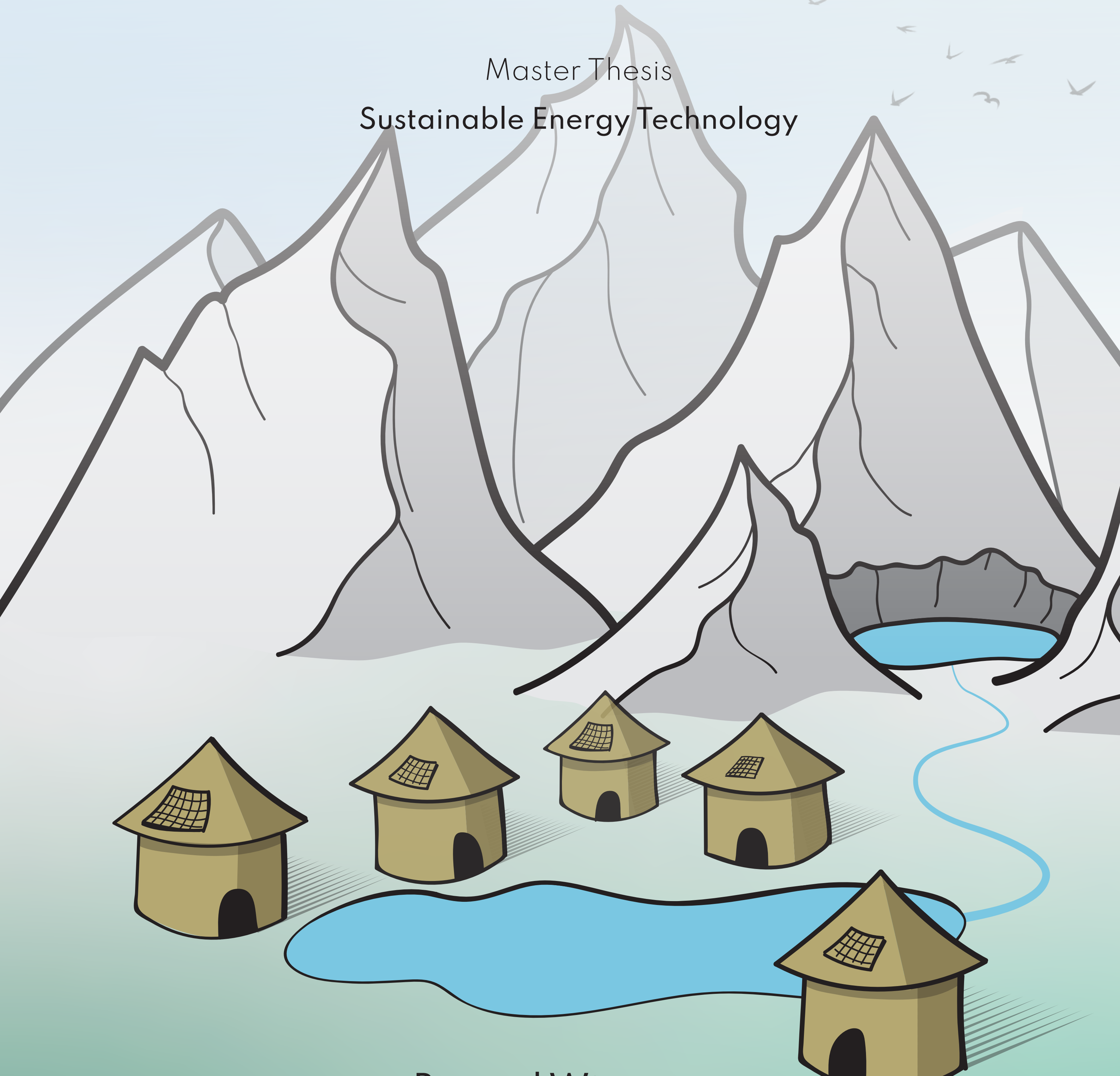
Feasibility study on small-scale **Pumped Hydro Storage**

For isolated mini-grids in a low-resource setting

Master Thesis

Sustainable Energy Technology



Berend Witteveen

TU Delft, July 2020

Feasibility study on small-scale Pumped Hydro Energy Storage

for isolated mini-grids in a low-resource setting

by

B.W.T. Witteveen

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Monday July 13, 2020 at 15:30.

Student number:	4310446	
Project duration:	June 1, 2019 – July 13, 2020	
Thesis committee:	Dr. ir. L. Kamp,	TU Delft, supervisor
	Dr. ir. L. Ramirez Elizondo,	TU Delft
	Dr. ir. K. Hemmes,	TU Delft
	Dr. L. Mackay,	DC opportunities

This thesis is confidential and cannot be made public until December 31, 2020.

TU Delft

Abstract

A large portion of the global population, mostly in the Sub-Saharan African region, still has no access to electricity. Due to the remoteness and limited accessibility of some communities, off-grid solutions such as mini-grids are required to electrify these regions. An essential part of such an isolated mini-grid is the energy storage system. DC Opportunities aims to establish these mini-grids as a third step in the electrification process. As a means of energy storage, the small-scale employment of the mature technology of pumped hydro storage (PHS) should be explored, making use of height differences in terrain often present in these areas. While PHS is the most common energy storage technology, it has thus far only be employed on a large scale and only recently research on its small scale applicability has been gaining ground.

In order to conduct a feasibility study on the use of PHS as a means of energy storage for isolated mini-grids in low-resource settings, such as those in Sub-Saharan Africa, local challenges are identified. These include a suitable operating range, quality of supply and power issues, limited component and material availability, potential arrival of the main grid, funding, low tariffs and revenue, a low-trust society, limited technical skills, theft and vandalism, political vertical networks and corruption, regulatory issues, secondary water use and environmental impact. Based on these challenges, a program of requirements is presented, which consider the technical, economic and socio-cultural requirements. Subsequently, the available design options are discussed, and based on the program of requirements a technical design synthesis leads to a provisional technical design.

This exploration has led to the conclusion that earth dam reservoirs should be used for the water storage system, Glass Reinforced Plastic or Mild Steel pipes for the water conveyance system and a binary unit utilizing a Pump-as-Turbine or a ternary unit employing a Pelton turbine for the powerhouse configuration; this configuration can be either designed for an one-time installation or scalable installation. Based on the provisional technical design and the local challenges, an organizational structure, using the existing local power structure, ensures the PHS plant embeds itself in the community through community involvement and participation, as well as local capacity building by the project facilitator.

The capacity requirements of the reservoir, as well as the diameter and material of the penstock, and the powerhouse configuration appear to be highly dependent on site-specific conditions. Therefore an energy flow model was developed, which in combination with a penstock selection tool and a generated demand profile is able to determine the requirements of a Hybrid Energy Storage System (HESS) utilising PHS as its main component for an isolated mini-grid. This model has been deployed for a case study in Adi Araha, Ethiopia, yielding positive results. Further exploration into the economic implications of the modeled system, and socio-cultural factors to be considered for the case study, led to the conclusion that for the case study a PHS plant could prove to be a technically, economically and socially feasible solution. Further research is however warranted, specifically on site.

The developed model was further employed to attain a conclusion on the general economic feasibility. While the socio-cultural factors are very site specific and can not easily be generalized, the results exhibit that for a situation where the gross head is at least 250 meter, and preferably around 300 meter, and the maximum power output requirements of the PHS plant is at least 150 kilowatt, technical and economic feasibility is attainable. Isolated mini-grids requiring a storage solutions, adhering to these conditions, should thus be further investigated to more accurately determine the feasibility of a small pumped hydro storage plant.

Acknowledgements

I would like to thank everyone who have helped made this thesis possible. Firstly, my supervisor from DC Opportunities, Laurens, for his guidance, and the rest of my coworkers there for their help, either with my thesis or in the form of pool table breaks. Secondly, my supervisors from the TU Delft, Linda, Kas and Laura, for their academic counseling. But most importantly, I would like to express my gratitude to the people closest to me who have supported me throughout the process of writing this thesis. My parents, brother and sister, and my girlfriend Carolina whose patience (and maybe even more, losing her patience) were an important motivation in finishing my thesis. Finally, my friends, in the Netherlands and abroad, and my housemates, for listening to my worries and discussing the contents of my thesis with me, over and over again; I am sure the prospect of dropping ”Beer's Thesis” as a conversation topic is something all of them look forward to. I would also like to express my sincerest hope that the electrification project of DC Opportunities becomes the success it has the potential to be. After all, access to electricity is a basic human need in this day and age, it gives people the opportunity to live a better life and it can help them to achieve their dreams (such as, writing and finishing a thesis).

B.W.T. Witteveen
Delft, July 2020

Contents

List of Figures ix

List of Tables xi

1 Introduction 1
1.1 Context 1
1.2 Problem statement 2
1.3 Research objectives and methodology 4
1.4 Literature review 6
1.4.1 Energy Storage Systems (ESS) 6
1.4.2 Pumped Hydro Storage overview 8
1.4.3 Small-scale pumped storage 9
1.4.4 Pumped hydro storage in isolated grids 9
1.4.5 Knowledge gap 10

2 Design criteria 11
2.1 Technical 11
2.1.1 Operating range 11
2.1.2 Quality of supply and power 13
2.1.3 Component availability 14
2.1.4 Main grid encroachment 16
2.2 Economic 17
2.2.1 Acquisition of funding 17
2.2.2 Low tariffs and revenue 18
2.3 Socio-cultural 19
2.3.1 Community trust and acceptance 20
2.3.2 Local technical skills limitations 21
2.3.3 Theft and vandalism 23
2.3.4 Political vertical networks and corruption 24
2.3.5 Regulations 24
2.3.6 Water balance 25
2.3.7 Environmental/ecological impact 25
2.4 Program of requirements 26

3 Technical design synthesis 29
3.1 Mini-grid architecture 29
3.2 Water storage system 30
3.2.1 Design options 30
3.2.2 Discussion 31
3.2.3 Decision matrix 40
3.3 Water conveyance system 41
3.3.1 Design options 41
3.3.2 Discussion 42
3.3.3 Decision matrix 47
3.4 Powerhouse 48
3.4.1 Design options 48
3.4.2 Discussion 50
3.4.3 Decision matrix 56

3.5 Provisional technical design . . . 56
3.5.1 Earth dam reservoir . . . 56
3.5.2 Penstock . . . 64
3.5.3 Powerhouse configuration . . . 66
3.5.4 Capital costs . . . 68

