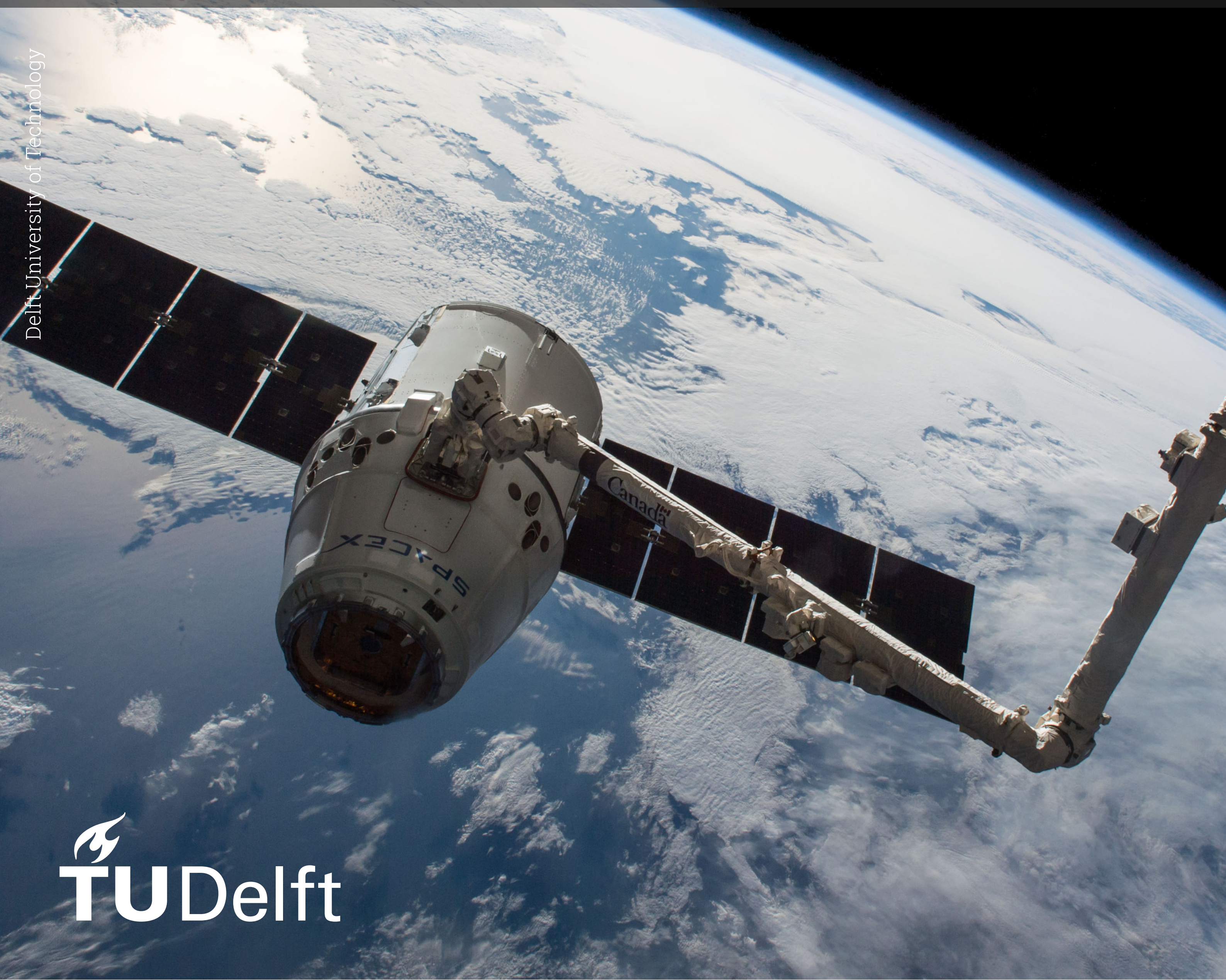
Pine Ridge Autonomous Energy System Design

Systems Integration Project

Charles Renshaw-Whitman (5513812) and
Laurens G. Braskamp (4411064)



Delft University of Technology

TU Delft

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Summary

Herein is presented a preliminary design for a renewable energy system for use by the Pine Ridge Indian Reservation community of South Dakota, USA. This design was completed for the class 'Systems Integration Project' at the TU Delft, as part of the requirements of the MSc Sustainable Energy Technology Degree. The designed system consists of a primary solar photovoltaic array, a hydropower installation, and accompanying battery-storage. The system is designed to provide sufficient energy and storage to the community that, under normal operating conditions, no power is drawn from or dumped to the grid. The principal aim of this system is to alleviate the community's historic energy poverty by the provenance of sustainable and affordable energy.

