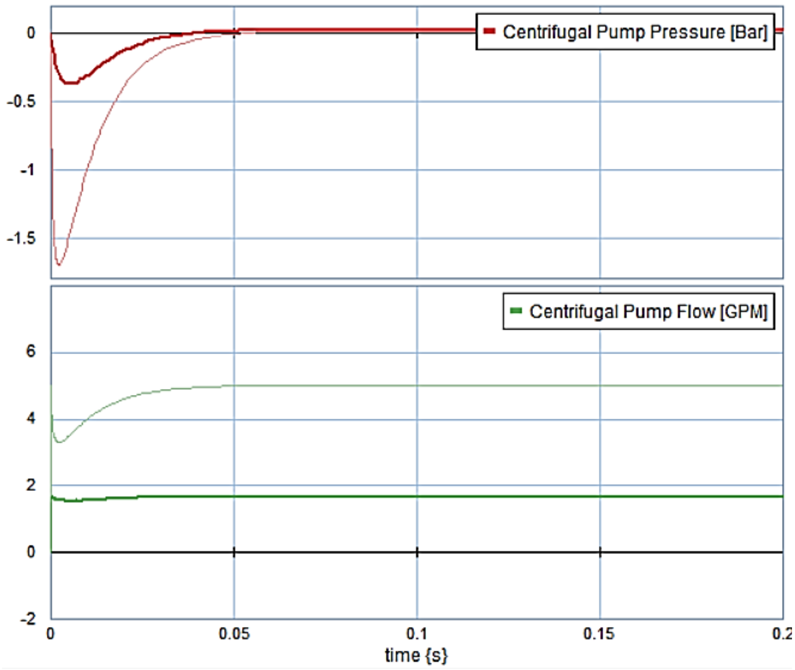

Figure 38: Centrifugal Pump Pressure and Flow rate Response

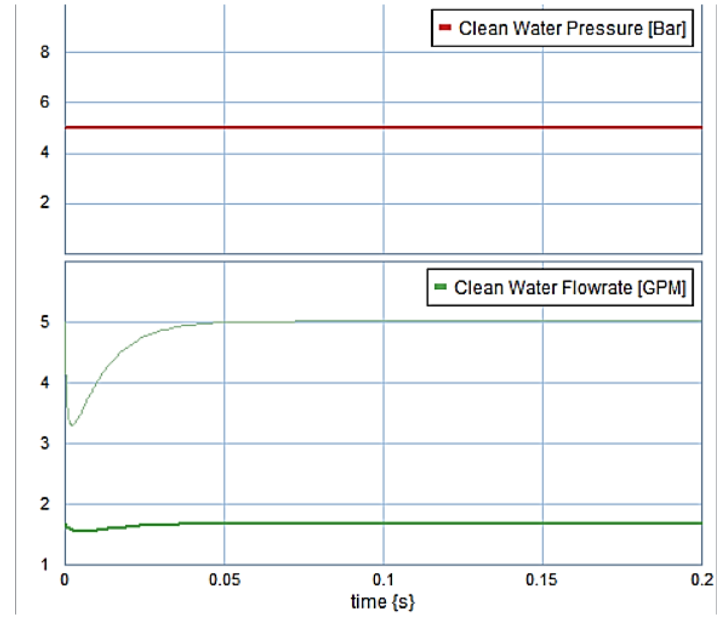

Figure 39: Clean Water Pressure and Flow rate Response

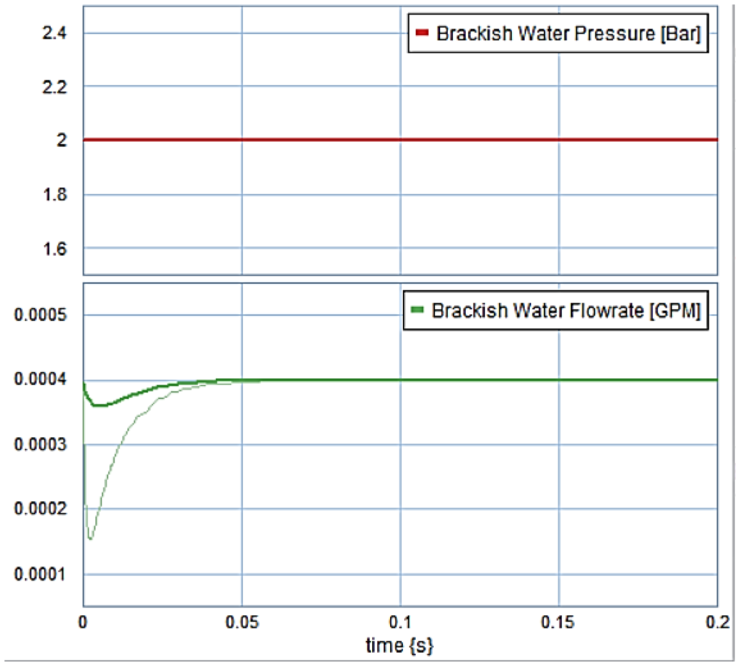

Figure 40: Dirty Water Pressure and Flow rate Response

3.7 Conclusion

Based on the results, it can be concluded that the system has transient and steady state response. The transient response is finished after a time period of 50 – 80 milli seconds. The paper uses mathematical models of multidisciplinary system and merge them as single model using bond graph language. Simulation is performed using the 20Sim software and the results concluded that if voltage source is decreased due to intermittent nature of renewable energy system the motor torque is also affected. Also when the hydraulic resistance of clean water side is increased the system becomes highly inefficient as all the water is thrown to the dirty side rather than being cleaned in reverse osmosis membrane. The practical understanding is that when the membrane is clogged with impurities the resistance to flow is increased resulting in poor performance of system which is visible from the modelling results. A differential pressure sensor can be used with alarm values to indicate an operator managing the system so that he can clean the membrane and efficiently run the system.

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CHAPTER 4: INSTRUMENTATION AND CONTROL DESIGN FOR A SOLAR POWERED REVERSE OSMOSIS DESALINATION SYSTEM FOR A COMMUNITY IN PAKISTAN

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A version of the manuscript in this chapter has been presented as a conference paper in the 2022 31st Annual Newfoundland Electrical and Computer Engineering Conference (NECEC), St. John's, Canada. As the primary author in this paper, Sheikh Usman carried out the research under the supervision of M. Tariq Iqbal as the co-author. The MEng candidate performed the literature review and was involved in system design, instrumentation system and control system design. Moreover, he prepared the first draft of the paper. The co-author supervised the research by actualizing the research ideas, reviewing and correcting the manuscript.

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Published Reference Link: https://research.library.mun.ca/15785/

Abstract

Accessibility of fresh water is the biggest challenge of today's world. In order to meet the increasing demand of clean water without impacting the environment renewable energy needs to be integrated with reverse osmosis (RO) system to provide a clean drinking water system. This paper provides system design which includes selection of renewable energy system, reverse osmosis system and control system that can be integrated together to form a complete clean drinking water system. This paper further provides an elaborative instrumentation system design system that will fulfill the needs of water for a community in Pakistan. Furthermore, control system strategy is discussed to ensure that all process parameters are measured that will enable the system to work at its required capacity. Lastly, the hardware prototype setup designed in the lab is discussed to measure process parameters and ensure the system is fulfilling the operational and control requirements.

Keywords

Solar Energy, Reverse Osmosis, Instrumentation Control System.

4.1. Introduction

Pakistan economy mostly relies on agriculture and around 22.2% of that contributes to its overall gross domestic product (GDP) [1]. In 1950s Pakistan has the water capacity of around 5000 m^3 per capita and it has decreased significantly now [2]. There is huge water crisis worldwide and countries are looking for different ways in order to extract water. Desalination of water is one of the solution available today for production of clean water but this process requires huge amount of energy which in turn is achieved by burning fossil fuels. Considering the excessively increasing requirement of water and saving the atmosphere at the same time renewable energy technology based reverse osmosis desalination system provides a good source of clean fresh water. Thankfully, Pakistan lies on the region of good solar irradiance ranging from 5–7 kWh per m^2 per day and sunshine hours of 1,500–3,000 per year [3] which can be used for solar powered reverse osmosis systems. The desalination process now is used worldwide and its utilization trend has shown an increase in the recent years [4]. The Solar powered reverse osmosis converts the brackish water to fresh water as the water passes through membranes and remove approximately 98% salt from it [5]. This paper focuses on providing a solution to a community located in Pakistan that has no access to clean water by selecting the separate systems available in the market on the basis of the community requirement. These systems can be broken down as electrical, mechanical and control system. Furthermore, the instrumentation design, control system strategy and hardware prototype is discussed.

4.2 Literature Review

In this section, several papers related to the photovoltaic-based reverse osmosis system are reviewed. Focus was given to papers in which instrumentation and control system work were applied. MIT research work showed how small solar powered system produced clean water for a village community in Mexico [6] and was enough for whole community. Another study was conducted in which analysis was done to understand the behavior of system according to the temperature of the solar panels. The study concluded that 10% more energy from the photovoltaic panels was generated when the system was cooled [7]. Another paper was reviewed in which elaborative instrumentation on just reverse osmosis system was discussed and concluded that performance of such system is highly depended on temperature and pH of the water [8]. Edward [9] study provides a new approach for reverse osmosis system instrumentation and control design by applying artificial intelligence based software technology in order to make the system robust and more efficient. Francisco [10] analyzed how the variation of renewable energy source can affect the output on desalination water production. His work includes the parameter of flow and pressure. Thomas [11] worked on reverse osmosis system without batteries. He further designed the instrumentation and data acquisition on LabView and analyzed the results of the system. Glueckstern [12] utilizes the microprocessor based programmable logic controller with active sensors to analyze the performance of on-line reverse osmosis system plant. It records all historical data for data analytics to further optimize plant performance in future. All these research approaches provided a great insight on how to design the system, select its instrumentation and finalize a robust control strategy.

4.3 System Description

The overall system will comprise of an electrical system which is based on the renewable energy technology powering up the main water desalination system which is based on reverse osmosis technology. The system will have important instrumentation and will provide that information to a centralized control system. The figure 41 below shows the complete block diagram of the system.

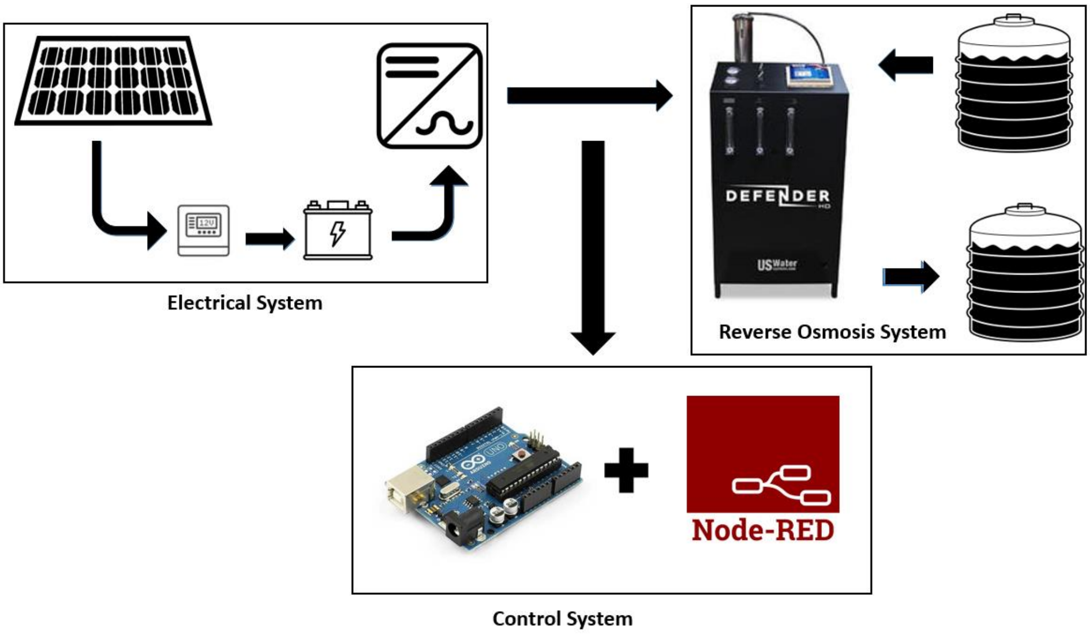

Figure 41: Block Diagram of Complete System

4.3.1 Electrical System

The electrical system will use the solar energy. The energy is converted and stored in the battery and used for running the motors of the system. The load of the system is 2.0 kW as the per the system design [13]. The table 13 below summarizes the important electrical parameters of the system design [13].

Table 13: Summary of Electrical Parameters [13]

Parameter	**Value**
PV Maximum Power	4.80 KW
Number of Batteries Required	20; 5 set of 4 strings
Inverter	4.30 KW
Renewable Energy Fraction	100%
PV Maximum Production	8418 KWH/Year
Battery Autonomy	44.6 hours
Battery Annual throughput	480 KWH/Year

Battery Nominal Capacity	27.9 KWH
Battery Usable Nominal Capacity	22.3 KWH
Inverter Mean Output	0.500 KW

4.3.2 Reverse Osmosis Desalination System

Reverse osmosis system converts unfiltered feed water to clean water when feed water is pressurized and passed through a membrane. The water flows through the membrane and more contaminants are accumulated to the more concentrated side of the membrane whereas clean drinking water is accumulated to less concentrated side of the membrane [14]. According to the water requirement of community which is 2964 liters of water per day [13] system available in market were reviewed and selected. The selected system is US water Defender system. The company offers various models but the model selected is DFWHRO-4000 in order to meet the requirements of the community. The figure 42 shows the physical hardware of the system [15]. The table 14 shows the important design parameters of the system [15].