4 Organizational design synthesis 69
4.1 Theoretical approach to community-based projects . . . 69
4.2 Planning phase . . . 72
4.2.1 Community involvement . . . 73
4.3 Implementation . . . 74
4.3.1 Installation . . . 74
4.3.2 Organizational structure . . . 74
4.3.3 Operational structure . . . 75
4.3.4 Theft/vandalism prevention . . . 75
4.4 Operation . . . 76
4.4.1 Energy and water management . . . 76
4.4.2 Maintenance and repair . . . 77
4.4.3 Water conveyance system . . . 77
4.4.4 Powerhouse . . . 77
4.5 Provisional operational design . . . 78

5 Case study: Adi Araha, Ethiopia 79
5.1 Site analysis . . . 81
5.2 Boundary conditions . . . 82
5.3 PHS model . . . 86
5.3.1 Input profiles . . . 87
5.3.2 Parameters and constraints . . . 89
5.3.3 PHS parameter determination . . . 91
5.3.4 Energy Management Strategy (EMS) . . . 95
5.3.5 Modelling results . . . 97
5.4 Financial assessment . . . 101
5.4.1 One-time installation . . . 101
5.4.2 Comparison to Battery Energy Storage System (BESS) . . . 103
5.4.3 Scalable design . . . 105
5.4.4 Secondary water use . . . 106
5.4.5 Conclusion on the case study . . . 107
5.5 General feasibility . . . 108

6 Conclusions 111
6.1 Research findings . . . 111
6.2 Future work and recommendations . . . 115

Bibliography 117

Appendices 131

A Power flow diagrams 133

B Steel tank costs 137

List of Figures

1.1 World electricity access . . . 2
1.2 The potential of solar power and wind power in sub-Saharan Africa. . . . 4
1.3 Methodology of the thesis. . . . 6
1.4 Simplified standard layout of a pumped hydro storage (PHS) plant. . . . 9

2.1 Overview of the multi-tier framework . . . 12
2.2 Simulated results of an average weekly load profile . . . 12
2.3 Simulated results of an average weekly load profile, adjusted for demand response . . . 13
2.4 MFN tariffs for electrical machinery in Sub-Saharan African countries . . . 15
2.5 Distances to the main grid in sub-Saharan Africa . . . 16
2.6 Percentage of Sub-Sahara African rural population living in poverty . . . 18
2.7 Visualization of the mini-grid window . . . 19
2.8 Regions in Sub-Saharan Africa including offices of hydropower contractors . . . 21
2.9 Contractor location of hydropower projects in Sub-Saharan Africa . . . 22
2.10 Mean years of schooling comparison in Sub-Saharan Africa . . . 22
2.11 Institutions involved in rural electrification regulation . . . 24
2.12 Core criteria and design criteria . . . 27

3.1 Proposed architecture of the assessed mini-grid. . . . 30
3.2 Required amount of cubic meters of water to store one kWh . . . 32
3.3 Maximum amount of energy which can be stored per cubic meter size . . . 32
3.4 Global map of precipitation . . . 37
3.5 Global map of annual average temperature . . . 38
3.6 Water consumption in liter per capita per day, related to the distance in minutes from the water source . . . 39
3.7 The head losses with respect to the gross head difference, for a 75 and 150kW power output . . . 43
3.8 The head losses with respect to the gross head difference, for a 300 and 600kW power output . . . 44
3.9 The carbon emission (kg/CO_2) per kilogram of material produced versus the embodied primary energy . . . 47
3.10 Turbine selection chart for mini-hydropower . . . 51
3.11 Circuit of a Variable Frequency Drive (VFD) . . . 52
3.12 Pump curve showing potential damage and instability occurrences . . . 52
3.13 Cross-section of an earth dam with impervious core . . . 58
3.14 Representational cross-section of a reservoir constructed on a dry gully site. . . . 59
3.15 Representational cross-section of a reservoir constructed on flat land, a turkey's nest site 59
3.16 Relation between surface area and excavated volume of soil . . . 61
3.17 Visualization of the expansion of an earth dam reservoir . . . 62
3.18 Relation between reservoir cost and the desired reservoir capacity . . . 64
3.19 Indication of the price of the most economical pipes for certain situations . . . 66
3.20 Feasible configurations for a PHS system when considering the design criteria . . . 67
3.21 Graphical representation of the total capital costs of a Pelton turbine and a centrifugal pump . . . 68

4.1 Summary of design options and their implementation, their characteristic and advantages 73
4.2 An overview of the organizational structure as discussed in Chapter 4. . . . 78

5.1 Rainfall and elevation maps of Ethiopia . . . 79

5.2 An overview of the village Adi Araha, Tigray, Ethiopia 81
5.3 Height profile of the proposed installation site. 82
5.4 An overview of the suggested installation site for the PHS system 82
5.5 An overview of the irrigation schemes present in the Tigray region 84
5.6 Weekly demand profiles for scenario 1 and 2 87
5.7 Generation profile of 1 kWp of installed solar power in Adi Araha, Ethiopia 88
5.8 Power discrepancy profile for scenario 1. 89
5.9 Power discrepancy profile for scenario 2. 89
5.10 Histogram of the number of instances a certain power output is required for scenario 1 . 91
5.11 Histogram of the number of instances a certain power output is required for scenario 2 . 92
5.12 Visualization of characteristic efficiency curve of a Pelton turbine. 93
5.13 Efficiency curve for the turbine mode of the PAT used in scenario 1 (PAT Multitec 125/ 7-9.2). 93
5.14 Efficiency curve for the turbine mode of the PAT used in scenario 1 (PAT Multitec 150 /2-11.2). 93
5.15 Histogram of the positive power discrepancies of scenario 1 94
5.16 Histogram of the positive power discrepancies of scenario 2 94
5.17 Simplified flow diagrams of the discharging and charging cycles of the HESS 96
5.18 Visualisation of the alternatives occurring during the charging cycle. 96
5.19 annual discrepancy profile and SOC of the batteries and upper reservoir for scenario 1, option 1 99
5.20 annual discrepancy profile and SOC of the batteries and upper reservoir for scenario 1, option 2 99
5.21 annual discrepancy profile and SOC of the batteries and upper reservoir for scenario 2, option 1 100
5.22 annual discrepancy profile and SOC of the batteries and upper reservoir for scenario 2, option 2 100
5.23 Cost breakdown for scenario 1, option 1 and option 2 102
5.24 Cost breakdown for scenario 2, option 1 and option 2 103
5.25 Projections of LCoS for several energy storage technologies 104
5.26 Logarithmic growth of reservoir capital expense with increasing capacity. 107
5.27 Model outputs of the required reservoir storage capacity for several desired power outputs 109
5.28 Model outputs of the LCoS for several desired power outputs 110

6.1 Visualisation for the final design conditions for a feasible Pumped Hydro Storage plant . 114

A.1 The power flow diagram of the energy management strategy for the charging cycle. . . 134
A.2 The power flow diagram of the energy management strategy for the discharging cycle. . 135

B.1 Relation between on one side the capacity and one one side the shell thickness with the diameter and height of a storage tank 138

List of Tables

1.1 Technical parameters of energy storage technologies 7
1.2 Economic parameters of energy storage technologies 8

2.1 Power requirement boundaries of the storage system. 13
2.2 Transportation costs in the four corridors of Africa 15

3.1 Water storage system decision matrix 40
3.2 Commonly used materials for the penstock of small-scale hydropower projects 41
3.3 The expected service life and maintenance costs for each material. 45
3.4 The multi-criteria decision matrix for penstock materials suitable for low and medium head applications. 47
3.5 A comparison between a binary unit with a Pump-as-Turbine and a ternary unit with a Pelton turbine. The cross indicates the most favorable option for the design criterion. . . 56
3.6 Soil suitability for the construction of homogeneous and zoned earth dams 57
3.7 Realistic reservoir dimensions and their associated costs 63
3.8 Example of pipe types 64

5.1 Weather data for Mek'ele region 81
5.2 Ranking of Ethiopia on several elements determining the ease of doing business 86
5.3 The parameters of the Battery Energy Storage System (BESS). 90
5.4 The parameters of the Pumped Hydro Storage (PHS) system. 90
5.5 Summary of the assessed options for each of the two scenarios. 95
5.6 required outputs of the energy flow model and the associated parameter 98
5.7 Results of the set parameters for the case study simulation 98
5.8 Results of the simulations of the energy flow model for scenario 1, option 1. 99
5.9 Results of the simulations of the energy flow model for scenario 1, option 2. 99
5.10 Results of the simulations of the energy flow model for scenario 2, option 1. 100
5.11 Results of the simulations of the energy flow model for scenario 2, option 2. 100
5.12 Summary of the costs for each element of the two options for scenario 1. 102
5.13 Summary of the costs for each element of the two options for scenario 2. 103
5.14 The LCoS of the simulated case study, and the parameters required to calculate the LCoS 104
5.15 The results of simulating with the Homer Pro software. 105
5.16 Levelised Cost of Energy (LCoE) for each option. 105
5.19 Summary of the four different configuration options to reach scenario 2, and their capital expenses and Levelized Cost of Storage. 106
5.17 Total capital costs for a scalable design, from scenario 1 to scenario 2. 106
5.18 The LCOS of scalable designs. 106
5.20 Two existing earth dam reservoirs in the Tigray region. Information obtained from [99]. . 106

B.1 Stainless steel materials used for the construction of steel water tanks. 137
B.2 Realistic tank dimensions and their associated wall thickness and cost 139

Acronyms

AC Alternating Current
BEP Best Efficiency Point
BESS Battery Energy Storage System
CapEX Capital Expenses
DC Direct Current
DER Distributed Energy Resources
DG Distributed Generator
EE Excess Energy
EMS Energy Management Strategy
ESS Energy Storage System
GIS Geographic Information System
GRP Glass Reinforced Plastic
HDPE High-Density Polyethylene
HESS Hybrid Energy Storage System
kW Kilowatt
kWh Kilowatt-hour
KPI Key Performance Indicator
LCoE Levelised Cost of Energy
LCoS Levelised Cost of Storage
LPSP Loss of Power Supply Probability
MS Mild Steel
MW Megawatt
MWh Megawatt-hour
OpEx Operational Expenses
PAT Pump as Turbine
PHS Pumped Hydro Storage
PV Photo-voltaic
RES Renewable Energy Source
SDG Sustainable Development Goal
SHS Solar Home System
SOC State of Charge
S-PHS Sea Pumped Hydro Storage
SPD Small Power Distributor
SPP Small Power Producer
SSA Sub-Saharan Africa
ttkm thousand tonne-kilometer
U-PHS Underground Pumped Hydro Storage
VFD Variable Frequency Driver
VSC Voltage Source Converter

1 Introduction

To indicate the importance of this work, the introductory chapter will state the context and problem this thesis concerns itself with. Subsequently, the research objectives are clearly defined, as well as the methodology used to answer these objectives. A literature review will assess the current research on the subject, leading to a knowledge gap to be filled. Finally, the general structure of this thesis is presented.