Contents

1 Introduction

The location chosen for our project is the Pine Ridge Reservation located in the south-west of the US state of South Dakota (SD), which has a population slightly under thirty thousand [16]. It as a community set aside by US law for indigenous peoples displaced by the nation's westward expansion - thus its inhabitants have a complex relationship with the US government.

This location was selected because these indigenous communities often suffer from energy poverty, and, because of their unique legal status, are regularly excluded or overruled as states enact their energy policies; however, as the indigenous people have a cultural heritage of ties to their land, they are often uniquely receptive to renewable energy solutions which both provide energy autonomy and mitigate environmental harms [7] [21].

1.1. Overview of Design Criteria and Assumptions

For the purposes of this power-system design, a number of important assumptions are made. We will focus exclusively on assumptions made in the technical design of the system (to the exclusion of social factors, to be discussed in a later report).

The first step in the design process was determining the system design requirements. We assume that the community wishes an energy system which could provide year-round for energy consumption at the level of the state-average *per capita* consumption. Further, as the community is one of the most impoverished in the country, we assume that the community will remain connected to the power distribution network (for access during, e.g., maintenance). Wishing to limit carbon emissions, we assume all total energy consumption will be electric. We use a population-size estimate from [16], SD average energy consumption from [22], characteristic monthly and daily consumption profiles from [21].

Having determined the load size, we turn to the power system. As solar power is cheap and often state-subsidised [2], we will assume sufficient solar power is installed to meet as large a fraction of the community's energy consumption as possible, accounting, however, for the associated cost of batteries. We neglect complicating factors such as the panel orientation, shading effects, etc, but do model the effect of ambient temperature.

For sizing, the relevant equations are (See [18], [19], [15])

$$P = \text{ESH} * P_{\text{rated}} * f_{\text{tilt}} = P_{\text{rated}} * f_{\text{tilt}} * \frac{\text{GHI}}{\text{GHI}_{\text{STC}}}$$

$$I_{\text{array}} = I_{\text{panel}} N_{\text{parallel}}$$
$$V_{\text{array}} = V_{\text{panel}} N_{\text{series}}$$

The secondary source we have selected as hydropower, as there are already examplary installations on the nearby Missouri river, such as the Oahe [14]. Over the course of the year, the Missouri's flowrate is relatively constant [12] - thus we assume that the installed hydropower is capable of producing any amount of power less than its capacity on demand (water must simply be diverted to the penstocks to lower the flowrate; the ramp-rate limits are governed by the turbine inertia, the modelling of which is discussed later. The power generated by a hydropower plant is (see [6] for nomenclature and details):

$$P = \dot{Q}\rho g h(1 - f_{\text{bypass}})\eta_{\text{turb}}$$

1.2. Main Components and Sizing

The system consists of 5 main components: the solar arrays, their MPPTs, inverters, hydropower installation, and batteries. The solar panel selected was that with the lowest per-W price in South Dakota [9]. The number of panels was initially chosen so that they would on an annual basis, produce the amount of energy consumed by the community. In the course of system-testing, it was observed that the diurnal profile of the solar power would necessitate a very large amount of batteries to be usefully employed - accordingly, the number of solar panels was reduced by half, and the hydropower installation upscaled by half from earlier designs.

The number of panels per MPPT was chosen by placing as many panels as possible in series and then in parallel (while respecting voltage and current restrictions). The number of these 'arrays' then corresponds to the number of MPPTs required. The chosen MPPT was [11].

We choose not to size inverters, as the battery-storage selected includes inverters in the price - for four batteries each with a 250 kW inverter, this gives an output capacity of 1000 kW, compared to the reservation's average consumption of 430 kW. It is assumed that the charge controller is able to determine if power should be sent to the batteries as DC or through the inverters.

The hydropower installation is assumed to have similar properties, appropriately downscaled, to those of the nearby Oahe dam [14].

The battery selected was chosen because it is one of relatively few grid-battery technologies currently deployed; despite this a data-sheet is not publicly available; a table is available on Wikipedia though this has no clear source for most of its entries [20]. This caveat given, we use these data.

1.3. System Summary

In summary, we have presented a preliminary sizing and component selection for a power system designed to minimise dependence of the Pine Ridge Indian Reservation on the grid while also alleviating the region's energy poverty. This system will generate energy from battery-connected solar panels and hydropower. The tables below provide some technical information regarding the selected system components.