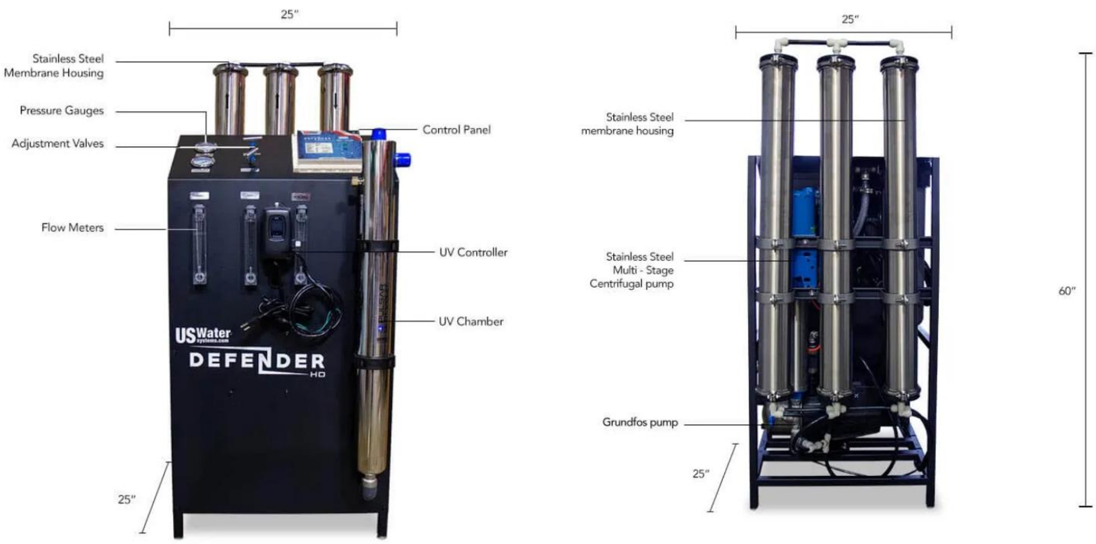

Figure 42: Physical Hardware of the Reverse Osmosis System [15]

Table 14: Important Design Parameter of the Reverse Osmosis System [15]

Parameter	**Description**

Configuration	Single Pass
Feed Water Source	City or Well Water
Standard Recovery Rate	48%
Recovery Rate with Concentrate Recycle	Up to 75%
Permeate Flow	2.78 GPM
Minimum Feed Flow	5.78 GPM
Membrane per Vessel	01
Membrane Quantity	02
Membrane Size	4” x 40”
Pump Type	Multi-Stage
Motor	1.10 KW
Pump RPM	3450 @ 60 Hz

4.3.3 Monitoring and Control System

Arduino embedded with Node Red is used as the overall control system for this water purification system. It is an open source platform to embed different sensors, develop control strategies and execute several operations. Arduino is only used for data acquisition from field sensors whereas the node red then takes care of all programming and control decisions. The biggest advantage of Arduino microcontroller is that it’s simple to use even for beginners and it has the capability to execute detailed control logics. The Arduino board available in the market and the Arduino IDE which is the programming software for performing the coding is used. On the other hand, Node red is an open source programming tool where you can develop codes and link the physical hardware by online coding. It contains a browser based programming platform where you can install several libraries to connect and communicate with the physical world [16]. The biggest advantage of using node red is that it uses easy to wire programming language where you can visualize the node flows and how the code sequence will execute. The figure 43 shows the programming environment of node red.

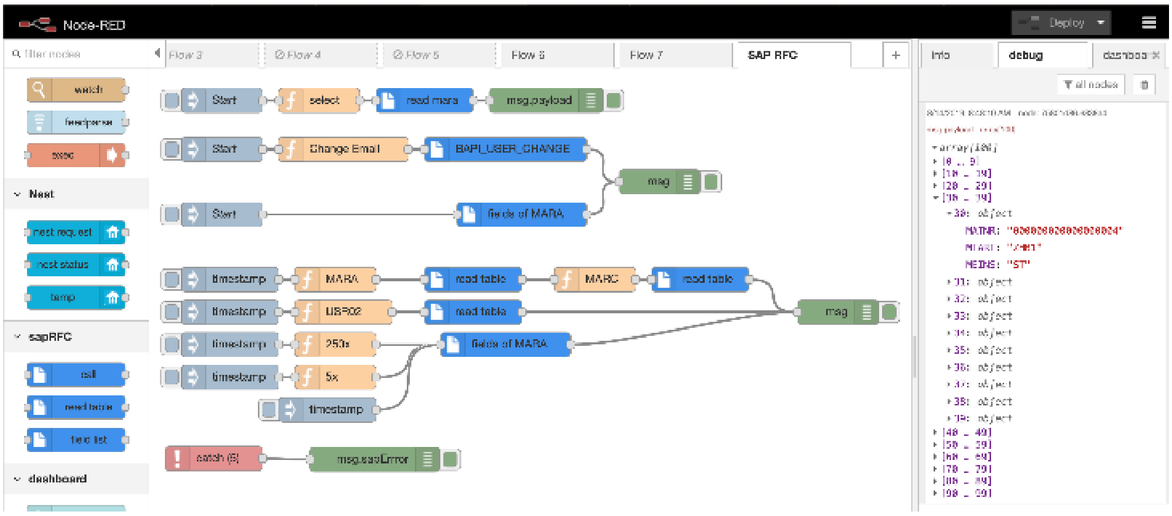

Figure 43: Browser based Programming Environment of Node Red

Lastly, in order to integrate the field devices with the online browser based control system of Node red, Firmata protocol is used for communication between Arduino (Input/Output Interface) and Node red (Control System). Firmata is a protocol for communicating with microcontrollers from a software based on computer. The protocol is loaded on the firmware of the microcontroller so that the microcontroller act as the support for that package [17]. The most commonly implemented versions of firmata is for Arduino and Spark.io. The figure 44 below shows the block diagram for the integration of field devices (Sensors) with Input/Output interface (Arduino) that can be communicated using firmata protocol with the control system (Node Red).

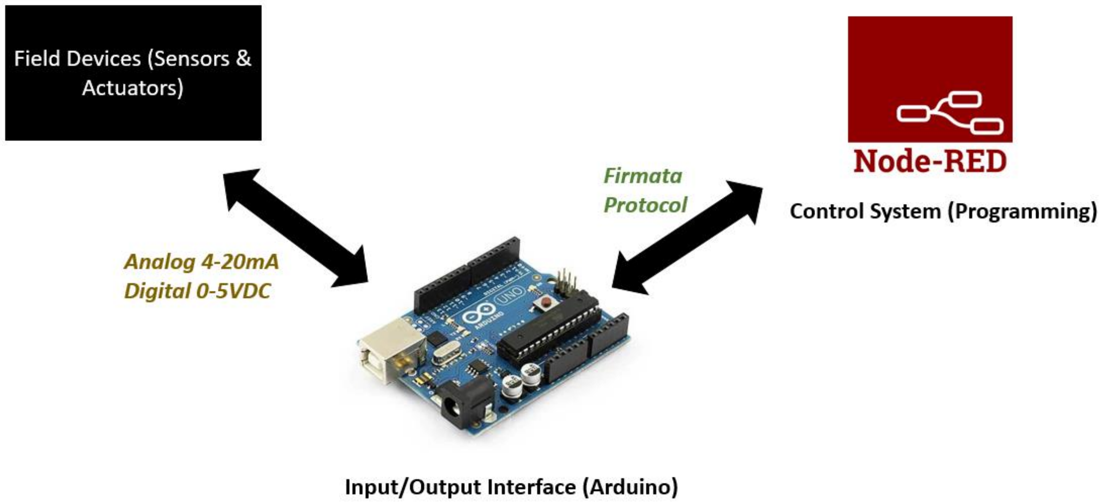

Figure 44: Block Diagram of Control and Monitoring System Implementation

4.4 Instrumentation System Design

4.4.1 Electrical System Instrumentation Design

The important parameter of the complete electrical system needs to be tracked in order to analyze the performance of the system. The instrumentation selected for the electrical system includes solar panel current and voltage measurement. Using the two parameters system can decide the available power at any point in the day.

4.4.2 Reverse Osmosis System Instrumentation Design

In order to ensure that the system is running smoothly several parameters need to be measured and tracked. The important parameter of the complete reverse osmosis system needs to be tracked includes feed water pressure, inlet temperature, pump status, pump pressure, outlet pressure after membranes and clean water tank level. Feed water pressure is measured to ensure that the system have the required inlet pressure available for smooth operation. The inlet temperature is measured to calculate the efficiency of the system because the conversion efficiency is dependent on the water temperature. The pump status is monitored for operational sequence and alerts. The pump pressure is measured to ensure pump is running at its full capacity and maximum efficiency is achieved. The outlet pressure and clean water tank level is measured to provide updates to the nearby community.

4.4.3 Complete Instrumentation and Control System Design

The overall process and instrument diagram will provide the snapshot of the complete instrumentation system. The figure 45 shows the complete system process and instrument diagram with all sensing points and control actuators.

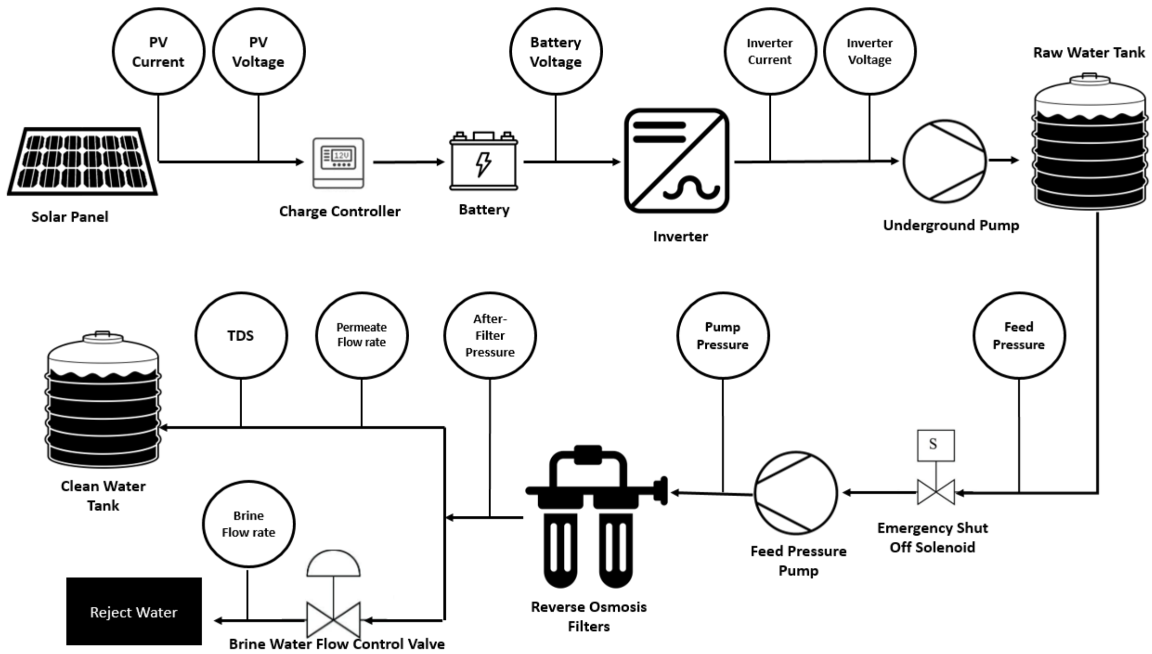

Figure 45: Complete System Process and Instrument flow Diagram

4.5 Monitoring and Control System Design

In order to ensure that the overall system works according to the operational requirement control system strategy needs to be implemented. The complete control strategy is elaborated further and three major control loops are explained.

4.5.1 Energy Monitoring Loop

The energy control loop works by taking solar voltage, solar current and battery voltage as the inputs. The system alerts the user about the available power to run the system and generates alerts for low solar power and low battery power. It can shut downs the system when the battery voltage drops down the set point level. The figure 46 shows the block diagram for energy control loop operation.

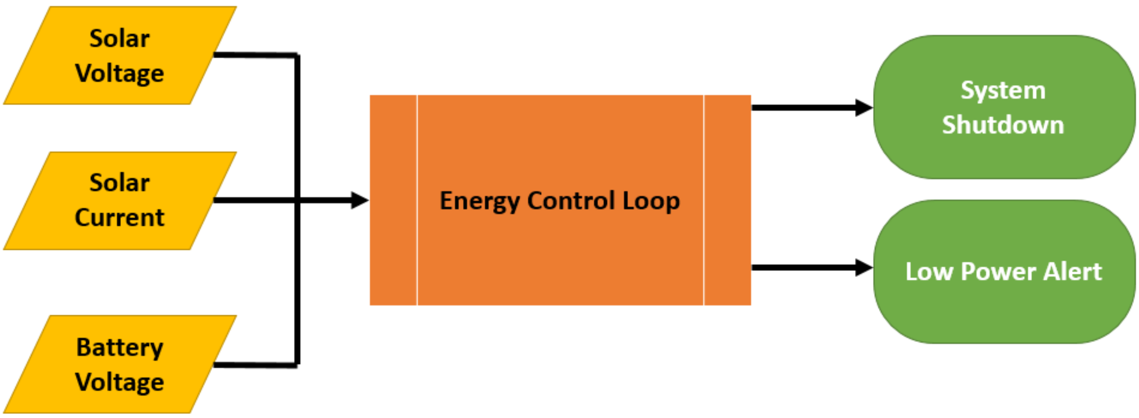

Figure 46: Energy Control Loop

4.5.2 Pressure Monitoring Loop

The pressure control loop takes the feed pressure, pump pressure and outlet pressure as the inputs and alerts the user according to desired values. The system is shut down if the feed pressure is lower than the set point. The differential pressure between the pump pressure and outlet pressure is also calculated to alert the user about the condition of membrane and for its replacement. The figure 47 shows the block diagram for pressure control loop operation.