1.1. Context

In 2015 the United Nations set the Sustainable Development Goals (SDGs), which are to be reached by 2030. One of these goals is considered central to reaching a better and more sustainable future for everyone: provide global access to clean, reliable and affordable electricity. While the global electrification rate is rapidly increasing [247], the developing South Asian and mainly the sub-Saharan Africa regions still have a high energy access deficit [236]. As of now, more than 700 million people are estimated to remain without electricity in 2040 [107]. Especially in sub-Saharan Africa the pace of electrification is lagging (see Figure 1.1), with 43 percent of the population still lacking access to electricity, predominantly in the rural areas [106]. With many of these people living in areas which are difficult to reach due to their remote location, often in geographically difficult terrain, decentralised electricity systems provide a solution. Off-grid electrification can be attained by two ways. Stand-alone Solar Home Systems (SHS) supply solar power and battery energy storage, usually for a single household. Alternatively, microgrids and mini-grids are standalone electrical systems connecting a community through wires, powered by solar panels, wind turbines and/or diesel gensets [142]. Microgrids are defined as systems with a generation capacity of 1-10kW, whereas mini-grids have a capacity ranging between 10kW to 10MW, according to he Alliance for Rural Electrification (ARE). Since 2012, only 6 percent of new connections were established using off-grid systems and microgrids. However, over the period to 2030, these decentralised systems are estimated to be the most cost-effective method to bring electricity to over 70 percent of currently unelectrified rural areas [106]. And while off-grid solutions such as Solar Home Systems can provide for a basic level of energy consumption, enterprises and mid-sized communities will need a larger supply of electricity. These electrification requirements can be supplied by implementing mini-grids, and as such, to stimulate proper development of these areas by providing both households as well as enterprises with sufficient electricity, there has been a substantial increase in businesses entering the market of microgrids and mini-grids [174].

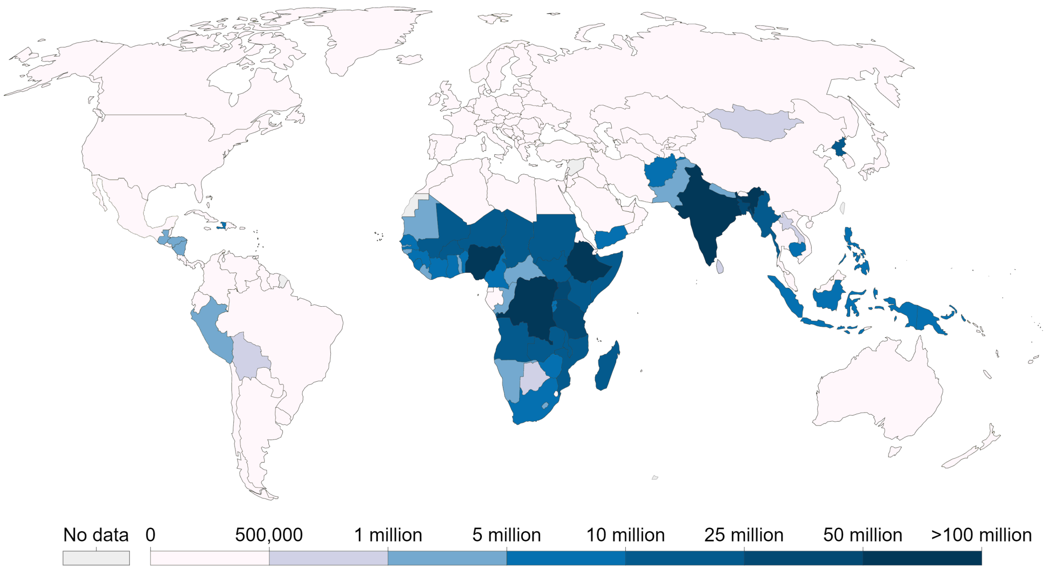


Figure 1.1: Number of people without access to electricity as obtained from [204]. A considerable lack of access can be observed in Sub-Saharan Africa, which additionally has a low electrification rate.

For the electrification of these rural areas, mini-grids using Direct Current (DC) show a lot of promise [139]. Compared to Alternating Current (AC), DC mini-grids have better reliability, efficiency and simpler control [192] [151] [208] [18]. It is especially useful for remote villages in developing regions, as many Distributed Energy Resources (DER) like photovoltaic panels and wind turbines, as well as most energy storage technologies, have DC power outputs and will thus only need a DC-DC converter, increasing the simplicity and efficiency of the mini-grid. Furthermore, many appliances are DC and non-linear, reducing the number of conversions needed even further. With advancements in DC technology many appliances which as of now run on AC will be available in DC in the near future, so since these mini-grids in developing regions are only just emerging now, they will be able to make good use of this development. Lastly, DC mini-grids have no need for reactive power management and frequency synchronization [71].

To provide a stable and reliable supply of energy, an Energy Storage System (ESS) must be integrated into the mini-grid. Due to the weather dependency and intermittency of Distributed Generators (DGs), energy storage needs to supply electricity to accommodate the varying load. Furthermore, fluctuations in the energy generated by the DGs create instability in the mini-grid, which the ESS can solve by balancing the power. Clearly, ESS will play an essential role in mini-grids, even more so when the mini-grid is remotely located and permanently runs in islanded mode. For a DC mini-grid, the ESS will have the function of providing energy when the DGs stop generating power due to lack of sun or wind. Moreover, to mitigate the high demand peaks, ESS can be employed for peak shifting. Additionally, to improve the stability of the mini-grid, energy storage is used for load levelling and voltage regulation [82]. A multitude of energy storage technologies can be used to supplement the mini-grid for these various applications [69]. However, for the case of stand-alone mini-grids, electro-chemical storage is by far the most explored form of energy storage [221].

1.2. Problem statement

DC Opportunities is a start-up based in Delft, with one of their main projects focusing on the electrification of rural areas in developing regions. The process of electrification is planned in 3 distinct stages:

1. Initial electrification stage using a central charging station and portable battery packs. This first stage accounts for the most basic energy demands, such as lighting, phone charging, radio, etc.

2. Subsequently, decentralised generation with solar panels purchased by community members allows for a modular expansion of the energy generation. In this stage, due to the growth of

generation, a higher load can be supplied and thus appliances with higher power consumption can be connected.

3. The third and final stage is connecting the community through a DC mini-grid, where large scale generation will combine with the individual decentralised solar panels to provide sufficient generation to supply large loads. In this stage, DC Opportunities considers energy storage as an essential part of these mini-grids, to provide constant and reliable power. This stage, specifically the energy storage, is therefor the focus of this thesis.

The problem owner DC opportunities thus considers a mini-grid with energy storage as a final stage of rural electrification. An important aspect to consider is these proposed mini-grids will have only photovoltaic (PV) panels as a means of energy generation. While many proposed mini-grids employ a mix of generating technologies, there are several reasons to commit to solar power only, especially for an isolated DC mini-grid:

- *Sustainable:* solar energy is a sustainable form of generation without emissions. Compared to diesel generators and even biomass generators, this is a much greener way of producing electricity.
- *High potential:* due to the high solar radiation present throughout the Sub-Saharan African region, solar power promises a lot of potential, more so than for example wind. This is visualized in Figure 1.2.
- *Developed market:* compared to other sustainable energy technologies, solar power is increasingly better developed and the standard industry learning makes it a competitive technology [60]. This is only expected to increase in the coming years.
- *DC output:* with a DC mini-grid, extra converters are required when adding wind or biomass generation, which use turbines. This adds additional costs and power losses, and increases the complexity of the mini-grid. For PV panels, this is not necessary due to their DC power output.
- *Easier expansion:* the electrification stages as described in this Section assume a gradual increase of distributed generation with constant addition of PV panels. While centralized generation becomes a requirement when stepping up to the mini-grid stage, it is easier to expand on an infrastructure with the same technology.
- *Easy maintenance and installation:* low requirements with regards to installation and maintenance are desired. If only a single technology is used, it requires significantly less maintenance and operation training than with multiple generation technologies. Moreover, installation of solar panels is relatively much simpler than the installation of e.g. a wind turbine.
- *Good transportability:* in addition to the above-mentioned factor, solar panels are easy to transport, while the components of a wind turbine or biomass plant present additional logistical requirements.
- *Inexpensive:* observing representative prices for the installation costs of PV panels [222] and small wind turbines [178] shows it is economically more attractive to increase energy storage capacity to store solar power than installing a wind turbine.
- *Biomass supply uncertainties:* the potential of biomass in Sub-Saharan Africa is uncertain, since competing uses of forestry and agricultural residues and waste are not well known. Combined with an extremely low agricultural production efficiency throughout the region, the potential of biomass is difficult to realise [114]. Finally, sustainable use of biomass resources also requires the evaluation of environmental, social and economic criteria. Correct evaluation of the sustainability of the biomass resources can however not be guaranteed in low-resource regions, where knowledge on this subject is scarce.
- *Location independent:* there is much less of a dependency on site-specific conditions for PV panels than other technologies. For example, small hydropower requires a flowing water source nearby, and biomass a sufficient supply line of sustainable waste and residue. Wind differs much per location, while the solar radiation shows a lot of potential throughout the region.

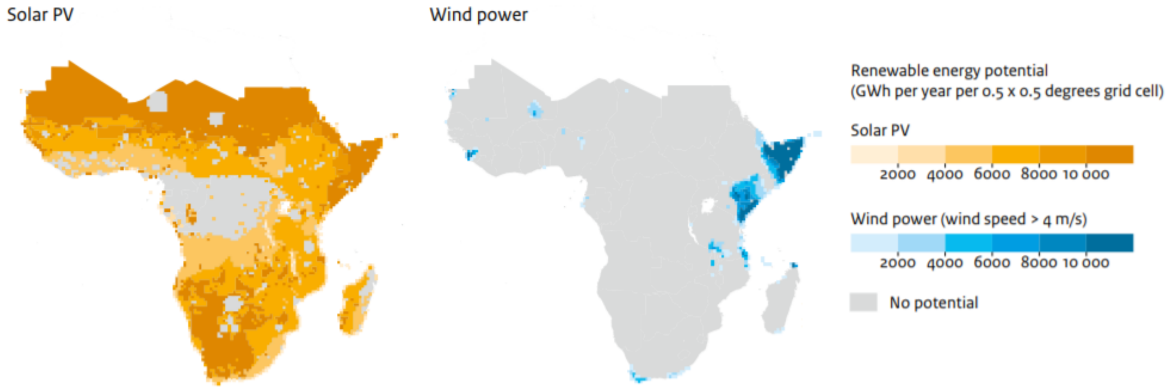


Figure 1.2: The potential of solar power and wind power in sub-Saharan Africa. Obtained from [143]

The above-mentioned reasons argue for using only solar power to generate electricity, allowing a standardized architecture which can be employed on every site without accounting for site-specific conditions. A small genset can however be installed as backup, but for the purpose of this thesis only solar power is considered. Such a standardized architecture makes mini-grids cheaper and easier to employ over a range of locations.