Overall, the system consists of

- 1376 LG NeON 2 Solar Modules, with rated capacity 461 kWp and 39 MPPTs
- A 484 kW hydropower installation (based on data from the nearby Oahe dam)
- 2065 kWh (nominal; usable 1032.5 kWh) of Tesla Powerpack Batteries (with built-in inverters).

	Load
Average Consumption (kW)	430
Peak Consumption (kW)	475
Sources	[16], [21], [5]

	Solar PV
Selected Unit	LG NeON 2
Number of Units	1376
Rated Power (kWp)	461
Estimated Cost (Million USD)	0.44
Sources	[9]

	Secondary
Rated Power (kW)	484
Estimated Cost (Million USD)	2.08
Estimated Required Flowrate (m^3/s,)	49.34
Sources	[6], [14]

	Batteries
Unit Selected	Tesla Powerpack
Unit Charge Capacity (Ah)	218.75
Unit Total Energy Capacity (kWh)	210
Max (DC) Operating Voltage (V)	960
Usable Energy (Estimated , %)	96.4
Sources	[20]

2
System Model and Control

2.1. Solar Power Model

The primary source, solar power is modeled using (hourly) GHI and Temperature data provided by the NREL for the given location [13]. The solar plant output as a function is given as follows:

$$P_{\text{out}}(t) = P_{\text{rated}} \frac{L(t)}{L_{\text{STC}}} \begin{cases} 1 - \alpha_{\text{P,T}} \left(T(t) - T_{\text{NMOT}}\right) & \text{if } T(t) > T_{\text{NMOT}} \\ 1 & \text{if } T(t) \leq T_{\text{NMOT}} \end{cases}$$

L signifies the Global Horizontal Irradiance (GHI), T the panel temperature, and P the power. 'STC' signifies "Standard Test Conditions" under which the solar panel is rated, while 'NMOT' means "Normal Module Operating Temperature". $\alpha_{\text{P,T}}$ is the temperature coefficient of the solar panel, which expresses the fraction of power production lost per degree Celsius as the panel exceeds its rated temperature (N.B. In our model, we assume that the difference between the panel and ambient temperature is a constant $\Delta T = 20\ ^\circ C$ for simplicity).

2.2. Hydropower Model

As noted in the preliminary report, the hydropower plant sized for this project is much smaller than the total flow rate of the river - the flow rate of water is a constant multiple of the power output

$$P_{\text{out}} = \eta \rho_{\text{water}} g \Delta h\ Q(t)$$

Here P is the power output, ρ_{water} the mass density of water, g Earth's gravitational constant, Δh the head of the dam, and Q the volumetric flow rate of water through the turbines (which generate power with a total efficiency η). The dependence of Q on time reflects the fact that the flow rate is controlled by the power system controller.

In order to model the ability of the whole power system to change its production in response to a change in load, the hydro plant is assumed to have a maximum ramp-rate, υ_{ramp}, representing the achievable output power change per second as a fraction of the rated output power.

$$\frac{\mathrm{d}P_{\text{out}}}{\mathrm{d}t} = \upsilon_{\text{ramp}} P_{\text{rated}} \begin{cases} 1 & \text{if } P_{\text{out}}(t) < P_{\text{set}}(t) \\ 0 & \text{if } P_{\text{out}}(t) = P_{\text{set}}(t) \\ -1 & \text{if } P_{\text{out}}(t) > P_{\text{set}}(t) \end{cases}$$

P_{set} is the control signal determined by the power system control, while P_{out} changes dynamically to match this. An plot showing the response to two step-function changes in the set point is shown in Figure 2.1 Here the ramp-rate is assumed to be 10% per minute, based on [3].

2.3. Battery Model

The battery is modeled simply as having a state of charge, and individual efficiencies for both charging and discharging operations. As our goal is to model the system-response to intermittency over the