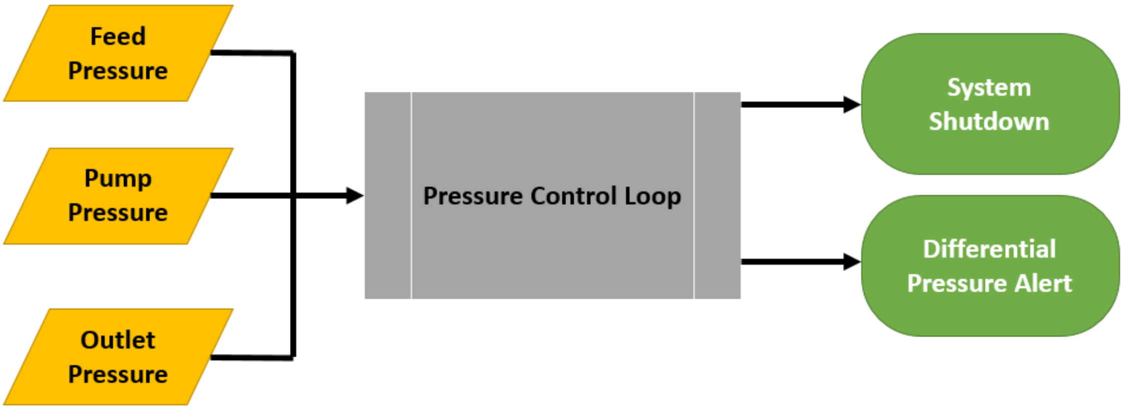

Figure 47: Pressure Control Loop

4.5.3 Product Monitoring Loop

The product control loop takes the input of the outlet water total dissolved solids (TDS), outlet flow rate and clean water tank level. The system is shut down if the TDS is higher than the set point. Alerts are provided about the availability of water level in the tank and forecast is made on the future availability of water based on the outlet flow rate. The figure 48 shows the block diagram for energy control loop operation.

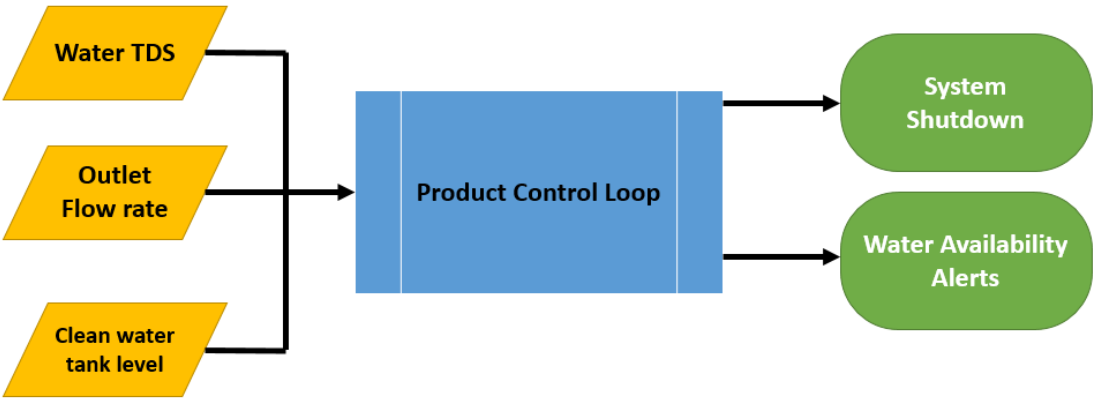

Figure 48: Product Control Loop

4.5.4 Complete Monitoring and Control Strategy

The overall control system strategy will provide the snapshot of the complete control system which comprises of three control loops elaborated earlier as energy, pressure and product control loops. The figure 49 shows the complete control system strategy.

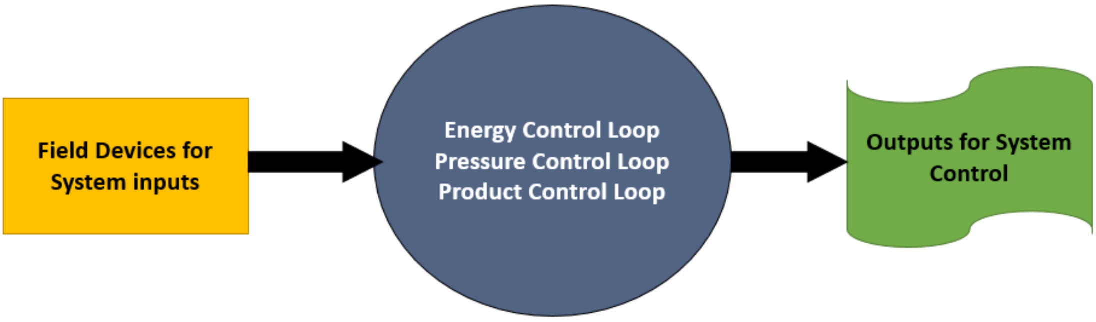

Figure 49: Complete Control Strategy

4.6 Hardware Implementation

In order to test the designed instrumentation and control system for the integrated solar powered based reverse osmosis system an experimental lab setup was created as shown in figure 50. The experimental lab setup has all major sensors required to control the system with Arduino microcontroller as the input and output interface. The elaborated control system was developed in the node red browser based control system and was integrated with field devices by firmata protocol. The system was found to operate as per the operational requirements.

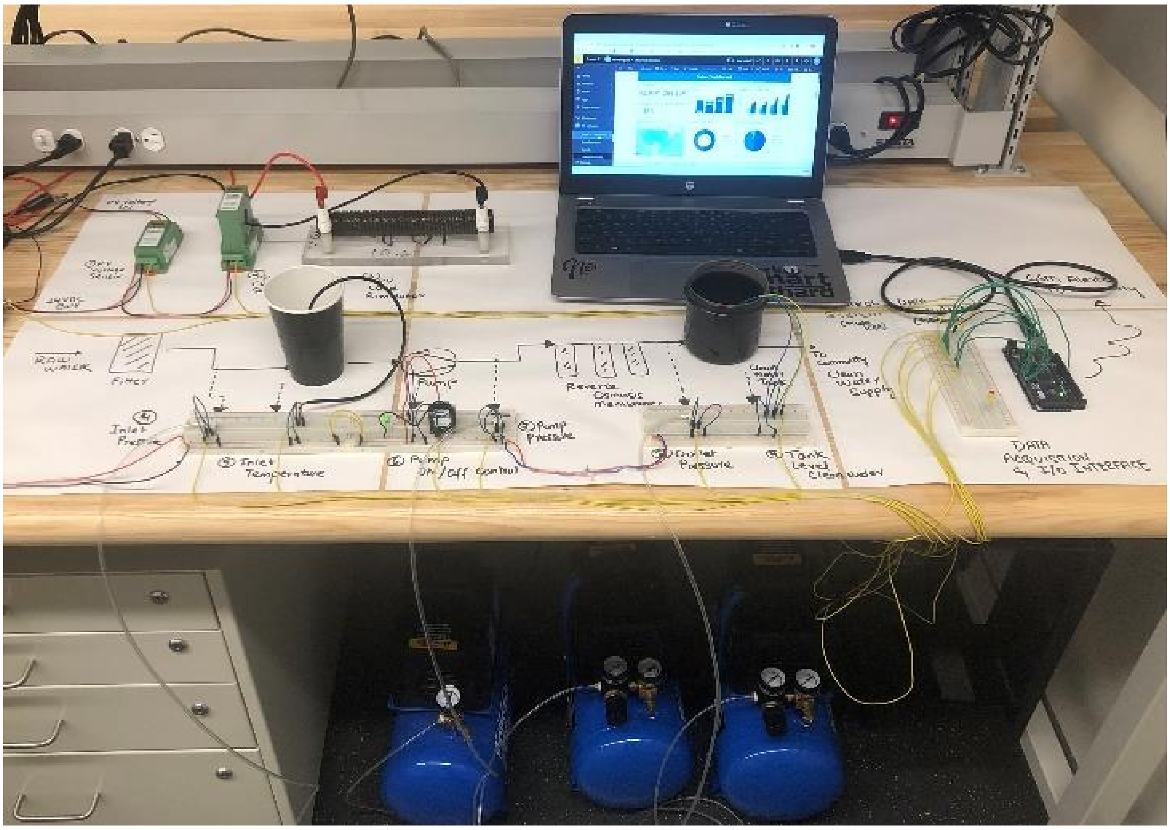

Figure 50: Experimental Laboratory Setup

4.7 Conclusion

The paper provides a unique system integration design by utilizing the Solar Energy for water availability (Reverse Osmosis Desalination System) using software based control system approach (Node Red) for a community in Pakistan. It further elaborates the important instrumentation required to ensure the system operation and monitoring of critical process parameters. Furthermore a detailed system design is elaborated using three control loops defined as energy, pressure and product. Lastly an experimental laboratory setup was created to verify the operation and monitoring of the system to ensure its stability.

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CHAPTER 5: DESIGN AND IMPLEMENTATION OF AN OPEN-SOURCE, INTERNET-OF-THINGS BASED SCADA SYSTEM FOR A COMMUNITY SOLAR POWERED REVERSE OSMOSIS DESALINATION SYSTEM

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A version of the manuscript in this chapter has been published in the MDPI Sensors Journal Special Edition 2022. As the primary author in this paper, Sheikh Usman carried out the research under the supervision of M. Jabbar Aziz Baig and M. Tariq Iqbal as the co-author. The MEng candidate performed the literature review and was involved in low cost, open-source, secured SCADA and alert system design and hardware prototype implementation. Moreover, he prepared the first draft of the paper. The co-author supervised the research by actualizing the research ideas, reviewing and correcting the manuscript.

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Abstract

Design and implementation of an open-source, internet-of-things (IOT) based supervisory control and data acquisition (SCADA) system for a community solar powered reverse osmosis is presented in this paper. A typical SCADA system available on the market is proprietary and has a high initial and maintenance cost. Aside from that, there is no SCADA system with alert system available to give users updates and status information concerning the system. The objective of this study is to develop a comprehensive design that takes advantage of an open-source SCADA system in order to address the world's most pressing problem, access to clean water. Designed reverse Osmosis system also uses renewable energy-based power sources. In this system, all data is stored and analyzed locally, which ensures the data is secure and allows the user to make data-driven decisions based on the collected data. Among the main components of this system are the field instrument devices (FIDs), the remote terminal unit (RTU), the main terminal units (MTUs), the web-based programming software and the data analytics software. The Node-Red programming and dashboard tool, Grafana for data analytics and InfluxDB for database management runs on the main terminal unit having Debian operating system. Data is transmitted from the FIDs to the RTU, which then redirects it to the MTU via serial communication. Node-Red displays the data processed by the MTU on its dashboard. As well as, the data is stored locally on the MTU and is displayed by means of Grafana, which is also installed on the same MTU. Through the Node-Red dashboard, the system is controlled, and notifications are sent to the community.

Keywords

SCADA, Node-Red, Internet-of-Things, Reverse Osmosis, Grafana, Solar Energy

5.1. Introduction

A supervisory control and data acquisition system (SCADA) integrates software and hardware to enable monitoring and control of any industrial process through sensors and control algorithms [1]. SCADA enables process to be better controlled and decisions can be made based on data analytics. In SCADA, sensors feed data to control systems through hardware components. The control system is used to process all the data and display it using a Human Machine Interface (HMI). A SCADA can record all events in a database. Additionally, the system includes a reporting system to ensure that alerts and status messages are delivered to users. A SCADA system minimizes downtime, increase system availability, and allows organizations to make more informed decisions with less effort. Among the most critical components of a SCADA system is a programmable logic controller (PLC) or remote terminal unit (RTU). During operation, the PLC or RTU communicates with the centralized computer, which contains SCADA software attached to a database containing historical data information. Field devices provide data to the PLC or RTU which process the data to the SCADA software and implement important decisions [1, 2].

Approximately 70% of the earth's surface is covered with water, however only 3% of it is fresh water, the remainder being frozen glaciers or unusable. [3]. Around 1.1 billion people worldwide don’t have access to water and almost 2.7 billion don’t have water availability for at least one month in a year [3]. One of the biggest challenges that the world is facing is huge water crisis worldwide and countries are looking for different ways in order to extract water. Desalination of water is one of the solution available today for production of clean water, but this process requires huge amount of energy which in turn is achieved by burning fossil fuels. This contributes to global warming which is another biggest concern. Considering the excessively increasing requirement of water various renewable energy technology based reverse osmosis desalination system can provide a good source of clean fresh water. The Solar powered reverse osmosis converts the brackish water to fresh water as the water passes through membranes and remove approximately 98% salt from it [4]. The complete system will be powered by the photovoltaic (PV) panels that convert solar energy to the form of electrical energy. The electrical energy then is further utilized to power the reverse osmosis-based desalination system. Therefore, after completing the sizing [5] and dynamic modelling using the bond graph method of the system [6], SCADA system is designed for the real-time monitoring that enables local data logging embedded with global system for mobile communication (GSM) based short message service (SMS) alerts system. The SMS alert system will provide all live updates to the community about the status of the system.

Throughout this article, information is organized on the following way. Section 2 of the paper presents a detailed literature review. Section 3 of this article describes the entire system in detail, while Section 4 describes the components in detail. This article presents a description of the implementation methodology in section 5 and discusses the results of the implementation, as well as a design and discussion of the prototype in section 6. In Section 7 discussion is carried out where as the article is concluded in Section 8.

5.2. Literature Review

Through the course of this study, a comprehensive literature review was conducted, and a number of useful sources were identified and are outlined in this section. In [7] a detailed SCADA/HMI was developed for a multistage desalination system. The desalination system consists of eight cycles with many field sensors. The control system used was Siemens S7 - 3000 PLC with WINCC SCADA software which is fee-based system. The authors highlighted the idea of having a redundant system in case the main server is failed. The authors further concluded that the multi-point interface (MPI) is used as the main control loop because it is faster than Ethernet connection. In [8] authors have developed a personal computer (PC) based SCADA system for reverse osmosis desalination plants. The basic setup includes LabView

Software which is fee based with a data acquisition card to build the complete system. This system provides a low-cost SCADA system where basic functionality and control for small systems can be achieved. The authors of [9] worked on the monitoring and control of multi-stage flash brine recirculation (MSF-BR) combined with the reverse osmosis (RO) system. The system is elaborated in detailed, and its process control and instrumentation strategy are explained. They used Rockwell Automation product called FactoryTalk View Site Edition (SE) which is widely used software in the field of automation and control. The whole process control system was developed and controlled by the user-friendly HMI. In [10], the authors have elaborated about controlling process by using distributed control system (DCS), SCADA and PLC. The research contribution educates the reader about the working of DCS system with focus on developing control system for the reverse osmosis plant. The authors have developed an Internal Model Based Control (IMC) strategy to control the overall plant. The control strategy works on the multivariable control system for making the system control robust. Further for the database management, a text file is generated that keeps the record for all the alarms and sequence of events. The data history is also saved in the database as a text file. In [11] authors have designed and implemented SCADA for the huge desalination process where five lines of desalination are running parallel to four coastal wells and two end of line pumps of permeated water obtained are merged as a single plant. The MOVICON 11.5 SCADA system is used as the software platform for the design. The work further explains the control system for each operation followed by the centralized control and monitoring system. Each process has its own algorithms for control system and all individual algorithms were synchronized to achieve the maximum efficiency. Extensive data set is available for generation of alarms, reports and creating historical database. In addition, the paper provides trends and monitoring of the system using the historian data to enable data-driven decision making. All of the above listed examples use proprietary software and hardware's.