An important reason for establishing isolated mini-grids in developing regions is their difficult accessibility, which is often caused by mountainous terrain. Energy storage will be a necessity in these isolated mini-grids. Disadvantages of electro-chemical storage include low life-cycles (Lead–acid) or high production costs (Lithium-ion, Sodium–sulfur), as well as the negative environmental impact of the chemicals in batteries [193]. As an alternative, DC Opportunities would like to explore the possibility of providing energy storage to their mini-grids using the technology of Pumped Hydro Energy Storage (PHS).

The ability to utilize advantageous terrain combined with a lower environmental footprint might make small-scale PHS the most optimal form of storage for mini-grids in certain locations. Moreover, for the application of an isolated mini-grid in a low-resource region, other characteristics, other than just technical and economical, determine the compatibility of a certain ESS. Locational influences also need to be considered: e.g. local knowledge, component and material availability, geographical situation, local demand and social-cultural aspects. This thesis aims to research the feasibility of using PHS in the setting of remote mini-grids in low-resource areas, mainly in Sub-Saharan Africa.

1.3. Research objectives and methodology

A distinguishable characteristic for an ESS in an isolated mini-grid, in contrast with conventional grid energy storage, are the relatively low power output and energy capacity requirements. Moreover, absence of support from the main grid, combined with intermittent energy generation, make the ESS responsible for the balance between generation and demand. Placed in a setting where resources and knowledge are scarce, additional factors come into play, and socio-cultural factors influence the feasibility of the system. To account for these conditions, a different perspective on the feasibility of technologies for energy storage is needed: this thesis focuses on the technology of PHS in particular. The research questions structure the aim of this thesis, while the methodology frames the method used to answer these questions.

Main research question

How can the technical, economical and socio-cultural feasibility of Pumped Hydro Storage, as a means of energy storage in a remote and isolated mini-grid in low-resource regions, be assessed?

Research sub-questions

1. Which design criteria need to be considered when employing a Pumped Hydro Storage (PHS) system in an isolated mini-grid in a low-resource setting?

2. What are the implications on the holistic design of a PHS plant when taking these design criteria into consideration?

3. How does a PHS plant, with a design suited to the design criteria, function in a practical application?

Research methodology The characteristics of both a PHS system and the desired setting are dynamic, influencing the feasibility assessment. Therefore, the methodology is aimed towards obtaining a generalized result on the feasibility while still accounting for different situations. The methodology is based on the design cycle as proposed by Roozenburg and Eekels [207] and considers all four phases of a project: design, planning, implementation and operation [35].

1. *Scope of research*. The context, problem statement and research questions abstractly indicate the scope and goal of the research (Chapter 1). This gives a rough indication of the intended behaviour of the designed energy storage system.

2. *Literature review*. Subsequently, the literature review determines the current research on small-scale PHS, as well as the role of energy storage in isolated mini-grids (Chapter 1).

3. *Analysis*. In the analysis the challenges hindering the implementation of a energy storage system based on Pumped Hydro Storage technology are presented (Chapter 2). These are divided in technical, economic and socio-cultural challenges, and focus specifically on remote and rural mini-grids in the Sub-Saharan African region. This is gathered from literature research.

4. *Design criteria*. Based on the challenges set forth in the analysis, the holistic design of a PHS plant to be used in this setting must abide by several criteria. These design criteria decide which design options are suitable, and whether the proposed design overcomes the presented challenges sufficiently. The design criteria associated to each challenge are also defined in Chapter 2.

5. *Design options*. Existing literature and market research through contact with manufacturers leads to an overview of the technical design options for the key elements in a PHS plant (Chapter 3).

6. *Technical design synthesis*. This is the generation of a provisional design proposal. In Chapter 3, a discussion compares the design options with the design criteria, which leads to a selection of the most suitable technical design options. This selection becomes a provisional technical design which satisfies the design criteria to the maximum extent possible.

7. *Provisional technical design*. The design options, determined to be suitable by the design criteria, are elaborated on in the provisional technical design (Chapter 4); because of the dependence on geographical and site-specific characteristics, multiple designs are presented for several situation. An important aspect of this elaboration is establishing capital cost equations, which can be used in the simulation step. This provisional design completes the design phase; for the planning, implementation and operation phase a organizational strategy is required.

8. *Operational design synthesis:* the requirements of the planning, implementation and operation of the provisional technical design are assessed, so every phase of the project conforms to the design criteria. This leads to a holistic design, which encapsulates all relevant aspects required for the design, planning, implementation and operation phases of a PHS plant in an isolated mini-grid in a low resource-setting.

9. *Simulation*. The technical behaviour and functioning of a PHS design can be modelled and assessed, but the results are very dependent on local factors. This makes it difficult to make a general conclusion on the feasibility. Therefor, a case study is selected to assess the technical (through a energy flow model) and economic (through an LCoS assessment) feasibility for a specific location (Chapter 5).

10. *Evaluation*. In the evaluation section, the entire design (technical design, implementation and operation) employed in the case study will be compared to the design criteria (Chapter 2), to determine to what degree the desired properties are adhered to.

11. *Value of the design*. Finally, the conclusion on the feasibility of the case study is relayed to a feasibility assessment of a more general application (Chapter 6). This discussion chapter includes the economic analysis of a general case, and it is discussed whether, and to what degree, the conclusion on the case study can be extended to a more general conclusion on the feasibility.

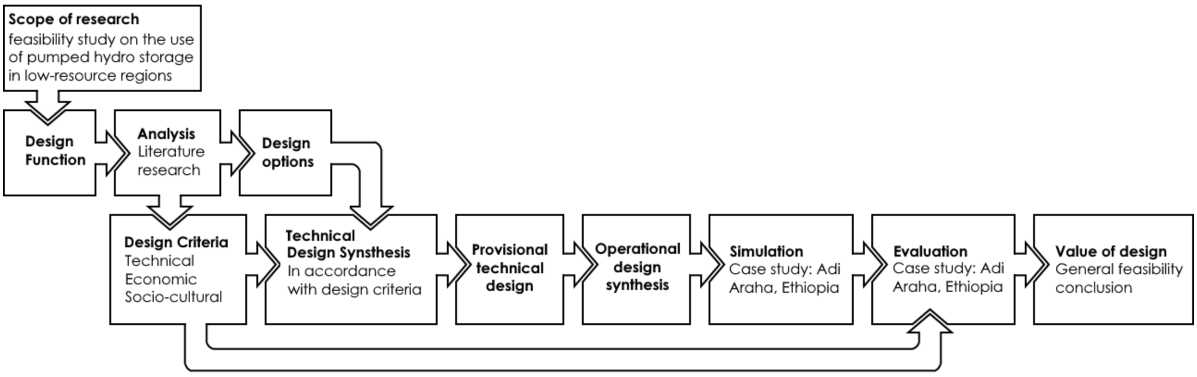


Figure 1.3: Methodology of the thesis.

1.4. Literature review

Pumped hydro energy storage is the most used storage technology in the world [23], with a global installed capacity of around 130 GW. These PHS plants are always built for bulk energy storage on a large scale, with sizes mostly ranging from 1000 to 1500 MW, but they can be as large as 3000 MW [202]. PHES has always been considered as a viable technology only when employed on a large scale, making use of its economy of scale advantage [149]. However, only recently small-scale PHS on a local level and its advantages are being studied more. Several studies place PHS in isolated mini-grids, research which this thesis will expand on. These studies are explored and subsequently the knowledge gap, which this work aims to fill, is discussed.

1.4.1. Energy Storage Systems (ESS)

An isolated mini-grid encounters several problems a conventional grid does not need to consider. Especially with a high or complete Renewable Energy Source (RES) integration, the stochastic behaviour of the renewable generation poses problems within the mini-grid. The power output is intermittent not only throughout the day, there are also seasonal variations. Lastly, with increased RES penetration, the primary control provided by conventional generating units with inertia falls away [188].

An ESS can provide a solution to these problems. Applications of an ESS in a DC mini-grid are the following [82] [80]:

- *Long term storage:* the seasonal discrepancies between generation and demand are balanced by an ESS.
- *Auxiliary service:* sudden fluctuations in the network voltage can occur in the form of spikes, surges, or undervoltage. This can be stabilised by the ESS. Furthermore, an ESS can employ droop control for stabilisation of the DC mini-grid [65].
- *Power supply support:* small fluctuations constantly change the reference load, which means distributed generators (DGs), such as solar panels, constantly have to change the amount of power they provide and cannot work at their rated power output. This can damage the generator and reduces the efficiency significantly. An ESS can assist with this by levelling the load, allowing the generators to keep a more constant power output.
- *RES integration:* the intermittent behaviour of renewable generation gives a fluctuating power output, and an isolated microgrid lacks a strong power source from a connection to the utility grid.

Therefore, this can cause large harmonics in the network voltage, making the microgrid unstable. An ESS can stabilise the power output of the distributed generators; by smoothing the output and controlling the ramp rate an ESS eliminates rapid voltage and power swings on the electrical grid. This facilitates the integration of renewable energy sources such as solar and wind power.

For the storage of energy a number of technologies are available. It depends on the characteristics technology which application they are capable of, how they add value to an isolated mini-grid and what the implications are of choosing one technology over another. Several important technical characteristics for the most prominently used energy storage technologies are presented in Table 1.1.

Table 1.1: Technical parameters of energy storage technologies [47] [131] [98].