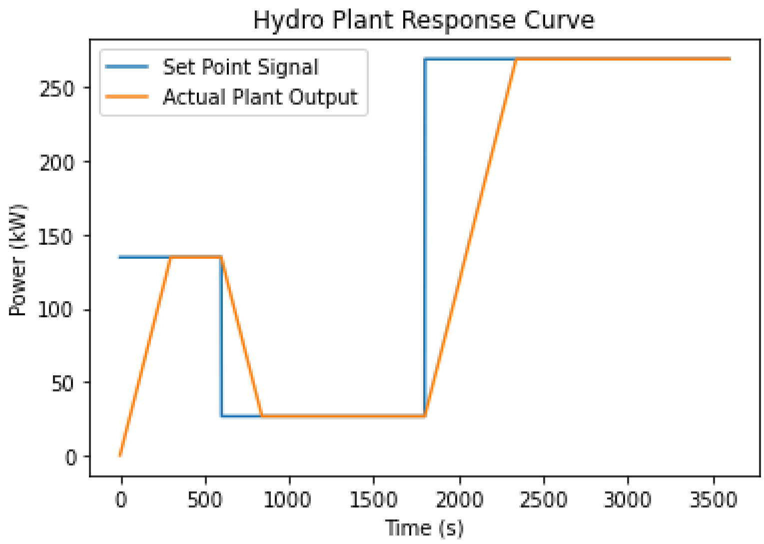

Figure 2.1: Illustration of the dynamic response of the hydro installation to changes in the set point

course of a week, we do not model the battery lifetime, the impact of environmental variables, or deviation of the voltage from the rated output. Further, we assume that, as the battery is meant to be used in contingency - and thus not cycled to its full depth on a regular basis - that the full usable energy is available for use, independent of the effects on lifetime.

Our selected battery, the Tesla Powerpack, does not have publicly available specifications other than those mentioned in the preliminary report - we thus take data from a residential battery of the same technology and supplier, the Tesla Powerwall. This battery has a round-trip efficiency (including AC-AC conversion, which our system does not implement; we use this nonetheless to be conservative) of 90%, and a usable energy of 50%. In absence of further information, it is assumed that the charge and discharge efficiencies are equal (and thus the square root of the round-trip efficiency).

2.4. Revised Control Diagram

A flowchart illustrating the system-control is shown in Figure 2.2.

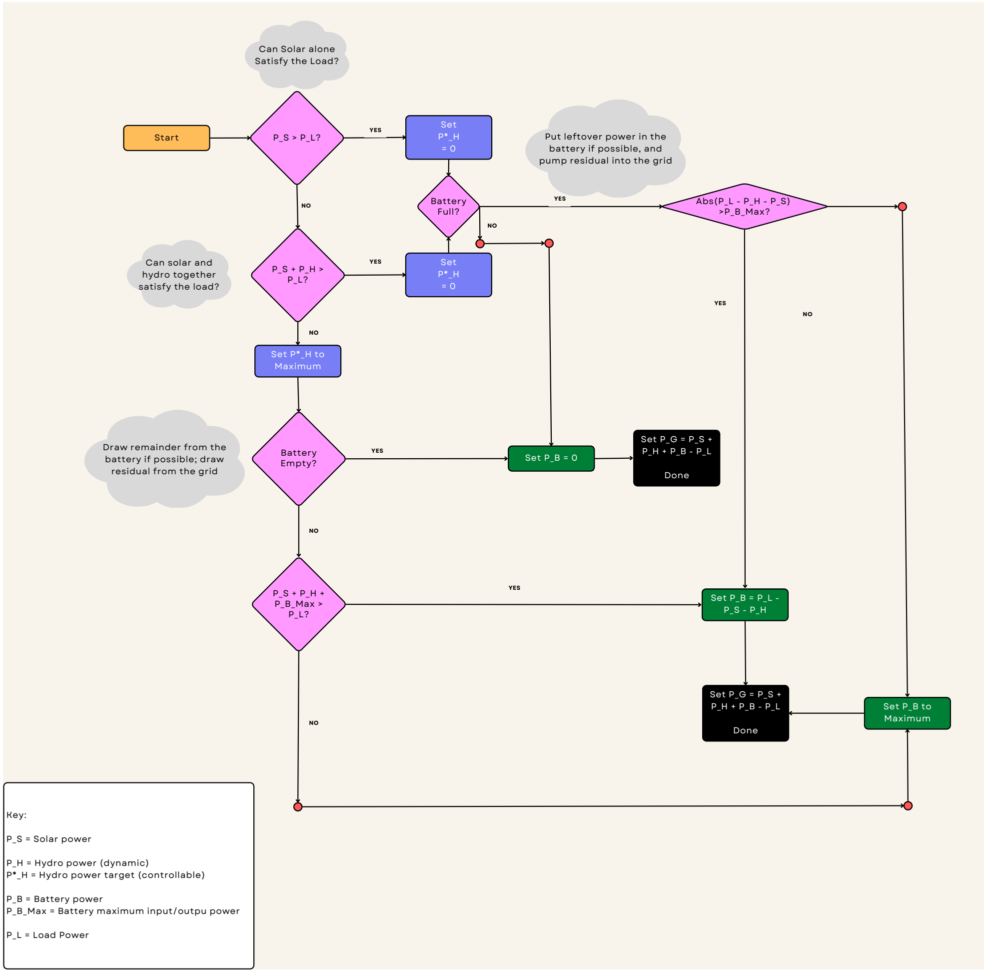

Figure 2.2: Control Diagram dictating the battery output power and hydropower set-point. The design accepts all solar power and sets the hydropower set-point to meet as much of the remaining load as possible; deficits are made up by the battery, and then the grid as a last resort.