A very large costal desalination plant of California was retrofitted and the authors [12] explained the work. Due to the increasing cost of electricity in California the management decided to operate the plant just on weekends because the cost of electricity is lower on weekends resulting in less utilization of the plant compared to its full design potential. The retrofit project executed increased the operational efficiency of the system which resulted in running the plant for all days in the week. Moreover, the plant's operating costs were reduced by 64%, which was a significant achievement. The retrofit work includes modification of mechanical systems as well as elaborating future improvement plan of including SCADA system for monitoring and predictive analysis. The research work further elaborated the modular expansion of the system with secured wireless SCADA network that will allow secure control and communication. In [13, 14] authors have developed a control system for the reverse osmosis desalination process using PC based SCADA system. The authors [13] majorly focuses on developing the fault tolerant based control system strategy whereas the [14] system focus on low-cost solutions with safety features. Detailed system architecture was discussed with using Adam 4000 modules for hardware and VisiDaq 3.1 for software integration. Each integration provides easy to program solution with full control. Another research [15], has elaborated a descriptive mathematical model for a large-scale multi-scale flash (MSF) desalination process. The input is passed through a series of signal processing steps including signal conditioning, filtering, steady state checks and limit value monitoring. Extensive mathematical modelling is carried out to ensure that the process is optimized. In order to ensure system robustness, a fail-safe dual redundant computer system configuration in hot standby mode is discussed with a robust SCADA system having a self-system backup capability in case of system failure. These are some examples where authors used commercial hardware and software with no consideration to the cost and energy needed for operation.

A study conducted at Massachusetts Institute of Technology demonstrated how a small solar powered system produced clean water for a village community in Mexico [16] and was enough for whole community. As part of another study, analysis was done to understand the behavior of system according to the temperature of the solar panels. The study concluded that 10% more energy from the photovoltaic panels was generated when the system was cooled [17]. Another paper was reviewed in which elaborative instrumentation on just reverse osmosis system was discussed and concluded that performance of such system is highly depended on temperature and pH of the water [18]. Edward Fredkin and Roger Banks in [19] provides a new approach for reverse osmosis system instrumentation and control design by applying artificial intelligence based software technology in order to make the system robust and more efficient. In [20], authors analyzed how the variation of renewable energy source can affect the output on desalination water production. This work includes the parameter of flow and pressure. The authors of [21] worked on reverse osmosis system without batteries. They further designed the instrumentation and data acquisition on LabView and analyzed the results of the system. Study utilizes the microprocessor based programmable logic controller with active sensors to analyze the performance of on-line reverse osmosis system plant [22].

There have been several approaches explored by researchers to ensure the instrumentation and control of desalination systems without providing real-time alerts to users. Others have designed SCADA systems with multiple servers, which has compromised the security of the system as data is stored remotely. Thus, a comprehensive design and implementation of an open-source, internet of things (IOT) based SCADA system is missing in the literature. In this paper our focus is to design an open-source, low cost SCADA system with the following features:

- With the latest SCADA architecture this study stands out particularly with respect to its use for reverse osmosis system.
- Designed system is configured on a local machine through Node-Red visual programming language that is accessible through the browser for easy control.
- The system incorporates local storage with restricted user authorization only.
- Intuitive dashboard and data analytics are provided with a Web-based real-time and

historian monitoring and control system.

- Maintains an alert system to inform the community the system status and updates.
- Designed system uses 100% open source technology.

5.3. System Description

The designed open source, internet of things-based SCADA system is depicted in figure 51. The system can be elaborated in two parts which includes electrical power system and water desalination system. In electrical power system, solar panels are used to charge the battery through the charge controller which ensures maximum power point is tracked. Full details of system design and dynamic modelling may be found in our earlier published work [5, 6]. This electrical power is then feed to inverter to run the electric motor. For the reverse osmosis desalination system, raw water is taken and passed through the high-pressure pump to achieve desired water pressure to enter the reverse osmosis desalination membrane. Membrane is the most important component in the reverse osmosis system as it has small pores that allow water molecules to pass through and stop contaminants. When water pass through the membrane, the dirty water is collected to the more concentrated side whereas the clean water is collected to the less concentrated side [23]. The clean water is then stored in a water tank to supply uninterrupted water to the community. In order to measure all the important parameters from the complete system several sensors are used. For demonstration purposes Arduino Mega 2560 (Arduino, Somerville, MA, USA) microcontroller is used that act as the Remote Terminal Unit (RTU) for all input and output communications. The sensor data taken from the electrical system includes solar panel voltage and current whereas the inlet water pressure, inlet water temperature, pump pressure, outlet pressure and clean water tank level are measured for the reverse osmosis desalination system. The pressure pump control is also provided to ensure in case of any fault the pump is turned off. In the design configuration, a low-cost computer was used with raspberry Pi Software x86 (Raspberry Pi foundation, Cambridge, Uk) which includes a 32-bit Debian operating system with a kernel version of 5.10 was installed on the x86-64 bit processor. The computer has Intel i5, 4 core central processing unit (CPU) with 4 gigabytes of random-access memory. Inside the programming terminal, Node Red version 3.0.2, node.js version 16.16.0 with dashboard version 3.1.7 is installed for programming and HMI design. For the purpose of database, InfluxDB version 1.5.3 is installed on the computer for storing data locally. In order to have data visualization and analysis, Grafana version 7.4.5 is installed on the same programming terminal. The system was programmed to provide important alerts to the community using the GSM system.

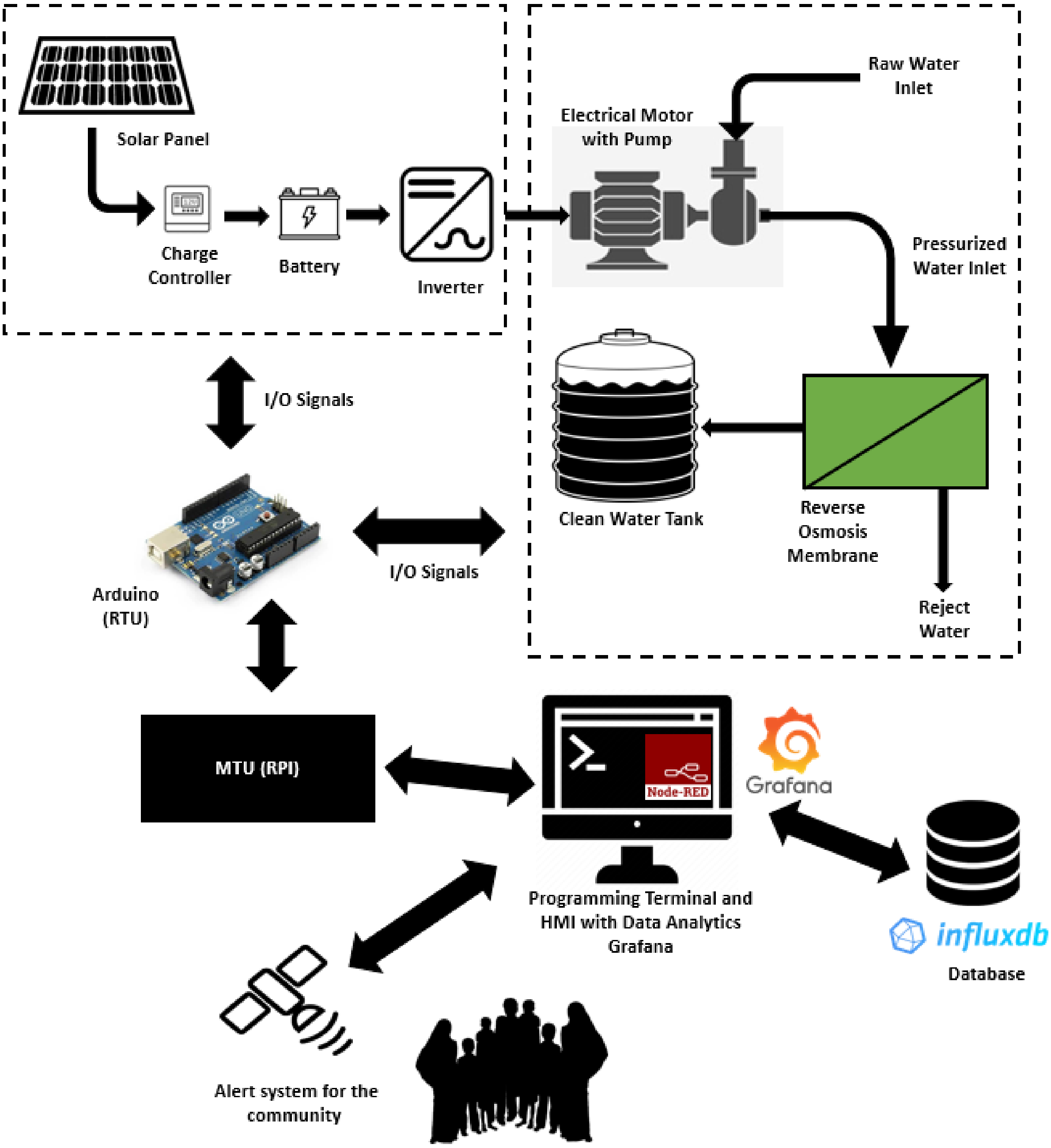

Figure 51: Proposed SCADA System for a Solar Powered Reverse Osmosis Desalination System Architecture

5.4. Components of the Designed System

As part of the system design all field sensors data is received by the RTU and sent to the Raspberry Pi - Node Red based Programming terminal (MTU). After that the Node Red based graphical user interface utilizes the data for displaying several parameters whereas control buttons and community notifications are also available. Further the data is stored into the local Influx DB database and used by Grafana for historical data analytics. The comprehensive detail of each component used in the design is described below.

5.4.1 Field Instruments Devices (FIDs)

Field Instrument devices are the highly important part of the system. The field instrument devices are capable of measuring what is occurring on the ground. The values are taken from the FIDs, feed to RTU and eventually send to open-source programming terminal (MTU). Based on the physical stimulus, measurements and actuation is divided into three sections in the designed system, which are stated below:

- Electrical System FIDs
- Reverse Osmosis Desalination System FIDs
- Actuators and Simulators FIDs

All the FIDs used in the system are summarized in Table 15 with their manufacturer, model and desired function.

Table 15: Sensors manufacturer, models and function

Sr.#	Manufacturer	Model	Function
1	CR Magnetics	CR5310	DC Voltage Transducer
2	CR Magnetics	CR5210	DC Current Transducer

3	TE Connectivity Measurements Specialties	4525-15AP	Inlet Pressure Transducer
4	Maxim	DS18B20	Inlet Temperature Transducer
5	TE Connectivity Measurements Specialties	4525-15AP	Pump Pressure Transducer
6	TE Connectivity Measurements Specialties	4525-15AP	Outlet Pressure Transducer
7	SongHe	B07THDH7Y4	Clean Water Tank Level Transducer
8	Lychee Limited	06-061-024	Relay Module for Pump On/Off
9	Mastercraft	2 Gallon Air	Compressor for Inlet Pressure Simulation
10	Mastercraft	2 Gallon Air	Compressor for Pump

			Pressure Simulation
11	Mastercraft	2 Gallon Air	Compressor for Outlet Pressure Simulation

5.4.1.1 Electrical System FIDs

CR5310 and CR5210 are used as the DC voltage and current sensors respectively. The CR5310 sensor provide the output in the range of 0 – 5 V DC and is directly proportional to the input range of 0 – 600 V DC whereas the CR5210 sensor has the current input range of 200 A DC. These sensors have a very important feature of isolation from input side to the output side which will make sure that the RTU is not damaged in case of any over voltage or current situation. In order to operate both the sensors a working voltage of 24 V DC is required. The Figure 52 shows the wiring diagram of the sensor. The technical specifications for CR5310 and CR5210 are also summarized in table 16.

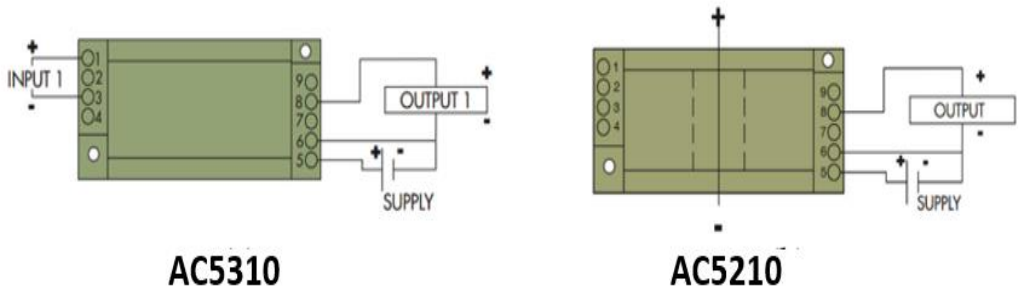

Figure 52: Current and voltage sensor wiring diagram [24, 25].

Table 16: Technical specification of current and voltage sensor [24, 25]

Sr.#	Specification	Value	Units
1	Accuracy	1.0	%
2	Linearity	10 to 100	% FS
3	Thermal Drift	500	PPM/C
4	Operating Temperature	0 to 50	C
5	Response Time	250	ms
6	Supply Voltage	24	V DC
7	Supply Current	35	mA

5.4.1.2 Reverse Osmosis System FIDs

Inlet pressure, pump pressure and outlet pressure are all measured by the same type of transducer. The TE Connectivity Measurements Specialties transducer serves as the single solution for all pressure measurements. The transducer is a small PCB mounted sensor based on the latest CMOS sensor conditioning circuitry to create a low cost high performance sensor. The sensor is an 8 pin device with pressure measurement port on top of it. The figure 53 shows the internal block diagram of the sensor whereas the figure 54 shows the connection diagram of the sensor.