Technology	Power rating (MW)	Self-discharge (% per day)	Energy density (Wh/kg)	Power density (W/kg)	Life-time (years)	Life-time (cycles)	Efficiency (%)
Electrical							
Capacitor	0-0.05	40	0.05–5	100,000	5	>50,000	60-65
Supercapacitor	0-0.3	20-40	2.5–15	500–5,000	20+	>100,000	90-95
SMES	0.1-10	10-15	0.5–5	500–2,000	20+	>100,000	95-98
Mechanical							
PHES	100-5,000	Very small	0.5–1.5	-	40-60	>13,000	75-85
CAES	5-1,000	Small	30–60	-	20-40	>13,000	70-89
FES	0.1-20	100	10–30	400–1,500	15+	>100,000	93-95
Electro-chemical							
Lead-acid	0-40	0.1-0.3	30–50	75–300	3-15	2000	70-90
NaS	0.05-34	20	150–240	150–230	10–15	2,500–4,500	80-90
Li-ion	0-100	0.1-0.3	75–200	150–315	5–15	1,000–20,000	85-90
NiCd	0-40	0.2-0.6	50–75	150–300	10–20	2,000–3,500	60-65
Metal-air	0-0.01	Very small	150– 3000	-	–	100–300	50
VRB	0.03-3	Small	10–30	-	5–10	>12,000	85
ZnBr	0.05-10	Small	30–50	-	5–10	>2,000	75
Chemical							
H2 Fuel cell	0-10	0	800– 10,000	500+	5–20+	1,000–20,000	25-58
Thermal							
CES	0.1-300	0.5-1.0	150–250	10–30	20–40	13,000	40-50
AL-TES	0-5	0.5	80–120	-	10–20	–	50-90
HT-TES	0-60	0.05-1.0	80–200	-	5–15	13,000	30-60

Apart from the technical characteristics, several economic characteristics are identified for these energy storage technologies. These are presented in Table 1.2.

Table 1.2: Economic parameters of energy storage technologies [47] [131] [98].

Technology	maturity	Capital costs [257]		Influence on environment	
		€/kW	€/kWh	Impact	Description
Electrical					
Capacitor	Commercialised	200-400	500-1,000	Small	Small amount of remains
Supercapacitor	Developing	214-247	691-856	Small	Small amount of remains
SMES	Developing	212-568	5,310-6,090	Negative	Strong magnetic fields impacting health
Mechanical					
PHES	Mature	1,030-1,675	96-181	Negative	Disturbance to local wildlife and water level
CAES	Mature	774-914	48-106	Negative	Emissions from combustion of natural gas
FES	Early commercialised	590-1,446	1,850-25,049	Almost none	-
Electro-chemical					
Lead-acid	Mature	1,338-3,254	346-721	Negative	Chemical disposal issues
NaS	Commercialised	1,863-2,361	328-398	Negative	Chemical disposal issues
Li-ion	Demonstration	2,109-,2746	459-560	Negative	Chemical disposal issues
NiCd	Commercialised	2,279-4,182	596-808	Negative	Chemical disposal issues, highly toxic
Metal-air	Developing	1,313-1,415	262-417	Small	Small amount of remains
VRB	Early commercialised	1,277-1,649	257-433	Negative	Chemical disposal issues
ZnBr	Demonstration	1,099-1,358	257-433	Negative	Chemical disposal issues
Chemical					
H2 Fuel cell	Research/developing /marketed	2,395-4,674	399-779	Negative	Remains and/or combustion of fossil fuel
Thermal					
CES	Developing	200-300	3-30	Positive	Removes contaminates during air liquefaction (Charge)
AL-TES	Developing	-	20-50	Small	-
HT-TES	Developed	-	30-60	Small	-

Pumped Hydro Storage is one of the most important storage technologies, but employment on a small-scale is hardly assessed. Several technologies can be used in conjunction to establish an ESS for an isolated mini-grid. Many of the technologies are however still in development, present high costs, or present significant impacts on the environment.

1.4.2. Pumped Hydro Storage overview

For the purpose of this thesis, where a PHS design under certain circumstances is considered, the general layout and components of a PHS plant should be clarified. A PHS plant works on the principle of converting electric energy to hydraulic potential energy. When there is a surplus of electric power, water is pumped from the lower reservoir to the elevated upper reservoir. The two reservoirs together compose the water storage system, and can be either natural or man-made.

In the case of an energy deficit, water is released through turbines, which convert the gravitational energy of water to kinetic energy. This is a cycle that can be repeated over and over again. For most PHS plants, the pump and turbine are the same hydraulic machine, connected by a shaft to a motor-generator, the electrical machine. The pump and turbine can however also be separate machines. Whichever configuration is used, the hydraulic and electrical machinery combined is referred to as the powerhouse.

As a means of conveying water from the upper reservoir to the powerhouse, a penstock is used. These are often closed conduit pipes, leading to high pressures due to hydrostatic pressure and water hammer, the pressure wave which occurs when the motion of the water is abruptly stopped. The effect of water hammer can be reduced with a surge tank or pressure valve. The flow rate in the penstock can be controlled with a control valve, or completely cut off in the valve chamber. All these components together are referred to as the water conveyance system. The components discussed are visualised in Figure 1.4.

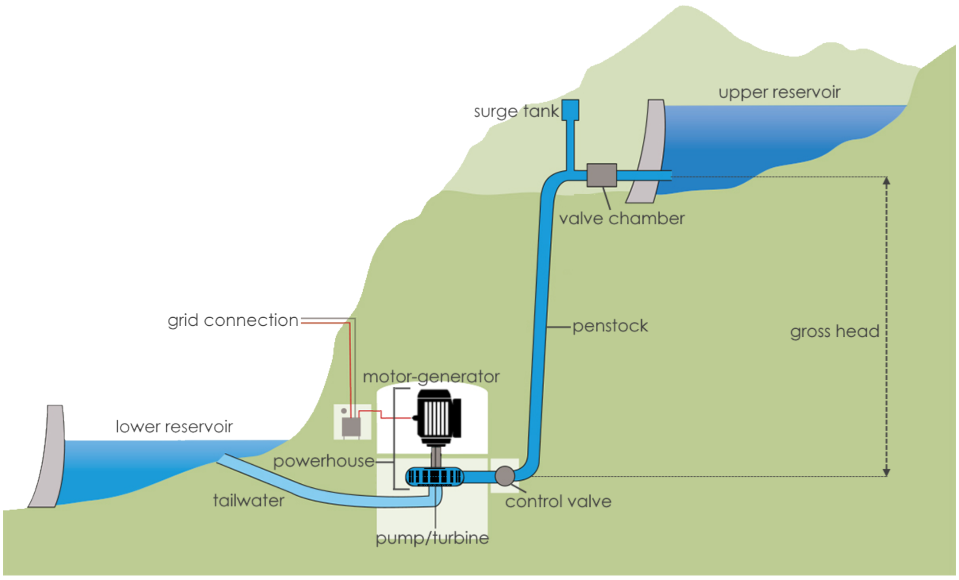


Figure 1.4: Simplified standard layout of a pumped hydro storage (PHS) plant.

The energy generated and stored is determined by the net head, which is calculated by subtracting head losses in the water conveyance system from the gross head. The gross head is the height difference between the inlet of the upper reservoir and the powerhouse.

Conventional pumped hydro storage is commonly employed on a large scale and this requires investment on a national scale [7]. There are many considerations to make in the design of the plant, and this design will vastly differ with the plant size and purpose, whether it is grid balancing or arbitrage. Local and small-scale PHS is increasingly being explored.

1.4.3. Small-scale pumped storage

While the upper limit of small-scale PHS or hydropower is arbitrary, the consensus is that sizes below 10 MW can be defined as small-scale [159]. While this can be further subdivided into degrees, this work will refer to the PHS size as small-scale due to the irregularity in definitions; however, some literature refers to degrees so a general understanding is required. PHS schemes below 2 MW are typically referred to as mini-hydro, micro-hydro are systems below 500 kW and pico-hydro below 10 kW [186].

Hydropower has distinct differences from pumped storage, but there are several similarities. Therefore researching literature on small-scale hydropower leads to useful insights which also apply to small-scale PHS. A much researched option for the power generation of micro-hydropower plants is the employment of centrifugal pumps used as turbines [3], an interesting technology to consider also for PHS.

PHS on a pico and micro scale have been researched to be utilized in buildings in Europe [66] and Latin America [74]. The pico-scale does not seem economically feasible, due to the economy of scale associated with PHS, this is further worsened by the constraints determined by the structure of the building. The structural integrity and the altitude of the building respectively limit the feasible capacity of stored water and the gravitational potential energy of the water. It is concluded in these studies that the topographical conditions can significantly decrease the costs of a PHS system and improve its efficiency, and synergy with the water supply is mentioned as a further social advantage. Unlike these studies, small-scale PHS is most commonly researched in the context of isolated grids.

1.4.4. Pumped hydro storage in isolated grids

Pumped storage is often considered as a viable energy storage technology in autonomous island grids, not interconnected with the mainland, where the landscape topology can be utilized. These isolated grids vary in size, and can not always be defined as a mini-grid. One study analyses the performance results of an established pico-grid for a small community of 13 households [147]. On a larger scale, two studies by Ma et al. focused on a techno-economic evaluation of a hybrid PV-pumped storage energy system for a mini-grid in a remote island near Hong Kong [144] [145].

With the aim of improving the penetration of renewable energy sources, several studies have considered the role of PHS in Greek islands not interconnected to the mainland. These studies research a size optimization of PHS for large isolated island energy systems, with the goal of exploiting rejected wind energy from an economic perspective [11] [120] [121]. Other research approaches the sizing of a PHS plant from a techno-economic perspective, where either the return on the investment is maximized using energy arbitrage, or the RES penetration is maximized [189] [41]. Finally, Caralis et al. [44] assesses a more general feasibility of wind energy combined with pumped storage (WPS).

1.4.5. Knowledge gap

A common trend in the current literature on small-scale PHS is the purely techno-economic approach. For each of the studies discussed, a specific scenario is assessed without regard for the more general feasibility in terms of socio-cultural factors, or site specific characteristics. Any additional implications of installing a small-scale PHS plant are ignored, while it would bring about a change of community life, rural economy and natural environment. Moreover, apart from the design phase, the other phases of planning, implementation and operation, accounting for local factors, have not been discussed in any research.

Furthermore, a oversimplification of the design as well as its functionality is maintained throughout most studies. Many inaccurate design assumptions lead to an unrealistic feasibility assessment. For example, a pump-turbine is often assumed with a determined efficiency, while these units are not manufactured for sizes below 5 MW. In the studies it is presumed there is no difference between large- and small-scale PHS, while these are in fact distinctly different.