3
Scenario Simulation and Cost Estimation

3.1. Scenario Analysis

Here we test the power system in a variety of scenarios designed to illustrate its behaviour and verify its sufficiency. Over the course of this analysis, the system was resized from the previous design in order to minimise the extent to which power would be dumped to or drawn from the grid during normal operating conditions. The solar and hydro nameplate capacities were modified by a factor of 0.5 and 1.5, respectively. The battery size was left unchanged. This reflects the difficulty of meeting a large amount of demand with intermittent sources such as solar, which requires expensive batteries.

3.1.1. Scenario 1: Winter

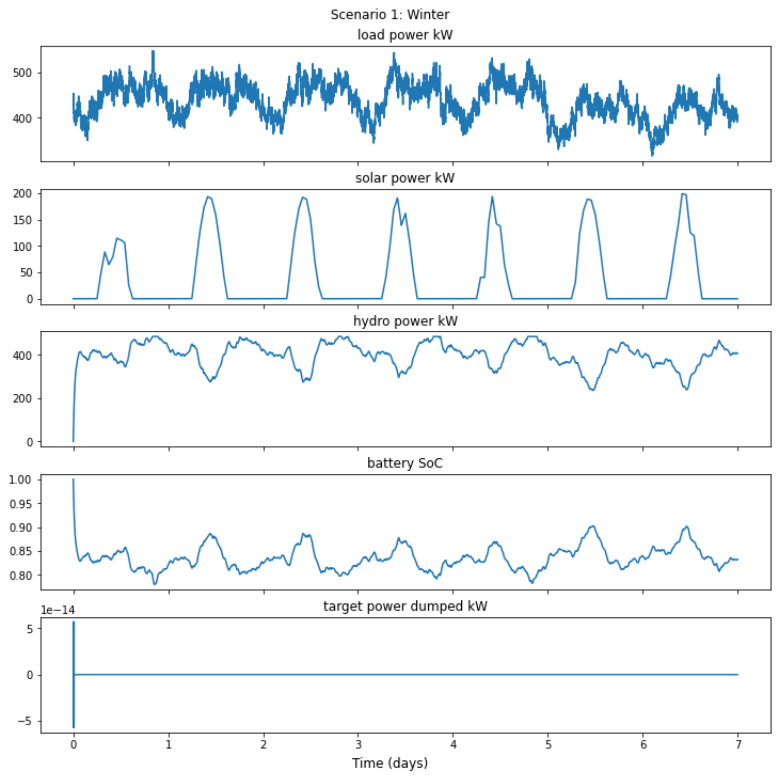

Figure 3.1: Illustration of the state of the system for a representative week during the Winter. Winter is characterised by a relatively even load-curve, and minimal solar energy.

Scenario 1 focuses on the performance of the system during a representative week during Winter (the meteorolgical data is from January, specifically). Summer is characterised by low solar energy availability, and a relatively constant load-curve (i.e. a high base-load). In this case, the system provides much of its energy from the hydro-power installation. The solar energy contributes less than half of what it does in the Summer scenario (a 200 kW vs 400 kW peak, combined with shorter days). The battery state-of-charge is very consistently around 80%. This indicates the battery is more than large enough for this scenario (and were this the only case to consider, could be safely reduced in size by perhaps a factor of 4). The goal of complete autonomy from the grid is upheld in this scenario, as no power is dumped to or drawn from the grid.

3.1.2. Scenario 2: Summer

Scenario 2 focuses on the performance of the system during a representative week during Summer (the meteorolgical data is from July, specifically). Winter is characterised by high solar energy availability, and a load-curve which oscillates more widely than its Winter counterpart.