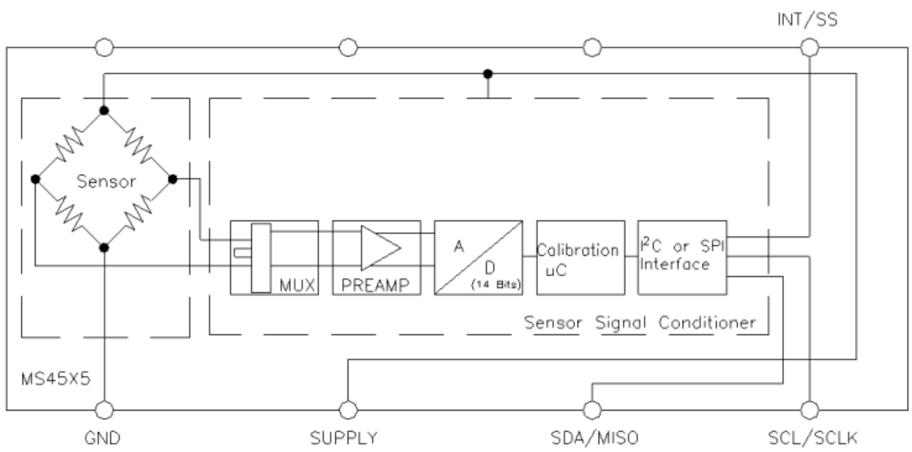

Figure 53: Pressure sensor internal block diagram [26].

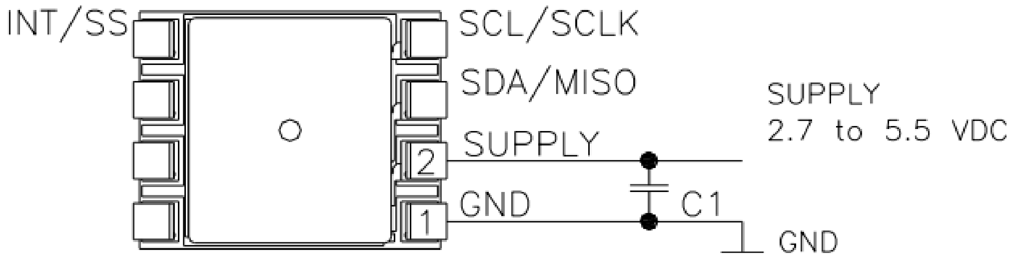

Figure 54: Pressure sensor connection diagram [26].

Further technical specifications of the sensor is summarized in table 17.

Table 17: Technical specification of pressure sensor [26]

Sr.#	**Specification**	**Value**	**Units**
1	Supply Voltage	2.7 to 5.5	V DC
2	Output Current	3	mA
3	Over Pressure	300	Psi
4	Accuracy	-0.25 to 0.25	% of Span
5	Operating Temperature	-25 to 105	C
6	Response Time	0.5	ms

Inlet temperature is measured using the Maxim DS18B20 sensor which is a one wire 12 bit temperature sensor. The sensor can be powered by 3 to 5 V DC and can measure any temperature between -55 C to 125 C. The sensor has a water proof packing making it super useful to use in wet conditions and in water applications. The figure 55 shows the physical and connection diagram for the sensor.

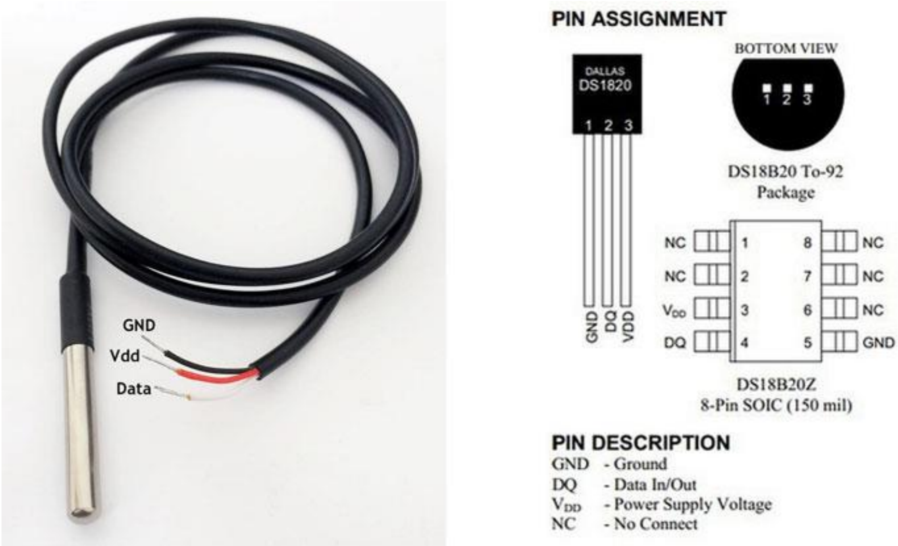

Figure 55: Temperature sensor physical and connection diagram [27].

Further technical specifications of the sensor is summarized in table 18.

Table 18: Technical specification of temperature sensor [27]

Sr.#	**Specification**	**Value**	**Units**
1	Supply Voltage	3.0 to 5.5	V DC
2	Thermometer Error	+/- 2	C
3	Standby Current	750	nA
4	Active Current	1	mA

Clean water tank level is measured using the water sensor module by SongHe. The sensor is easy to integrate, compact, lightweight and has traces of copper to detect the level of water. This sensor works by having a series of exposed traces connected to ground and interlaced between grounded traces and the sensor traces. The figure 56 shows the connection diagram for the sensor.

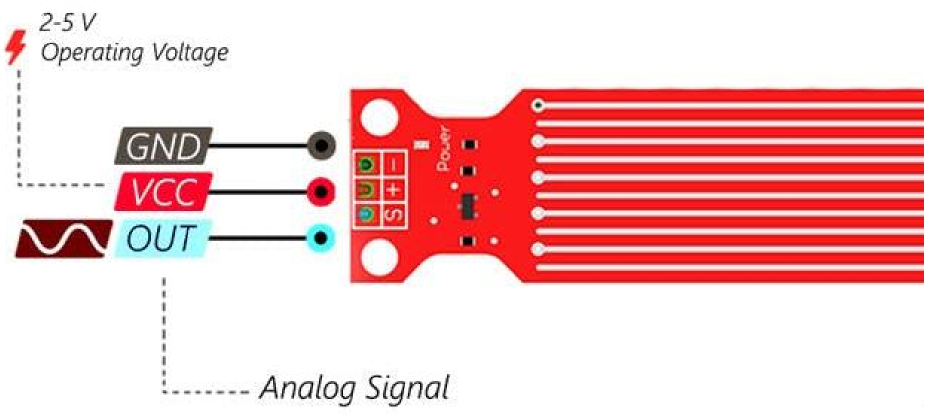

Figure 56: Water level sensor physical and connection diagram [28].

Further technical specifications of the sensor is summarized in table 19.

Table 19: Technical specification of water level sensor [28]

Sr.#	Specification	Value	Units
1	Operating Voltage	3.0 to 5.5	V DC
2	Working Current	< 20	mA
3	Working Temperature	10 to 30	C
4	Output Voltage	0 to 4.2	V DC

5.4.1.3 Actuators and Simulators FIDs

The relay module (Lychee Limited 06-061-024) is used for the controlling of the main pump from the RTU. The RTU provide 0 V DC for off signal and 5 V DC for the on signal to the relay module which in turn will turn the pump on or off. The device has the capability to be used in normally open or normally closed configurations. The figure 57 shows the all components installed on the device.

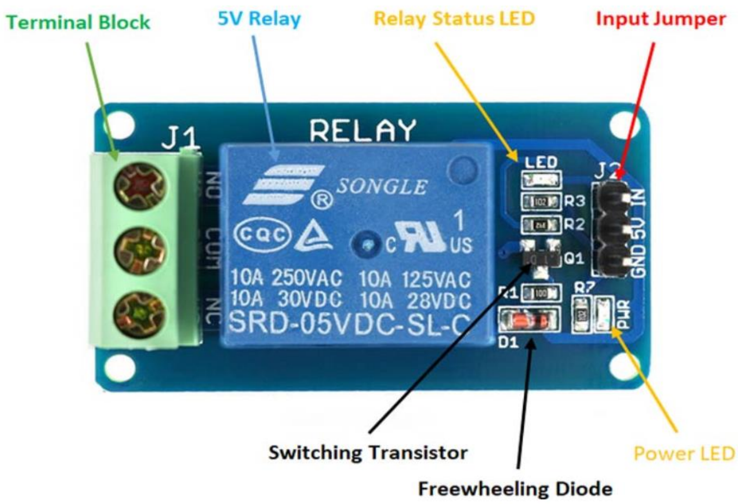

Figure 57: Relay module physical hardware and connection points [29]

Further technical specifications of the sensor is summarized in table 20.

Table 20: Relay module technical specifications [29]

Sr.#	Specification	Value	Units
1	Maximum Output	30 250	V DC V AC
2	Voltage Input	5	V DC
3	Operation Time	10	ms
4	Release Time	5	ms
5	Maximum On Off Switching	30	Operations/min
6	Operating Temperature	-25 to 70	C

The three master craft compressors are used to simulate the pressure values to the system. These compressors features an oil free design which ensures less maintenance. It is a single hand operation device with quick setup. The rubber feet's of the compressor allows more stabilize operation. The unit has local pressure gauges to check the pressure readings. The figure 58 shows the major parts of the compressor device which includes a pump for building up the pressure and discharging into the tank, an electric motor for the rotation of pump, a tank to store the compressed air and few pressure gauges to show the discharge and inlet pressures.

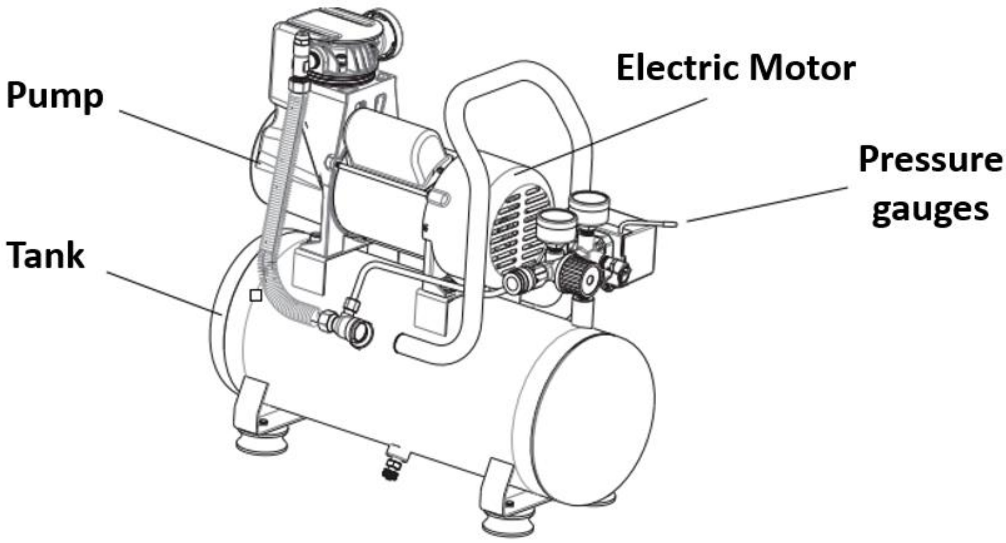

Figure 58: Major parts of compressor [30]

Further technical specifications of the sensor is summarized in table 21.

Table 21: Technical specification of compressor [30]

Sr.#	Specification	Value	Units
1	Power	1.0	Hp
2	Voltage Input	120	V AC
3	Frequency	60	Hz
4	Duty Cycle	50	%
5	Tank Size	3	U.S. Gallons
6	Pressure Range	0-125	PSI
7	Compressor Capacity	3 @ 40 PSI	CFM

		2 @ 90 PSI	

5.4.2 Remote Terminal Unit (Arduino Mega 2560)

The Arduino Mega 2560 microcontroller board is used as the RTU. It is based on the Atmega2560 controller chip. The board has 54 digital input and output pins out of which 14 pins can be used as pulse width modulation (PWM) output pins. Further the board has 16 analog inputs and 4 universal asynchronous receiver transmitter (UART) pins. The board consist of a 16 MHz crystal oscillator provided with a standard universal serial bus (USB) connection, a power jack for external power supply from the DC adapter, an in-circuit serial programming (ICSP) header and a reset button. The figure 59 shows the detailed pin configuration of the RTU. The SCADA system design presented in [31] uses Arduino mega Atmega2560-based microcontroller as a RTU.

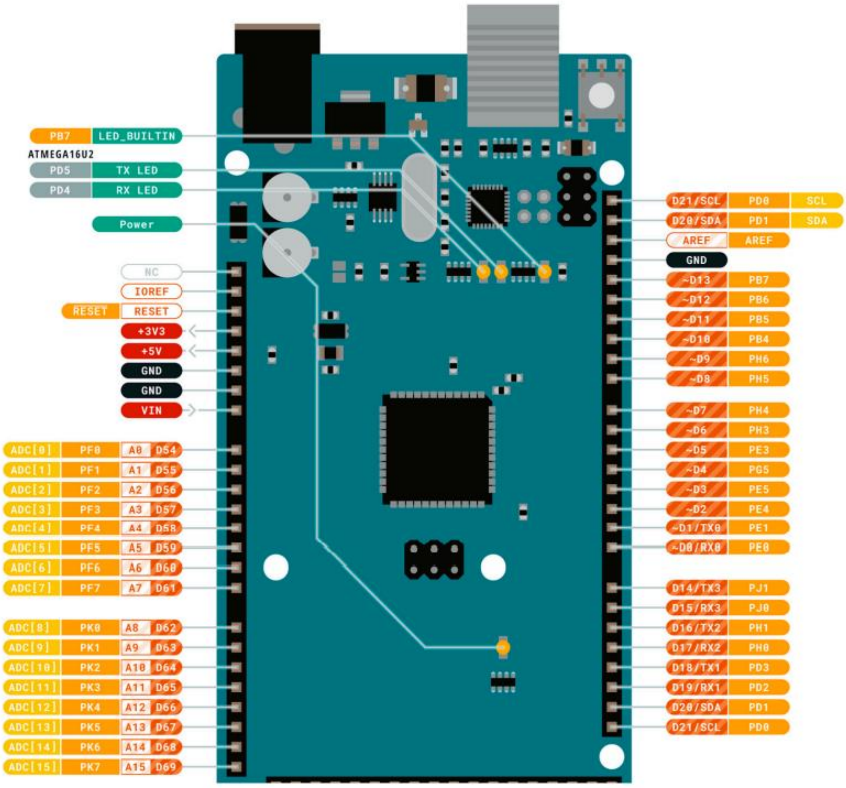

Figure 59: RTU Pin Configuration [32].