Lastly, while the studies focus on isolated grids, these are mostly large autonomous grids, with apt support from conventional generating units. Only [44] and [144] consider PHS on the scale of a mini-grid for a community or village, where energy storage is essential for the generation and demand balance. Apart from encountering the previously mentioned issues, these studies are also focused on well-developed areas and do not account for other factors such as a lack of resources and knowledge, and social and cultural factors influencing the approach and success of a project, especially in Sub-Saharan Africa. No study sets forth the challenges a PHS plant installed in mini-grid in such a region might face. In fact, research suggest that dismissal of rural community and societal dynamics leads to the failure of many rural electrification projects [196]. As these socio-cultural factors are also neglected in the existing studies on small pumped-hydro storage, only the technical challenges are assessed, which thus makes existing research incomplete.

2

Design criteria

Pumped Hydroelectric Energy Storage is by far the most widely employed storage technology, providing 96 % of the energy storage capacity worldwide [198]. However, almost all of the operational PHES plants provide energy storage on a large scale, with capacities mostly in the range of 1,000 to 1,500 MW and some going up to 3,000 MW [202]. Furthermore, these plants are designed to be implemented in the main electrical grid, providing storage and support for a large AC network. For many of these plants the site at which they are built was chosen not only because of the topology, but geological conditions such as natural reservoirs were important for the site selection.

The context of this thesis places the technology of PHES in a different setting than the currently operational plants. The aim of this thesis is to assess the feasibility of PHES specifically in isolated mini-grids in low-resource regions in Sub-Saharan Africa. This specific setting present several challenges which an Energy Storage System (ESS), more specifically a PHS plant, is likely to face.

In this chapter, the technical, economic and socio-cultural challenges are explained. Each challenge subsequently leads to a design criterion. The combination of all these criteria forms a program of requirements, which the complete design of the PHS system should adhere to ensure a successful implementation and operation.

2.1. Technical

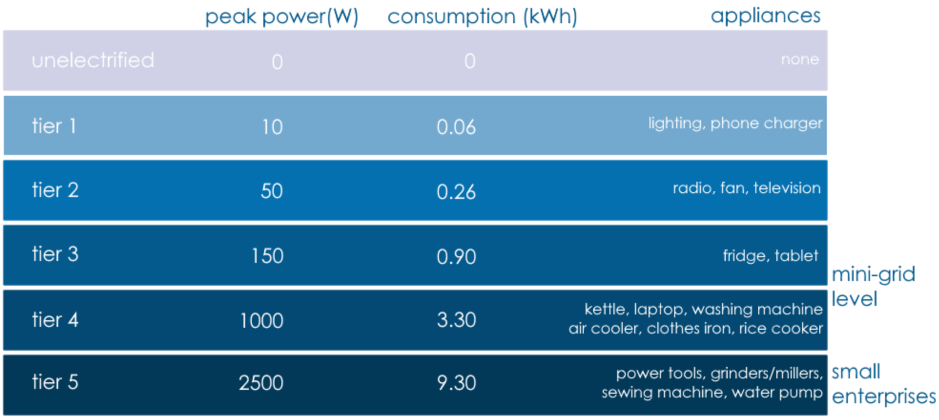
There are four technical challenges identified. These challenges and their associated design criteria mostly influence the technical design of the PHS plant.

First, since the mini-grids target rural communities, the energy requirements of these communities must be defined, and how these requirements translate to the PHS system; this is defined as the operating range. Secondly, assuring a quality of supply and power is required. Thirdly, component availability and difficulties in accessibility of the target communities are discussed. Finally, the chance of main grid connection of the mini-grid and its implications is considered.

2.1.1. Operating range

The operating range of the Energy Storage System (ESS) encompasses the maximum power output required by the ESS and the storage system's energy capacity. It is bounded by the fact that the PHS plant will operate in an isolated mini-grid. This means there is no connection to the main grid, and thus that the ESS is independently responsible for balancing generation and demand.

The IEA predicts 140 million people in Sub-Saharan Africa will be connected through 100.000 to 200.000 mini-grids in 2040 [108]. The rural communities to be connected by mini-grids range between 200 and 1000 households and small enterprises. A design criterion which needs to be applied, is a limit to the required capacity and power output of the system. This requires a load profile for the above-mentioned range of connections. Narayan [166] established a stochastic load profile model, specifically for the purpose of predicting energy needs for rural electrification. Through a multi-tier framework, the levels of electrification for a rural household are placed in three distinct tiers, as presented in Figure 2.1. Between tier 3 and tier 4, energy needs become significantly larger, requiring the formation of a mini-grid.



	peak power(W)	consumption (kWh)	appliances	
unelectrified	0	0	none	
tier 1	10	0.06	lighting, phone charger	
tier 2	50	0.26	radio, fan, television	
tier 3	150	0.90	fridge, tablet	mini-grid level
tier 4	1000	3.30	kettle, laptop, washing machine air cooler, clothes iron, rice cooker	mini-grid level
tier 5	2500	9.30	power tools, grinders/millers, sewing machine, water pump	small enterprises

Figure 2.1: Overview of the multi-tier framework [166], showing for each tier the approximate peak power (W), daily energy consumption (kWh) and the additional electrical appliances (included are the appliances from the previous tiers) for a single household.

As explained in 1.2, larger scale energy storage becomes a necessity when mini-grids are established. To determine the energy requirement range over which the feasibility is bounded, the load profile of 200 households as the lower limit and 1000 households as the upper limit is simulated and shown in Figure 2.2, with the assumption at least 40 percent of these households will be at the fourth electrification tier.

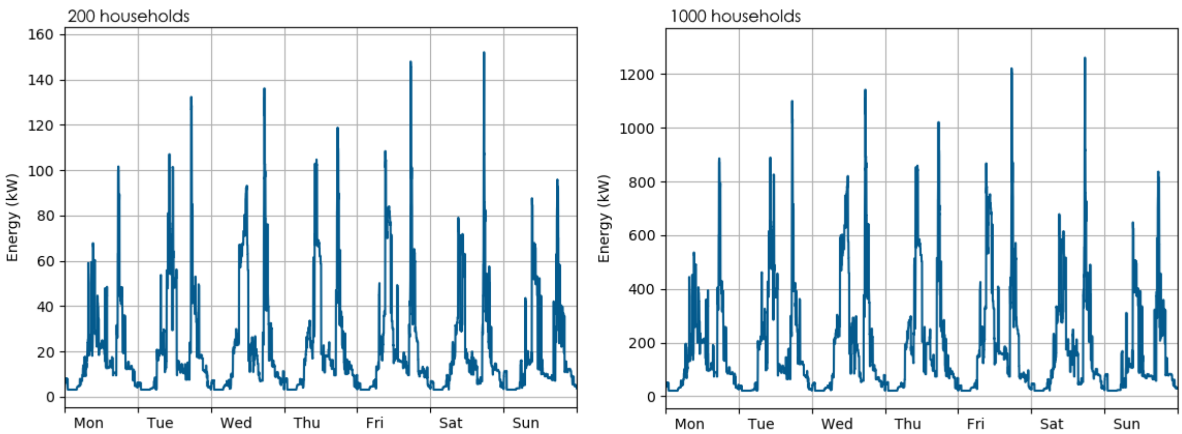


Figure 2.2: Simulated results of an average weekly load profile. *Left:* the lower energy requirements limit of 200 household of which 10% tier 1, 15% tier 2, 30% tier 3, 40% tier 4 and 5% tier 5. *Right:* Upper energy requirements limit of 1000 households of which 25% tier 3, 60% tier 4 and 15% tier 5.

Large demand peak can be observed, and these peaks find themselves in the evening hours, when solar generation is non-existent. However, for an isolated mini-grid, it is common practice to employ demand response and energy curtailment [86] [141]. Therefore, the ESS is not solely responsible for the generation meeting the demand. A more accurate estimation of the mini-grid power requirements, and thus the requirements of the energy storage, is represented by a load profile adhering to demand response. Shiftable loads for each tier are determined; these are the appliances that can easily be run at more convenient times than at peak demand. The demand is capped, and the shiftable loads are thus not allowed to run during peaks. The loads, which according to the model developed by Narayan run during peak times, but are determined to be shiftable according to demand response:

- Tiers 1-3: none
- Tier 4: clothes iron, washing machine, kettle and rice cooker
- Tier 5: clothes iron, washing machine, kettle, rice cooker, power tools, grinders and sewing machine

The total required energy exceeding the demand cap, called the shifted load, is proportionally divided over the hours between 7am and 5pm, which is the time of day where solar irradiation is available and the above-mentioned appliances can be utilized. To divide the shiftable loads proportionally, a larger fraction of the shifted load will be added to moments of lower demand. This is achieved by calculating a factor q for each moment in time (t), in the following manner:

$$q(t) = \frac{load_{cap} - load(t)}{load_{cap}}$$

$$q(t) = \frac{q(t)}{\frac{1}{n}\sum_{t=420}^{1020} q(t)} \tag{2.1}$$

Where, since the load profile is on a minute by minute basis, 420 and 1020 represent 7am and 5pm respectively. For each moment in time, this factor q is subsequently multiplied by the total shifted load, and added to the demand at that particular moment. This results in the following load profiles, for the lower and upper limit:

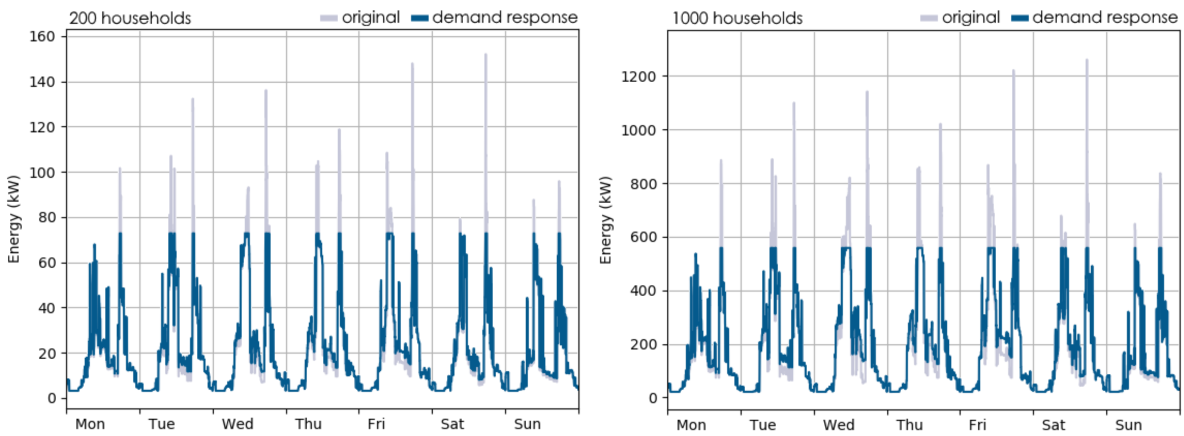


Figure 2.3: Simulated results of an average weekly load profile, adjusted for demand response. *Left:* Lower limit of 200 households. *Right:* Upper limit of 1000 households.