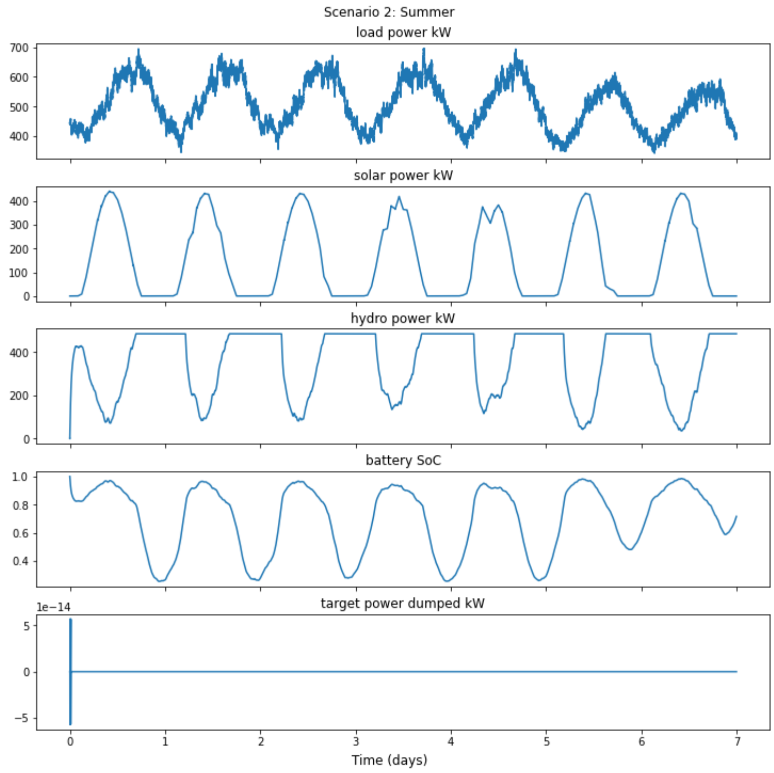

Figure 3.2: Illustration of the state of the system for a representative week during the Summer. Summer is characterised by a sine-like load-curve, higher overall consumption, and large amounts of solar energy.

In this case, the system strikes a roughly even balance between drawing hydro and solar power. The evening-overhang in power consumption compared to solar energy production was a driving design condition for the size of the hydro-power installation. The battery state-of-charge oscillates broadly between roughly 20% and 90%; this range is good, as it indicates that the battery has not been made too large, while still leaving comfortable margins; thus the Summer case also drives the design of the battery. The goal of complete autonomy from the grid is upheld in this scenario, as no power is dumped to or drawn from the grid.

3.1.3. Scenario 3: Solar-Failure (Summer)

Scenario 3 geminates the conditions of the above scenario, while adding a hypothetical long-term failure of the solar installation. This scenario was chosen in order to characterise the extent to which such a large failure would harm the system's grid-autonomy; Summer was chosen as it was observed above to be the design-driving condition for much of the system. In reality, smaller failures of individual solar modules or array-arms are perhaps more likely than a system-wide failure, so this case should be considered a worst-case analysis of this particular type of failure.

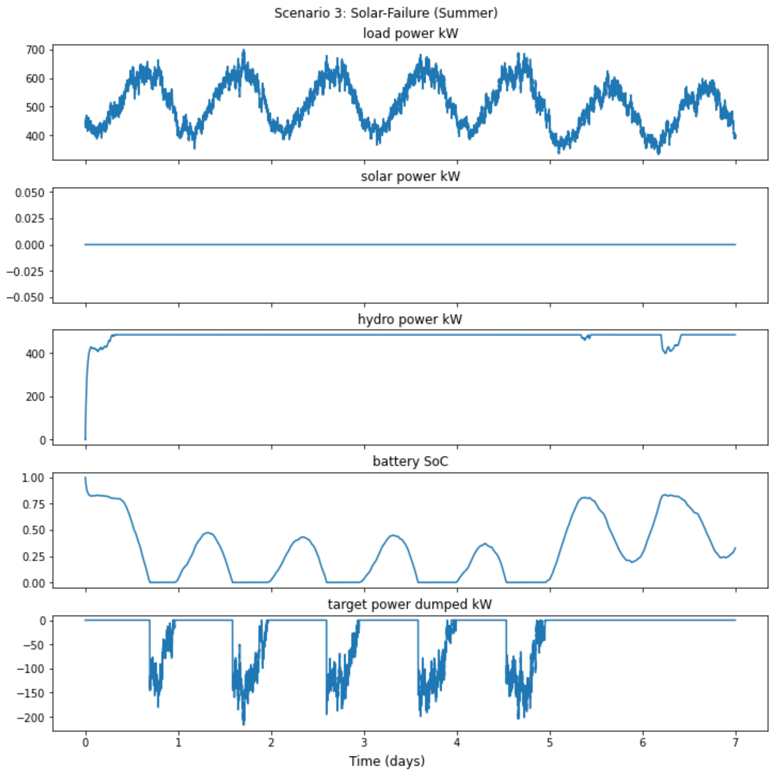

Figure 3.3: Illustration of the state of the system for a representative week during the Summer after a hypothetical week-long outage of the solar array. Compared to previous cases, the battery is highly depleted and the hydro nearly always at maximum; the remainder of power is drawn from the grid.