The table 22 summarizes the technical specifications of the Arduino Mega 2560 board.

Table 22: Technical specification of RTU [32]

Sr.#	Specification	Value	Units
1	Operating Voltage	5	V DC
2	Input Voltage (Recommended)	7-12	V DC
3	Input Voltage (Limits)	6-20	V DC
4	Digital I/O	54	Pins
5	Analog Input	16	Pins
6	Current Per I/O Pin	40	mA
7	Flash Memory	256	KB

8	Static Random Access Memory	8	KB
9	Electrically Erasable Programmable Read-Only Memory	4	KB
10	Clock Speed	16	MHz

The Arduino Mega is programmed using the Arduino compiler Integrated Development Environment (IDE). The IDE is a versatile editor where programmer can install different libraries, make own programs and debug them to check for errors. The code written in IDE is called sketches. Arduino codes are written in C++ language with an addition of special methods and functions. The IDE has a serial monitor option where programmer can interact with the board for real-time monitoring and debugging. The serial plotter is another important feature of the IDE where real-time graphs of your serial data can be plotted and waveforms can be analyzed. The library structure of any sketch is a folder comprised of files with C++ Code (.cpp) and header files (.h). After you have coded your desired task in the IDE, you can compile the code to check for errors followed by upload the code to the Arduino mega 2560 board using standard USB serial connection and run it physically. The figure 60 shows the IDE and its major components.

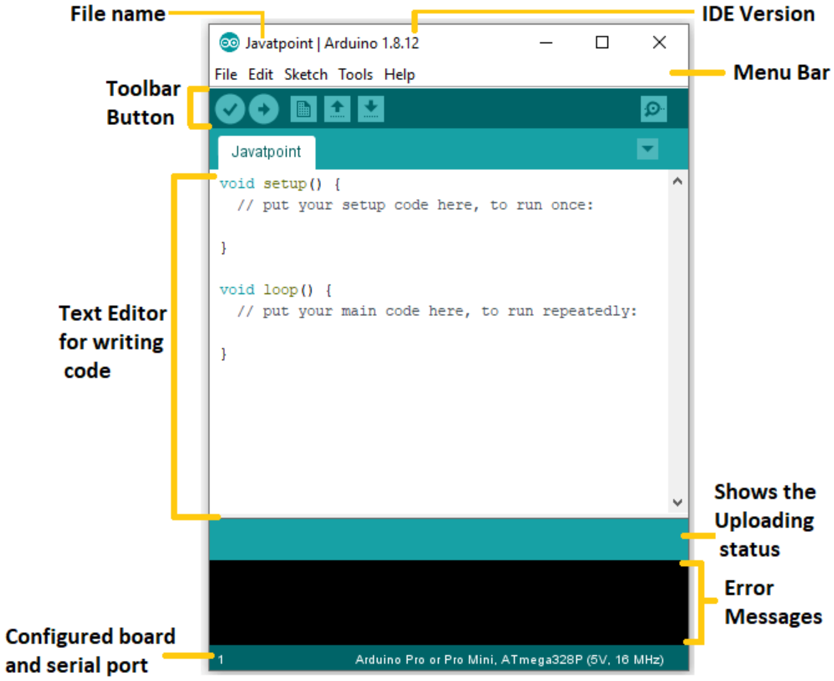

Figure 60: IDE major components [33].

5.4.3 Main Terminal Unit (MTU)

The main terminal unit is the back bone of this whole system. This unit is responsible for the data acquisition, programming, data visualization and data storage. In order to understand this unit it can be divided into two categories which includes hardware and software. The details of both categories are further explained in below sub sections.

5.4.3.1 Hardware (Physical Device)

An old MacBook Air (13-inch, mid 2012) is used as the main hardware for the main terminal Unit. The unit has 128 GB of flash storage and has 1.8 GHz dual core Intel Core i5 processor. The unit has 4GB of RAM, have an Intel HD Graphics 4000 Card with 1400x900 screen ratio for quality display. Further, the unit has a SD card slot, 2 USB 3.0 ports, thunderbolt, Magsafe 2.0 and a headphone port. The device has 802.11n Wi-Fi for wireless networking and is IEEE 802.11a/b/g compatible. The device has a compact 50 watt hour lithium polymer battery which can run the system in standby for 30 days and up to 7 hours when using wireless and web. The device operates on 100 – 240 V AC with a frequency range of 50 – 60 Hz inside an operating temperature range of 10 -35 C.

5.4.3.2 Software (Operating System, Applications and Database)

For the better understanding of each component with in the software package, the system can be divided into three parts which are stated below and explained further in subsections.

- Operating System
- Applications
- Database

5.4.3.2.1 Operating System

The Arduino Mega 2560 microcontroller board is used as the RTU. It is based on the Atmega2560 controller chip. The board has 54 digital input and output pins out of which 14 pins can be used as pulse width modulation (PWM) output pins. Further the board has 16 analog inputs and 4 universal asynchronous receiver transmitter (UART) pins. The board consist of a 16 MHz crystal oscillator provided with a standard universal serial bus (USB) connection, a power jack for external power supply from the DC adapter, an in-circuit serial programming (ICSP) header and a reset button. The figure 9 shows the detailed pin configuration of the RTU. The SCADA system design presented in [34] uses Arduino mega Atmega2560-based microcontroller as a RTU.

5.4.3.2.2 Applications

The application software's used for the development of the system includes Node-Red and Grafana. Node-Red is a flow-based programming tool, originally developed by IBM's emerging technology services team. This software is now part of the OpenJS foundation. Node red is an open-source programming tool where you can develop codes and link the physical hardware by online coding. It contains a browser-based programming platform where you can install several libraries to connect and communicate with the physical world. The major advantage of using node red is that it uses easy to wire programming language where you can visualize the node flows and how the code sequence will execute. In programming there are "black boxes" which you call as "nodes" that has well defined purpose and can be linked by wire programing for data flow. The programing embedded with the visual representation of the flows allows the software to be used by a variety of users. The web-based programming technology is based on Node.js for editing the flows. New nodes can be easily imported as the software has a huge community where developers can program their nodes and share with the rest of the community. The new flow then can be easily shared as java script object notation (JSON) files. The Node- Red version 3.0.2 with the node.js version 16.16.0 was used for the development of the system. The figure 61 shows the web-based programming environment of the software. In [35], the authors used Node-Red as a preferred IoT platform and stressed the importance of configuring the system on a local machine to ensure system security and privacy.

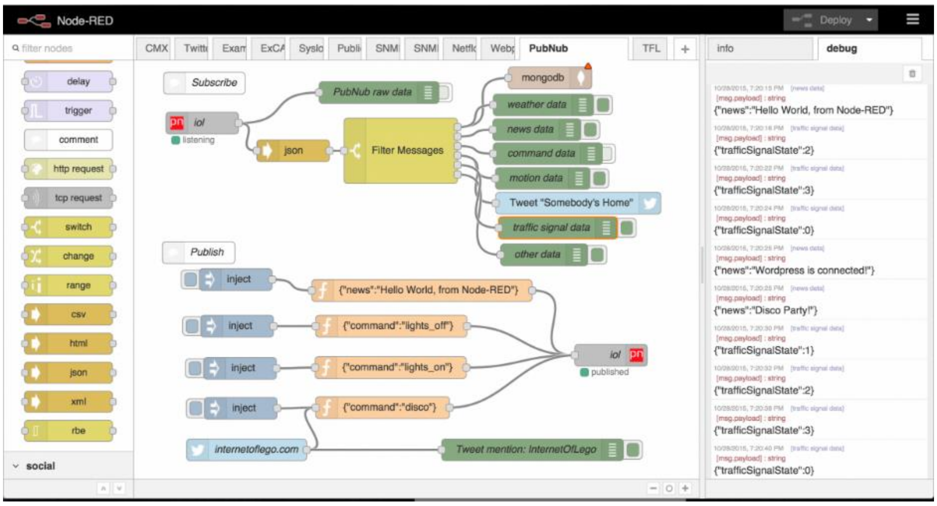

Figure 61: Node-Red web based flow programming environment [36].

One of the biggest node and feature of the Node-Red is the dashboard module. This allows a set a nodes to quickly create a live dashboard. User can add the following but not limited to widgets to the dashboard which includes:

a. *Audio out*

b. *Button*

c. *Charts*

d. Drop down Menus

e. Forms

f. Gauge

g. Notification

h. Slider

i. Switch

j. Text

The Node-Red dashboard version 3.1.7 was installed for the development of the system. The figure 62 shows a template of dashboard created in Node-Red.

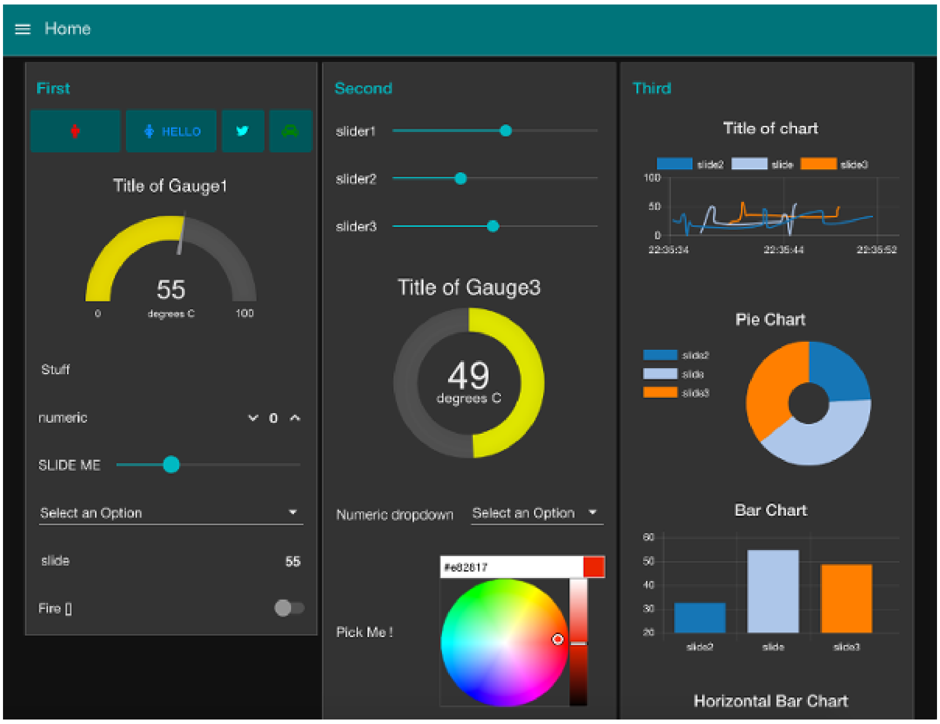

Figure 62: Node-Red Dashboard [37].

The other most important software application used for the development of the system is Grafana. Grafana is the open source analytics and monitoring solution for every database. The Grafana version 7.4.5 was used for the creation of this system. By the help of this software, user can write query, visualize, create alerts and understand data no matter where it's stored. It allows the user to create, explore and share all the data through beautiful, flexible dashboards which makes decisions easier and better. The software does not restrict your database type rather it can be from your kubernetes cluster, raspberry pi, different cloud services or even google sheets. With these capabilities user can understand all relevant data, create relationship between them and most importantly helps in identifying the root cause analysis for incidents as quickly as possible. The figure 63 shows the dashboard sample from Grafana.

Figure 63: Grafana data analytics dashboard sample [38].

5.4.3.2.3 Database

A database is an organized collection of structured information that is saved in the electronic form inside the storage of a computer system. The database is normally controlled by the by a management software that manages the saved information inside the storage location. InfluxDB version 1.5.3 is used as the database for this system. It provides smart data platform with everything to create time series database. It allows users to create multi-tenanted time series database, dashboard tools, data processing and monitoring. The extensive community groups allows developers to collaborate and build efficient ways to store, manage and retrieve data.

5.5 Implementation Methodology

In the implementation of the design, all the field instrument devices (FIDs) need to be connected to the remote terminal unit (RTU). The Table 23 below summarizes all the FIDs interconnection to the RTU pins.

Table 23: Field instrumentation devices interconnection

Sr.#	**Field Instrument Device**	**Signal type**	**Remote Terminal Unit Pin**
1	Solar Voltage Senor	Analogue	A0
2	Solar Current Sensor	Analogue	A1
3	Inlet Pressure	Analogue	A2
4	Inlet Temperature	Analogue	A3
5	Pump Pressure	Analogue	A4
6	Outlet Pressure	Analogue	A5
7	Clean Water Tank Level	Analogue	A6
8	Pump On/Off Control Relay	Digital	D6

The FIDs data coming to the RTU is send to the MTU using the serial communication between RTU and MTU. The RTU is programmed with the firmata protocol to make the communication easier and faster. Firmata is a protocol for communicating with microcontrollers from a software based on computer. The protocol is loaded on the firmware of the microcontroller so that the microcontroller act as the support for that package. The most commonly implemented versions of firmata is for Arduino and Spark.io. The firmata source code can be found as Appendix A. After the communication between the RTU and MTU is achieved using the firmata protocol, Node-Red programming was carried out. The Node-Red execution and programming is explained using the series of algorithms. The Algorithm 1 explains the field sensor data acquisition, display in Node-Red dashboard and storage in InfluxDB database. The Algorithm 2 elaborates the System operation whereas the Algorithm 3 outlines the alert system to the community. After the data acquisition is completed the data is stored in the InfluxDB database and later called by the Grafana for data analytics and visualization.