Associated design criterion The demand profiles, adjusted for demand response, can be used to find an approximation of the peak power and nominal energy capacity requirements of the storage system. Since only solar generation is assumed, and the peak demand is after sunrise, this peak demand will have to be provided entirely by the ESS. Therefor, the peak power output requirement from the PHS plant turbine ranges between 75 and 580 kW.

For the range of energy capacity requirements, the daily energy needs are calculated. Subsequently, this can be multiplied with the days of autonomy of the storage system, which is the number of days it should be able to provide energy without any generation (e.g. cloudy days). For an isolated mini-grid, this is usually taken as 3 days [155]. This leads to a range of storage capacity requirements of 1,440 kWh at the lower end, and 12,200 kWh at the upper end.

The design criteria for the operating range are summarized in Table 2.1.

Table 2.1: Power requirement boundaries of the storage system.

	Lower limit	**Upper limit**
households	200	1,000
nominal storage capacity (kWh)	1,440	12,200
peak power from storage (kW)	75	580

2.1.2. Quality of supply and power

The objective of installing an Energy Storage System (ESS), is to off-set the intermittent nature of the renewable energy source in the mini-grid. As established in 2.1.1, a mini-grid becomes necessary at a certain level of electrification of a remote and isolated community. The multi-tier framework presented has already been used to determine the energy demand, but can be further used to determine the supply requirements. For electrification tier 4 and 5, the tiers when mini-grids should be installed, a near constant supply of energy is needed [29], ensuring a high quality of supply. Furthermore, energy storage can be used to mitigate both long-term and short-term system transients. Long-term transients are generation variations over hours and days from a wind turbine or PV array, due to weather patterns. Short-term transients are for example step changes in load power or in source voltages [243]. An ESS can thus improve the power quality in the mini-grid.

A good quality of supply and quality of power presents the following advantages:

- Building trust: a near constant and reliable supply of electricity cements the trust of the mini-grid customers, and improves their satisfaction and level of acceptance of the technology. The importance of obtaining a high level of trust and acceptance is further explained in 10. Community trust and acceptance.

- Increase in revenue: instead of discarding excess energy, it can be stored and sold later to the customers. Many customers will however need this stored energy at the same instance, for example in the evening hours when it is time to cook. A successful balance of generation and load means all these customers can be served, increasing the amount of energy that is sold. Moreover, with flexible tariffs the customers could be prepared to pay higher tariffs at peak times, as long as their supply of energy is guaranteed. This again requires community involvement so the reasoning behind peak tariffs is understood and accepted. Finally, with a constant supply of reliable energy, more customers would be prepared to be connected to the mini-grid, increasing the customer base.

- Appealing to ‘anchor customers’: an anchor customer usually a business enterprise with a large energy demand, which requires a constant supply of energy and is likely to reliably pay for the electricity, making it a stable source of revenue for the mini-grid operator. This can be for example large farms or plantations, mines, or mobile phone towers, and a Power Purchase Agreement (PPA) can even be signed to ensure long-term revenue. These financially attractive customers often require a constant and reliable supply of energy, and a successful balance of generation and demand will entice them to sign a contract with the mini-grid.

Associated design criterion In order to ensure a good quality of supply and power, the PHS plant should balance demand and load at all times, minimizing the amount of excess and deficit energy, and improve the power quality in the mini-grid.

2.1.3. Component availability

In most African countries, the national utility charges below-cost tariffs, especially for rural customers [223]. This means their retail tariffs are non-cost-recovering. Operating a mini-grid near areas served by the national utility grid, will set a de facto price ceiling on the retail tariff. This is because the potential customers will think the cost-recovering tariffs of the mini-grid are unfair and too expensive compared to the nearby grid connected communities. This challenge implies that in order to charge cost-recovering tariffs, the mini-grid should be sufficiently far removed from the national utility connection so the de facto tariff ceiling can be avoided. It thus means remote villages are targeted, bringing along another challenge: limited accessibility due to poor infrastructure, and high transportation costs. Developing economies in Sub-Saharan Africa suffer from high transportation costs due to the following factors [15]:

- low availability and poor condition of road infrastructure.

- Inefficient logistics due to aging truck fleets and low utilization of trucks.

- National policies restricting competition, leading to the formation of cartels in the transportation sector.

- High fuel costs, especially for landlocked countries.

These factors accumulate in transport prices often exceeding the value of the goods being transported [94]. Sub-Saharan Africa can be divided into four geographic corridors: Western, Eastern, Central and Southern Africa. The average transportation costs of each of these corridors vary substantially , as shown in Table 2.2.

Table 2.2: The transportation costs in the four corridors of Africa, in euro per kilotonne-kilometer (kt-km). Information obtained from [195] [225].

	Southern Africa	West Africa	East Africa	Central Africa
Transport cost (€/kt-km)	60	70	80	110

A pumped hydro storage plants consists of several components. The water storage itself requires mostly civil construction works, but depending on the construction method, construction materials might need to be transported to the site. The pipes for thep enstock and the electro-mechnical equipment will certainly need to be transported to the site. Due to the high transportation costs and logistical complications due to unreliable infrastructure in remote areas, the transportation of components and materials becomes an issue.

Moreover, the components of the PHS plant need to be attainable. Some of the largest manufacturers of electro-mechanical machinery in the world, such as Andritz Group, Alstom, Voith and KSB have a significant international presence, including offices and manufacturing facilities in Sub-Saharan Africa. While they may not be present in every country, Figure 2.4 shows that tariffs on electrical machinery are relatively low for most countries, and even decrease due to the existence of customs unions within Sub-Saharan Africa.

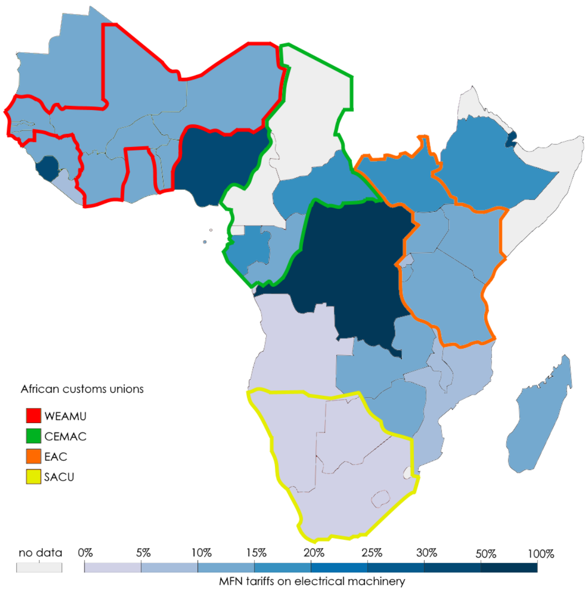


Figure 2.4: Most-Favored Nation tariffs for electrical machinery in Sub-Saharan African countries, data obtained from [184]. The map also includes the countries involved in a customs union together.

While for the initial stage of installation it thus seems feasible to obtain the electro-mechanical machinery from anywhere on the continent, for a reasonable price due to low import tariffs, the transportation of the equipment should also be considered. This is also a huge factor for the pipes of the penstock, the weight of which can accumulate to thousands of kilograms. Moreover, more advanced electro-mechanical equipment is only available in large industrial cities.

Associated design criterion The above challenge lies in the fact that the absence of local industry means many components and materials will need to be transported, but with high transportation costs and limited accessibility due to poor road infrastructure, it is difficult to get heavy components and materials at the site for a reasonable cost. The components and materials used should thus either be locally available or easily transportable.

2.1.4. Main grid encroachment

As mentioned, to be cost-recovering a mini-grid often has higher tariffs than the national utility, who in African nations often employ tariffs for rural customers which are below-cost. This disparity can lead to envy and dissatisfaction among a community, demanding connection to the main network. This in turn creates political motivation to connect a mini-grid to the national utility network. While this may take several years, depending on the distance of the mini-grid to the national utility network (see Figure 2.5), there is a good possibility that the main network will eventually reach and connect to the mini-grid; there is as of now in sub-Saharan Africa a focus on grid extension as the eventual goal to reach electrification [28]. When this happens, the main functions of the energy storage, balancing the generation and demand, and network stability improvement, become obsolete. Due to this, companies run the risk their investment proves to be worthless if the grid is extended [206]. One of these investments is the energy storage system, in this case the PHS plant.

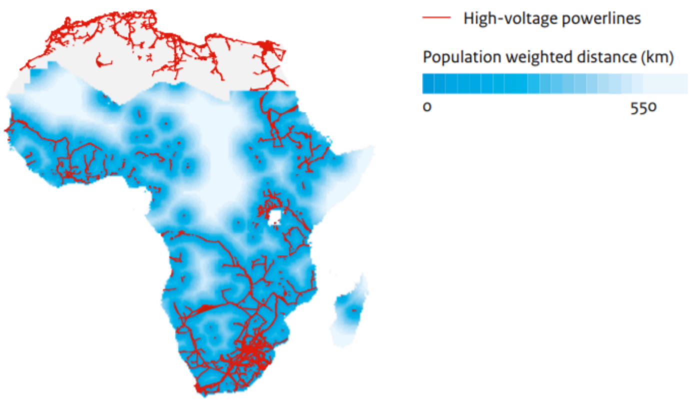


Figure 2.5: Distances to the main grid in sub-Saharan Africa. Obtained from [143]

There are however ways to keep the PHS plant useful, even if the mini-grid is no longer isolated. This depends on the option chosen by the mini-grid operator, when the main grid arrives:

- The mini-grid can convert to a Small Power Distributor (SPD). In this case, the mini-grid infrastructure will remain, but will not generate electricity anymore. Instead, it buys electricity at wholesale price from the national utility and distribute it at retail price to its customers. This is an unlikely option for the proposed DC mini-grids, due to large investments in PV arrays and the losses and difficulties presented by connection and conversion between the AC main grid to the DC mini-grid.
- The mini-grid operator can decide to only produce electricity, which it sells to the main grid network. In this scenario, it will no longer sell energy to customers at retail price. For this decision, the PHS plant could function as a means of energy arbitrage.
- As a compromise between both of the above options, the mini-grid can operate as it normally would, but use the electricity from the main grid either as backup or to supplement its own energy generation. This islanded operation is the most obvious choice for a commercially operated mini-grid, since energy is still generated locally and can be sold to customers at retail price. There is a profound implication for the PHS plant however. Since energy from the main grid can be used to balance the generation and demand, this function is not required anymore. However, the PHS plant can still be used for this purpose since operating costs would be lower than purchasing electricity from the national utility. Otherwise, it can again be used for energy arbitrage.
- The final option is a buyout. The operator might be forced to take this option, because the community is pushing for cheaper electricity from the main grid. However, if trust has been built withing the community, they might decide to remain connected through the DC mini-grid. After

all, connection to the main grid requires again a connection charge for each household, and the reliability of most main grids in SSA is low [220]. In the case of a buyout however, the PHS plant can still be used for energy arbitrage, but with little mechanisms and support for this in place it is likely the PHS plant will be discontinued.