As is clear, in the absence of the solar array, the system is unable to match the demand of load; this indicates that the solar and hydro plant have been sized reasonably (as alternatively, if the hydro plant alone could meet demand, there would be no need for expensive solar panels at all). However it is also clear that the objective of grid-autonomy is no longer maintained; daily draws of over 200 kW are made from the grid, for a weekly total of roughly 4300 kWh. While the degree to which autonomy is important to the local community should play a role in making such a decision, for the purposes of this report, it was determined that this scenario should not be permitted to drive sizing, as it is comparatively unlikely and would dramatically increase system-costs.

3.2. Cost Estimation

In this section is offered a rough estimate of the cost of creating the designed system.

3.2.1. Capital Cost Breakdown

The principal costs of concern are the capital costs. In particular, we consider the costs of the hydropower installation, the solar panels and associated MPPTs, and the batteries. These costs are summarised in the accompanying table.

Item	Estimated Unit Capacity Cost	Installed Capacity	Total Capital Cost	Percent of Total Capital Cost
Hydropower Installation	4287 USD/kW	484 kW	USD 2,074,908	49.0%
Solar Panel Modules	320 USD/module	461 kWp (1376 modules)	USD 440,320	10.4%
Solar MPPT Units	700 USD/unit	39 units	USD 27,300	0.6%
Batteries	1638 USD/kWh (usable)	1033 kWh (usable)	USD 1,692,054	40.0%
Total			USD 4,234,582	100.0%

Item	Estimated Unit O&M Cost	Installed Capacity	Total O&M Cost	Percent of Total O&M Cost
Hydropower Installation	43.78 USD/kW	484 kW	2119 USD/y	57.7%
Solar PV + Storage Installation	33.67 USD/kW	461 kWp	1552 USD/y	42.3%
Total			3671 USD/y	100.0%

The unit cost of hydropower is estimated using that of the nearby Oahe dam, adjusted for inflation[14]. It is worth noting that the system was designed iteratively to adequately meet design objectives - economic optimisation was not (and in the authors' opinion, due to the estimates' imprecision, should not yet be) performed on the preliminary cost estimates here.

3.2.2. O&M Cost Estimation

Operation and Maintenance (O&M) Costs are estimated per unit of capacity based on data from [22]. This report provides data for 'solar PV with storage', which was used to estimate the combined O&M costs of the solar PV and battery system. Overall, the estimated annual costs of the system are less than 0.1% of the estimated capital costs. Hence, for the calculation of LCOE, these costs are ignored.

3.2.3. Levelised Cost of Electricty

The so-called 'Levelised Cost of Electricity' (LCOE) is a standard metric for measuring the amortised cost of the production of a single unit of electricity [8]. For simplicity, in calculating the LCOE, we neglect the ongoing costs. We assume the system lifetime to be 25 years, roughly in line with the warranty of the solar modules [9], with the acknowledgement that some parts of the system, especially the hydro installation may last much longer, while others, such as the batteries, may degrade more rapidly, making this a rough approximation.

Further, the LCOE here presented is the 'overnight' cost of the system - it excludes the costs of installation, construction, and obtenance of capital (not due to lack of importance, but because they exceed the scope of this report). This said, this 'overnight' LCOE is then simply the total energy generated divided by the system cost:

$$\text{LCOE}_{\text{overnight}} = \frac{\text{Cost}_{\text{system}}}{E_{\text{lifetime}}} = 45.07 \text{ USD}/\text{MWh}$$

For an overnight LCOE of roughly 45 USD / MWh. This is roughly double what the average European consumer pays after taxes [4] - though this is not unreasonable given that utility-scale installations are able to benefit from economies-of-scale. It bears reiterating that a primary aim of this project is the elimination of energy poverty - thus such a cost is acceptable only if the system can be built without placing a large cost-burden on the community - ideally the state would recognise the economic case for reducing long-term energy subsidies (to say nothing of the human one for reducing energy poverty) and provide some of the funds as a grant or a loan with favourable terms.