Algorithm 1: Field Sensor Data Acquisition, Storage and Display

Initialization;

1. Start Service Node-Red
2. Check Service Node-Red
3. If Running
    a. Open localhost:1880
    b. While Read and store data from pins A0, A1, A2, A3, A4, A5 and A6 using /dev/ttyACM0
        i. Send A0, A1, A3 and A6 to chart display
        ii. Send A2, A4 and A5 to gauge display
        iii. Send A0 to Solar Current tag database
        iv. Send A1 to Solar Voltage tag database
        v. Send A2 to Inlet Pressure tag database
        vi. Send A3 to Inlet Temperature tag database
        vii. Send A4 to Pump Pressure tag database
        viii. Send A5 to Outlet Pressure tag database
        ix. Send A6 to Tank level tag database
    c. End
4. Else Check System
5. End

Algorithm 2: System Operation

Initialization;

1. Start Service Node-Red
2. Check Service Node-Red
3. If Running
   a. Open localhost:1880/ui
   b. Click System On button
   c. Click Pump On button
4. Else
   a. Click Pump Off button
5. Else If
   a. Click System Off button
   b. Pump Off button Automatically activated by interlocking
6. End Check System
7. End

Algorithm 3: Alert System for Community

Initialization;

1. Start Service Node-Red

2. Check Service Node-Red
3. If Running
    a. Open localhost:1880/ui
    b. Set Clean Water Level Lower Set Point Variable
    c. Set Clean Water Level Upper Set Point Variable
    d. While Read Dashboard button status and Pin A6
        i. If A6 value is less than the Clean Water Level Lower Set Point
            1. Send Message to community: “Warning, The clean water level availability is very low”
        ii. End
        iii. If A6 value is greater than the Clean Water Level Upper Set Point
            1. Send Message to community: “Notification, The clean water level availability is very High”
        iv. End
        v. If System ON button is active
            1. Send Message to the community “System Status: The System has been turned ON!”
        vi. Else If System OFF button is active
            1. Send Message to the community “System Status: The System has been turned OFF!”
        vii. Else If Pump ON button is active
            1. Send Message to the community “System Status: The Main Pump is running!”
        viii. Else if Pump OFF button is active
            1. Send Message to the community “System Status: The Main Pump turned OFF!”

ix. Else if Send Maintenance Alert Button is active

1. Send Message to the community "Alert, The System will remain non-operational today because of maintenance activity. The system will be back online tomorrow. Apologies for the inconvenience caused!"

x. Else if Send System Normalization Alert Button is active

1. Send Message to the community "Alert, The system has been restored and fully functional after the maintenance shutdown"

xi. End

e. End

4. End Check System
5. End

JavaScript code for algorithm 1 and 3 are presented in Appendix A.

5.6 Prototype Design and Results

The proposed experimental system setup is shown in figure 64 (Front view) and 65 (top view) using the above stated hardware and operating principles. As shown in the figure all the field devices are wired to the RTU which is then connected to the MTU (MacBook Pro) using USB cable. A 24 V DC and 5 V DC bus was created to power all the field devices. Two ABRA DC power supplies AB-3300 were used to generate the desired voltage which has the functionality to provide variable voltage and current. The power supply has the voltage range from 0 – 60V DC. A 10 Ohm, 300-Watt power rheostat is used as a load to generate the solar current. The variable power supply is further used to generate the required solar voltage. The three compressors are used to simulate the pressure values at different stages of the process. Two water cups filled with water are used to measure the water temperature and level in the hardware prototype. The Metex M3800 digital millimeters were connected to measure voltages and current on point of interest to cross-check the measurement of field parameters.

Figure 64: Hardware prototype of system (Front view).

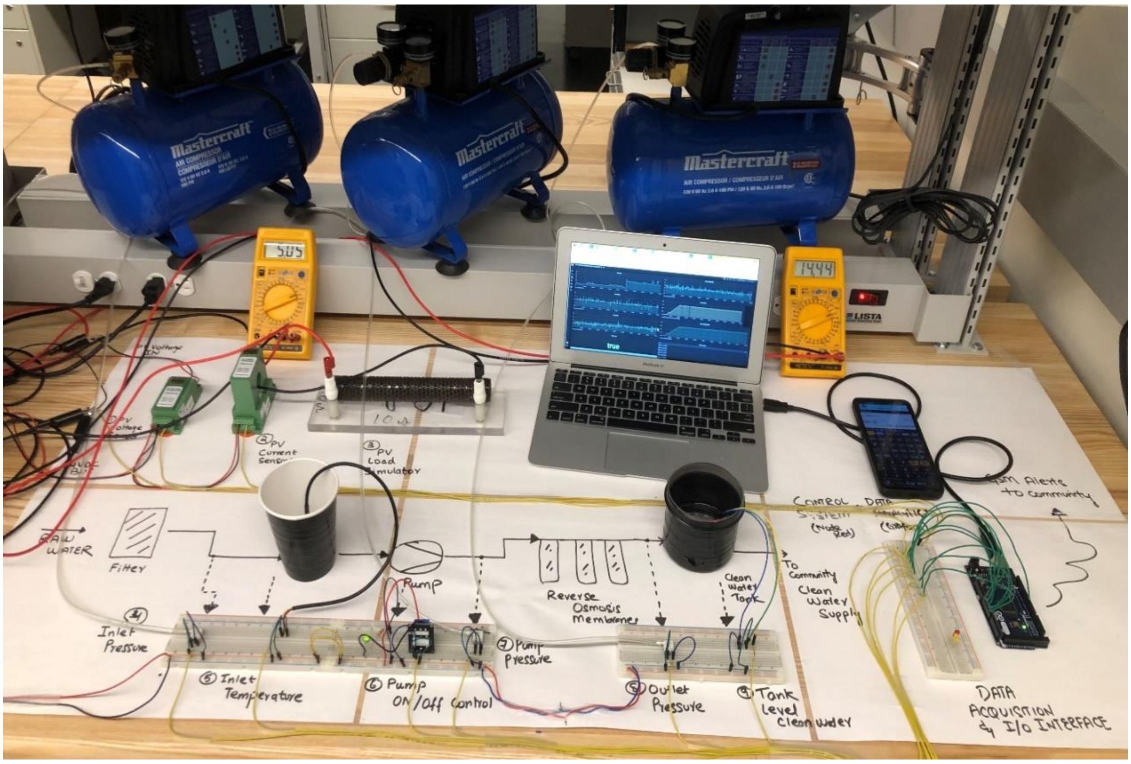

Figure 65: Hardware prototype of system (Top view)

All system was powered up and steps are done to check the system operation. Firstly, Arduino IDE is opened in the MTU and firmata is uploaded to the microcontroller as shown in the figure. Node-Red Programming is carried out in the web-based programming environment and all logical operations were constructed as flow sequences. The figure 66 shows the Node Red programming flow diagram (code provided in Appendix A). Flow based servers and UIs were developed using Node-Red visual programming language [39, 40].

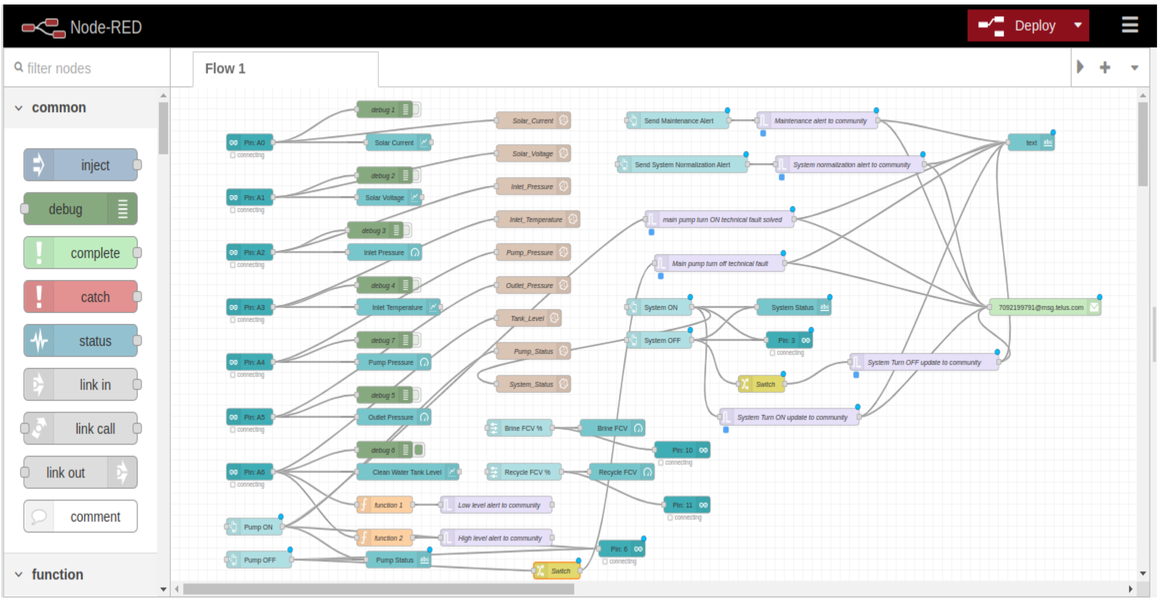

Figure 66: Node-Red programming of the system.

Node-Red dashboard was created with all major functions required for smooth system operation and sending messages alert to the community. The figure 67 shows the Node-Red Operational dashboard available for the user.

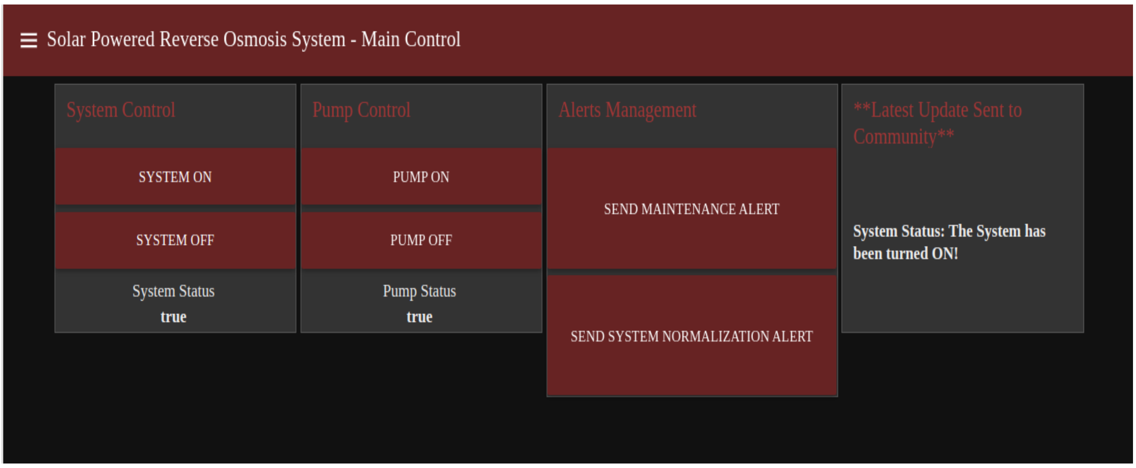

Figure 67: Node-Red Dashboard for Operation.

The Node-Red real time monitoring dashboard was created to show the live values of several process parameter. Scaling of the analog return values were performed to read the actual pressure. The figure 68 shows the Node-Red real time monitoring dashboard.

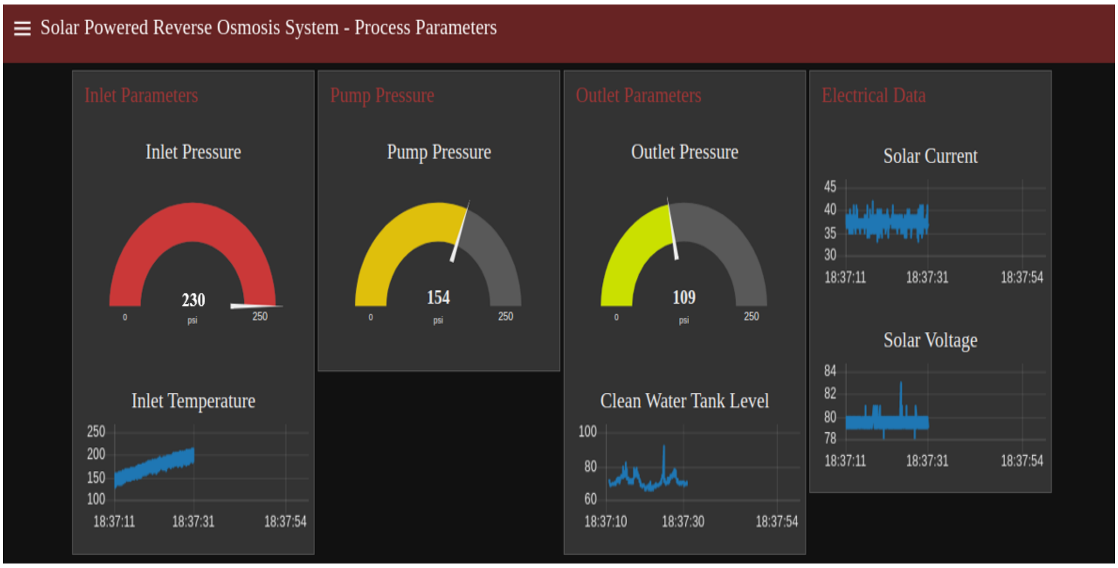

Figure 68: Node-Red Dashboard for Real-Time Monitoring.

In order to store the data on local server InfluxDb is used as the database and tags of all process parameters were created. The figure 69 shows the database structure and tags generated in the system.

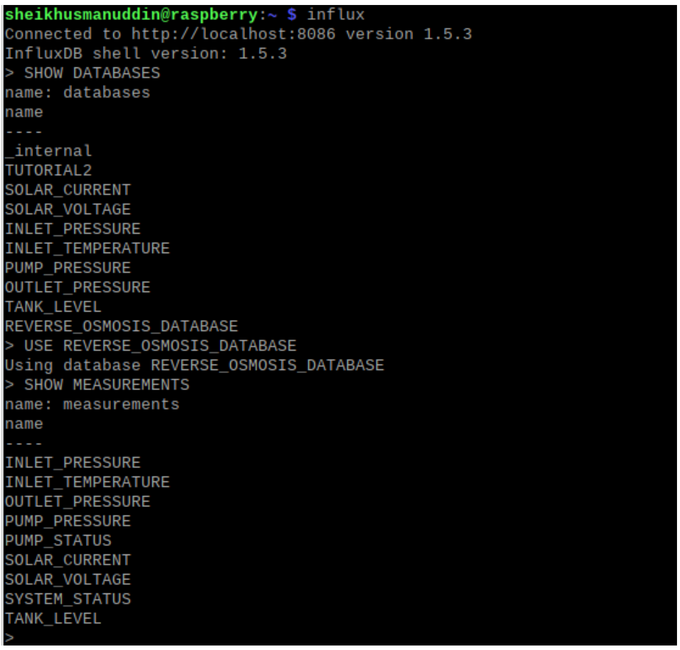

Figure 69: InfluxDB database tag generation.

The figure 70 further shows the last values stored inside the database that are directly coming from the Node-Red programing to verify the operational functionality of the database.

```
> SELECT*FROM OUTLET_PRESSURE 10
ERR: error parsing query: found 10, expected ; at line 1, char 29
> SELECT*FROM OUTLET_PRESSURE LIMIT 10
name: OUTLET_PRESSURE
time                value
----                -----
1665074754970220051 0
1665074757487287431 108
1665074757510673715 106
1665074757545755363 105
1665074757776176506 106
1665074757780819804 105
1665074757795003298 104
1665074757803238538 105
1665074757881305242 104
1665074757916199604 105
>
```

Figure 70: Verification of database functionality.

Finally the stored database is called inside the Grafana web based data analytics tool. The figure 71 shows the dash board generated in Grafana visualization tool for viewing historical data and carrying out data analysis.

Figure 71: Grafana based dashboard for historical data trending and data analytics.

The GSM based system functionality was also verified by using the Node-Red online operational dashboard and messages were received on the mobile phone from Node-Red. The figure 72 shows all the messages received.

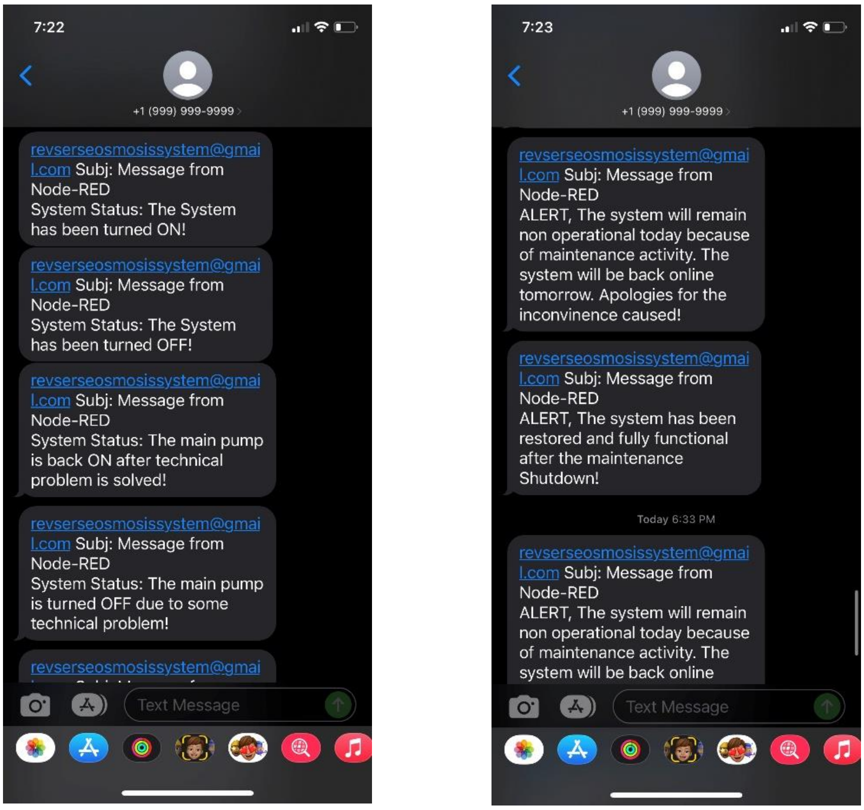

Figure 72: System alert messages received on mobile phone.

5.7 Discussion

This section aims to highlight some of the main features and benefits of the open-source, internet of things-based SCADA system of solar powered reverse osmosis system for a community realized following successful testing.

- System Configuration: The System is designed in a unique configuration where web-based approach is used for both logical programming and data analytics.
- System safety: As a measure of system safety, the field devices are isolated using a remote terminal unit (RTU) to ensure that the system side is protected in the event of abnormal conditions.
- Open Source: The complete system is based on free and open-source software that can be easily installed on any operating system. There is no license fee or yearly fee associated with the operation of the system. Hence, eliminating the operational cost of the system.

- Availability and Reliability of System: Since all the components used in the system are easily available in the market and all work is done locally including creation of local database ensure the user to have continuously reliable and available system.
- Data Acquisition, Monitoring and Control: All data is locally collected using the RTU and monitored on a web-based monitoring and control system for operation and maintenance.
- Data Storage: Data is locally stored in local server using InfluxDB, where using the Grafana based system you can have historian for data viewing.
- Alert System for the Community: All important alerts regarding the system are promptly communicated to community members that rely on this water source for their daily needs. Consequently, if there is an abnormal water situation, the community is informed and can respond appropriately.
- User Friendly Dashboard: An easy-to-use dashboard provides easy access to real-time and historian data.
- Security: Due to the fact that the system stores data locally and does not transmit any information to a remote server, the system is a fully private and secure system.
- Easy to Use System: The system will require a one-time training to any operator and can be easily used by any user.
- Data Analytics: The System has the capability to carry out extensive data analytics as the data is now available at Grafana server that has very high processing and data analytics power.
- Comprehensive guide for future research: The results of this research will serve as a guide for the development of clean water systems that are easy to install in any community, regardless of whether it is connected to the grid or not.

5.8 Conclusion

Globally, use of clean energy and clean water scarcity remain the two biggest challenges. This paper discusses an elaborate system design that ensures the reverse osmosis desalination system, powered exclusively by renewable energy. There is a detailed description of the majority of field instrument devices required to monitor and control the system in the paper. Field devices are integrated with RTUs to acquire data, which is then transmitted to the MTUs for processing and control. A highly interactive and real-time monitoring and control HMI was also developed with the use of the Node-Red visual programming language. Furthermore, the most challenging aspect of the operation of any system is to ensure that its security is not compromised. Thus, in order to ensure the security of the system, InfluxDB is used as the database and is executed locally on the same MTU, storing the data on the local server so that only authorized personnel will be able to access it. As data-driven decisions and predictive analyses play a pivotal role in increasing the efficiency and performance of any system, Grafana is subsequently deployed on the same MTU as a web-based data analytics and predictive analytics application. A major advantage of all these applications is that they are free of charge and do not require a license or an annual fee, as well as being open source with easy access to updates. As a final point, the most important gap in all such systems and previous research work was the absence of a user alert system, as in a typical situation, users would have to visit the system in person to know the status and quantity of water available.

Research such as this can be applied to many existing reverse osmosis-based desalination plants in many parts of the world to ensure that data analytics can be used to make better data-driven decisions. It offers a programming-based integration method without any external hardware for extensive alert systems that can be used separately with a variety of systems. Renewable energy is used throughout the system, thereby contributing to its environmental friendliness. Based on the testing of the system, it has been demonstrated that it can be used to remotely control and log data accurately in real-time.

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CHAPTER 6: CONCLUSION AND FUTURE WORK

6.1 Conclusion

The availability of clean drinking water is one of the biggest challenge of the world. Countries are trying to implement methods to avoid water crisis. Water is a basic necessity for everyone whether it is being used as a source of drinking, cleaning, and sanitation or by tons of process utilization. Worldwide the population is increasing exponentially that result in increasing demand for clean drinking water. All these concerns are highlighted time to time by the United Nations and in order to tackle this challenge United Nation has listed "clean water for all" as the sustainable development goal number 6. Almost all processes in the world require power for execution from conventional power generation methods.

Pakistan is a developing country with many challenges to focus on. The country holds a very strategic geographic location in terms of sea and air routes. The population of the country is increasing significantly which further put burden on communities to have clean and affordable drinking water and energy. This research focuses on a community located in the biggest city of Pakistan, Karachi, which has limited access to clean water and heavily rely on tanker system. The tanker system are trucks filled with water and provide clean water at high cost to the poor population of the community. To tackle the challenge of this community water desalination system was proposed in this thesis with solar powered system so that both of the world biggest challenges are addressed.

An extensive literature review was carried out where different photovoltaic cells available in market, different types of water desalination system, details about reverse osmosis desalination system, understanding of existing Karachi water supply system and challenges, drinking water quality standards in comparison to Pakistan drinking water quality standard and extensive research papers were studied and compared. This review finalized the goad and objectives for the complete research work.

Based on the literature review it was concluded that solar powered reverse osmosis system turns out be the most feasible and sustainable solution hence system design, sizing and economic analysis was conducted. Since the design of the system has to be for the application for community in Pakistan, the data that is to be utilized in designing and running the model needs to be from Pakistan. Therefore, solar irradiance and daily average temperature data was collected from city called Karachi, located in Southern Sindh region of Pakistan. Furthermore community population was considered with requirement calculation for clean drinking water on daily basis. After data collection, HOMER Pro was used to not only build a system design and do photovoltaic sizing, but also to carry out a techno-economic feasibility analysis of proposed system. Finally, the model analysis was conducted and it provides the required number of solar modules and batteries needed in order to meet the load demand of reverse osmosis system that can easily provide clean drinking water to the community. The model also provided all relevant cost information including capital cost, maintenance cost, net present cost etc.

Once the system design, sizing and economic analysis was complete, a dynamic model of the system could be built. Since the system includes multi-disciplinary domains, bond graph language was used to make the complete model of the system. Bond graph approach establishes a common vocabulary for understanding relationships and similarities among various modelling methodologies. It provides a uniform domain independent graphical representation of multidisciplinary models from which linearized state equations, system transfer functions or differential equation can be formed and solved. 20 SIM software was used for the complete modelling and simulation of the system. The main components of the model includes electrical system modelling, pump modelling and reverse osmosis system modelling. Once the model was complete, it was used to run tests for a variety of different scenarios that the system might encounter when being used in real life scenario compared with the baseline simulation result. These scenarios included when supply voltage is reduced due to intermittent solar radiation, increased hydraulic resistance for clean water side when reverse osmosis membrane is clogged, increased pump impeller loss, increased brine water flow rate, reduced inlet pressure etc. All these tests gave successful results i.e. the overall system behaved as expected under all the above mentioned conditions.

After the successful simulation based testing of the system, instrumentation and control of the system was designed. The system was divided and important field instrument devices required for electrical system and reverse osmosis system were highlighted. An elaborative process and instrument diagram was also generated so that the complete system flow can be seen. Control system which includes Arduino as remote terminal unit and node red as the main programming terminal were choses and monitoring and control loops were established. Finally, a low cost, open-source, internet of things based supervisory control and data acquisition system (SCADA) was developed. A detailed prototype was built in the laboratory where field instruments devices were installed followed by remote terminal unit and computer as main terminal unit. This computer system uses Node-Red as the main programming terminal, Node-Red graphical user interface as the monitoring and control human machine interface, InfluxDB for local data storage to ensure security and privacy and Grafana for data analytics. In order to ensure that the community remain aware about all the updates and status of the system and elaborative alert system was integrated in the SCADA system.

The main contributions of this thesis are listed below:

- System design, PV sizing and economic analysis for a solar powered reverse osmosis desalination system based on a community in Karachi Pakistan.
- Dynamic modelling of the system using bond graph modelling as the system incorporates multi-disciplinary domains of electrical, mechanical and hydraulic systems.
- Design of field instrumentation devices for reverse osmosis system monitoring and control loops.

- Development of hardware prototype for an open-source, low-cost, internet of things based SCADA system with local database and Grafana based data analytics provision.
- Development of an alert system for the community to be aware about status and updates from the system.

6.2 Future Work

While the research presented in this thesis focused on the design and analysis of a solar powered reverse osmosis system for a community in Pakistan, the innovative design and SCADA system approach can be used for a number of different desalination plants. Moreover, there are few things that can be further investigated in the design and analysis of a solar powered reverse osmosis system to ensure that the work can be easily translated into reality:

- Firstly, the resources used for the PV design and system sizing were specific to Karachi Pakistan. The region had excellent solar irradiance which provided an ideal condition for system design. Also the community size defined the load of reverse osmosis system. It would be important to investigate the feasibility of reverse osmosis system based on different locations where solar irradiance is not much and community size is varying. This could have implications on system sizing and overall design.
- Secondly, the dynamic modelling is a very vast field and there can be many inputs added to the system in order to see the most realistic and actual response. These factors could include system leakages, pressure pump faults, electrical jerks, detailed membrane and pump modelling utilizing a team of chemical and mechanical engineers etc.
- As mentioned above, the design approach is versatile and can be used on different desalination system. The SCADA design is unique, low-cost, secure and provide reliable monitoring, control and alert system, which can be applied on different existing

desalination plants to make them work effectively.

Appendix A: Node Red JSON Code

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List of Publications

1. Sheikh Usman Uddin, M. T. Iqbal, "Design and Economic Analysis of a Solar Powered Drinking Water Reverse Osmosis Desalination System for a Community in Pakistan." Presented at the 12th IEEE Annual Conference on Computing and Communication Workshop and Conference (CWCC 2022), Las Vegas, United States of America
2. Sheikh Usman Uddin, Geoff Rideout, "Dynamic Modeling and Analysis of Solar Powered Reverse Osmosis Desalination System for Pakistan using the Bond Graph Model." Presented at the IEMTRONICS 2022 (International IOT, Electronics and Mechatronics Conference), Toronto, Canada.
3. Sheikh Usman Uddin, M. T. Iqbal, "Instrumentation and Control Design for a Solar Powered Reverse Osmosis Desalination System for a Community in Pakistan." Presented at The 31th Annual Newfoundland Electrical and Computer Engineering Conference (NECEC 2022), St. John's, NL.
4. Sheikh Usman Uddin, Mirza Jabbar Baig, M.T.Iqbal, "Design and Implementation of an Open-Source, Internet-of-Things based SCADA System for a Community Solar Powered Reverse Osmosis System" published in MDPI Sensor Journal Special Edition (2022).
5. Sheikh Usman Uddin, Abdul Azeez, Onyinyechukwu Chidolue, M. T. Iqbal, "Design and Analysis of a Solar Powered Water Filtration System for a Community in Black Tickle-Domino." Presented at the IEMTRONICS 2022 (International IOT, Electronics and Mechatronics Conference), Toronto, Canada.