3.2.4. Note Regarding Environmental Considerations and the Choice of Sustainable Energy

Often, one of the principal motives for the use of sustainable energy is the aim of reducing carbon dioxide emissions. In the present case however, the project aim is to eliminate energy poverty in the region - thus the power generated would, for the most part, not have been consumed in the counterfactual world where the project is not undertaken. That is, the project does not abate carbon emissions (and technically the system components embody some amount of embedded emissions as well). What then is the reason for selecting an renewable energy rather than more flexible fossil-based solutions?

The answer is threefold: on the one hand, the Pine Ridge community consists of indigenous peoples with a historic relationship to the land - to the effect that environmental sustainability (both globally by reducing carbon emissions, and locally by limiting polluting smog) is especially important to the community; on the other hand, the reservation community is impoverished and rather remote from the surrounding area - the delivery of fossil fuels would be both environmentally hazardous, and unduly expensive given the community's remoteness. Finally, the construction of an autonomous energy system offers an economic benefit - rather than continuing to rely on ineffectual state subsidies, the community will generate its own power for a fraction of the cost (c.f. the concluding economic recommendation).

For the sake of a crude comparison, the carbon intensity per kWh of our system may be estimated: [10] report average amortised carbon intensities of roughly 50 and 27 gCO_2 per kWh for solar and hydropower respectively - we shall assume a figure of 35 gCO_2 per kWh. [17] reports 89,000gCO_2 per kWh (of battery capacity). For an estimated 94 GWh lifetime production, this corresponds to roughly 1 gCO_2 per kWh (of system use) from battery production - the system total may thus be estimated as roughly 36 gCO_2 per kWh. This is to be compared to the US average of roughly 388 gCO_2 per kWh -

a big improvement. Large benefits, the calculation of which is beyond the scope of this report, accrue also from the decrease in local air pollution due to fossil-fuel combustion, as well as social benefits accruing from increased electricity accessibility.

4 Conclusion

4.1. Concluding Summary

This report discusses the design of a renewable energy system tailored to the Pine Ridge Indian Reservation community of South Dakota, USA. The system consists of a primary solar array and a secondary hydropower installation, along with appropriate battery storage. The system was designed to require no grid-connection during normal operating conditions, with the aim of ensuring energy-autonomy to the community in order to alleviate historic energy policy. Simulations were performed with historical meteorological data to assess the system's ability to meet these design criteria, through which it was confirmed that the system is capable of adequately supplying a simulation of the area's residential load - though recourse to the grid is necessary if part of the system is down for maintenance.

4.2. Economic Note and Recommendation

The Pine Ridge community, as noted previously, suffers from a chronic lack of access to affordable energy. As such, insofar as access to electricity is a boon to the community with value quite distinct from an individual's willingness to pay, a framework of cost-effectiveness, rather than cost-benefit analysis is appropriate. Accordingly, the authors assess the value of the system compared to the principal alternative which would be used to accomplish the same objective, rather than presenting financial metrics such as NPV and RoI. In particular, the problem with such metrics is that electricity must be assigned a certain dollar value, the assignment of which is here undesirable because the poverty of the community prevents them from paying as much as they actually value the energy - thus from the perspective of the community, the 'value' of energy will greatly exceed their ability to pay, constituting (alongside other factors like concern for equity) a rationale for state subsidy or intervention.

The principal alternative to the design of an autonomous system is the improvement of pre-extant access to the energy grid. To estimate the cost and effectiveness of such an approach, we compare South Dakota's (federally-funded) energy-poverty alleviation program, LIEAP; for the fiscal year 2021-2, this program was allocated 41 million USD (of which 24.5 million was exceptional, and 17.4 million regular) [18]. Pine Ridge Reservation contains roughly 2% of the state's population; if the reservation receives proportionally from this amount (they likely do not, given the reservation's independent status vis-a-vis the federal government), this amounts to roughly 1 million dollars annually. [1] discuss the ongoing failure of such programs to alleviate energy poverty - to the effect that such programs mitigate the consequences of such poverty rather than actually decreasing the amount of energy poverty. For comparison, the state would in the *status quo* case spend an amount approaching 25 million USD (undiscounted) over the 25-year assumed system lifetime - and with little long-term effect.

Accordingly, given the large cost of current assistance programs compared with the anticipated system-lifetime costs, the authors can strongly recommend the construction of such a system for the community as an effective means of eliminating energy poverty. If possible, the authors recommend the state redirect funds from LIEAP to the development of this community energy system, in order to help the community pay for it.

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