Associated design criterion The main grid arriving to the area where the mini-grid is installed, can mean the discontinuance of PHS plant and thus a loss of investment. However, several design criteria can be set up so the PHS plant has a better chance of remaining useful even after grid connection.

First of all, the mini-grid should be either installed at a community sufficiently far away from the main grid, or the national electrification plan concerning grid extension should clearly state the community is not due for electrification in the next decade. With shifting political views, this is however an unreliable assurance and should not be used to decide a site for a mini-grid. Therefore, remote communities should be targeted, not just for the sake of the mini-grid but likewise for the PHS plant. This however is not a design criterion by itself, but more a challenge, which has already been translated to a criterion in 2.1.3.

The design criterion that is implied by the chance of main grid connection, is that it should be possible to use the PHS plant for energy arbitrage, and energy arbitrage must be facilitated by the main grid of the country. Since this research focuses solely on the PHS plant and not the mini-grid as a whole, this is the only option that should be accounted for.

2.2. Economic

The economic challenges concern issues with funding, low revenues and the issue of a cost-revenue gap which often troubles isolated mini-grids. The economic challenges influence the technical design, but also the strategies for implementation, operation and maintenance.

2.2.1. Acquisition of funding

Decentralized electrification efforts, like an isolated mini-grid, are generally carried out through non-governmental entities such as cooperatives, community user groups, or private entrepreneurs [223]. This is the same in the case of this research, where DC Opportunities is considered the problem owner. They will establish what is known as a Small Power Producer (SPP), which are independently operated, small-scale electricity-generating plants located near their customers, in this case through an isolated mini-grid. Such an isolated SPP sells electricity directly to retail customers.

There is however initial investment required to set up a SPP and the associated mini-grid infrastructure, including the ESS. Historically, for many SPP projects in Sub- Saharan Africa funding has come in the form of grants from governments, donors, or nongovernmental organizations [223]. Subsidies supplied by governments are often channeled through the Rural Electrification Agency (REA) of a country, and play an important role in the financial feasibility of a mini-grid. Whether funding is obtained through NGOs or REAs, an important factor in acquiring this funding is to impress the donor of the grant. An Energy Storage System can influence the attractiveness of a mini-grid project for investors and donors, either in a negative (e.g. environmental impact, unprofitable extra expenses, etc.) or a positive way (e.g. additional uses, extra profits, etc.).

An additional challenge is presented by the dependence on donors and subsidies. This kind of funding is not sustainable, due to shifting priorities in these kind of organizations [190]. This leads to the issue of receiving capital to start the project, but potentially losing money due to operational costs while funding dries up. If the funding is discontinued and the operational costs are thus too high, a situation can occur where the tariffs are no longer cost-recovering and the system is not financially feasible.

Finally, a dependence on donors brings the risk of establishing a patron–client relationship with donors, and the project becomes donor driven [256]. If the project then becomes primarily accountable to the donors instead of to the targeted communities, the focus can become more oriented on pleasing the donors instead of doing what works best for the community.

Associated design criteria Negative side-effects of the ESS lessen the appeal of the entire project so should be avoided. Instead, positive side-effects should be pursued to attract potential subsidies and donors. Moreover, in order to avert the risk of a cost-revenue gap, the PHS plant should not rely on funding during its lifetime. This is ensured by keeping the operational and replacement costs and requirements low. If the system is designed to be durable, funds from donors are no longer required as soon as the PHS plant is up and running.

2.2.2. Low tariffs and revenue

A cost-revenue gap is prevalent in many isolated mini-grids, due to three reason: the target customer base is among the poorest on the continent, decentralized electrification is expensive, and national utilities in Africa offer electricity for below-cost tariffs making it difficult to compete. All these reason are explained further below.

The focus of the proposed mini-grids is on communities and villages which are difficult to connect to the main grid. In these rural communities, more than 50 percent of people have an occupation in the agricultural sector [58]. In sub-Saharan Africa, a lack of modernised agriculture leads to subsistence and rudimentary farming, with low productivity and output. These areas have a seasonal economy, where communities depend on the agricultural cycles of planting, cultivation and harvest, and follow the patterns of rainfall. A consequence of this is low incomes and high poverty rates in rural Africa, affecting more than 60 percent of the population in some countries, as presented in Figure 2.6. More than three quarter of the extremely poor live in rural areas [61].

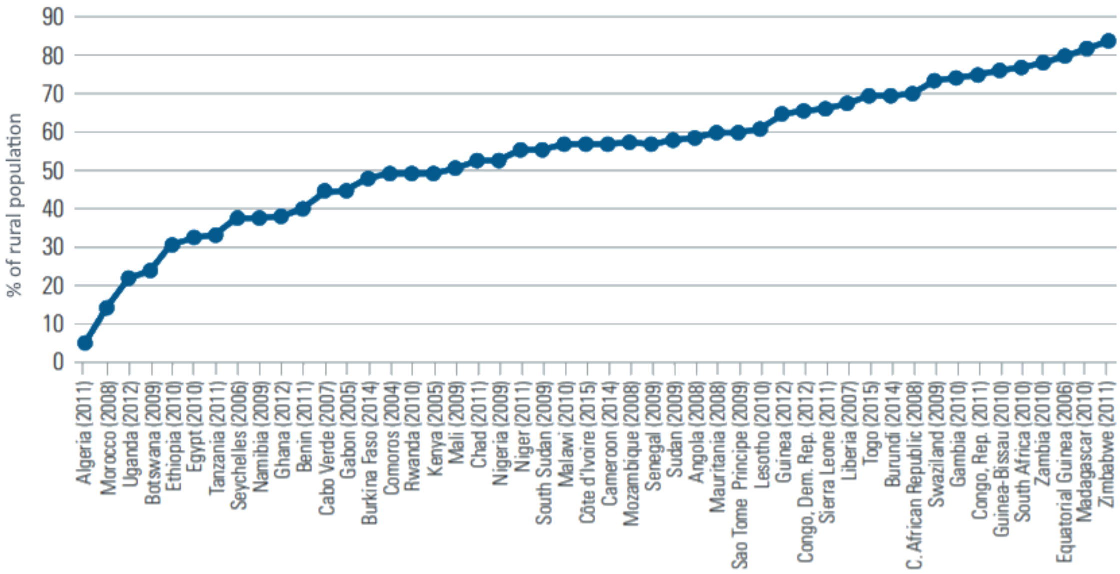


Figure 2.6: Percentage of the rural population living in poverty, as obtained from [172]. In many countries, especially in Sub-Saharan Africa, the percentage is more than 50 percent.

Connecting these rural areas to the national electricity grid can rapidly increase in expenses, with high investment cost of transmission lines (upwards of 22,750 €/km in most African countries) and of distribution lines(12,000 €/km) [76], and should only be done for densely populated areas with sufficient demand potential. The electricity tariffs of the national grid in African countries range from less than 0.04 €/kWh (subsidised) to 0.23 €/kWh (non-subsidised). Due to these high connection costs and low tariffs, conventional African utilities usually make a loss every time they connect a rural customer to the grid [93]. These conditions lead to a window where rural electrification is best achieved with mini-grids, as visualized in Figure 2.7.

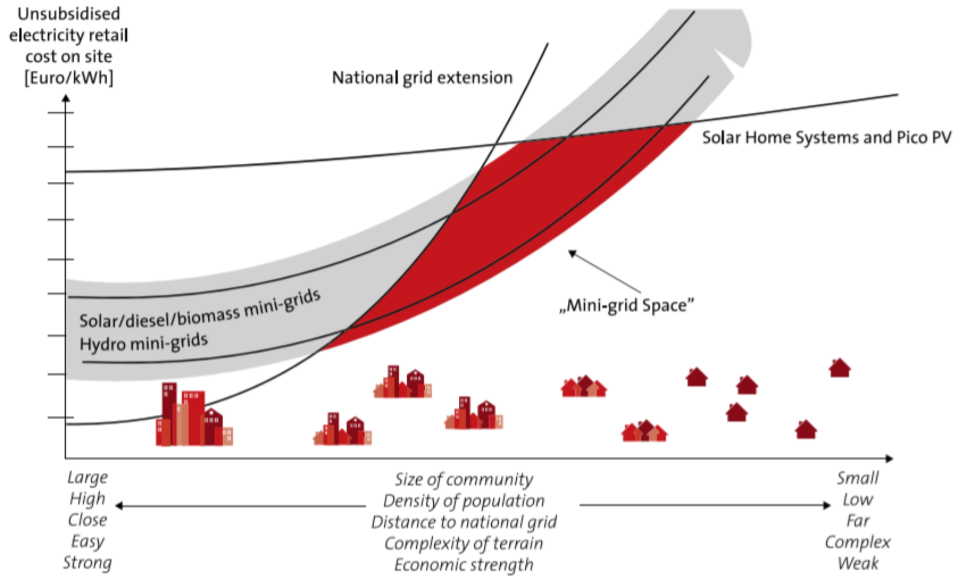


Figure 2.7: Visualization of the mini-grid window, dependent on local conditions: the size of the community, the density of the population, the distance to the existing national grid, the topography and general socio-economic factors such as energy demand and economic growth potential. Obtained from [76].

Most national utilities in SSA set a below-cost tariffs, which leads to a de facto price ceiling. This means it is unlikely customers close to the main grid are willing to pay a higher tariff than the one set by the national utility. The underpricing of African national utilities is shown in the surveys of the Africa Infrastructure Country Diagnostic (AICD). These surveys show that out of 21 national utilities in Sub-Saharan Africa, only 10 were allowed to charge tariffs that covered their historic operating costs, and only 6 of 21 national utilities were allowed to charge tariffs that covered historic operating and capital costs [67]. The de facto price ceiling, while more prevalent in mini-grids in closer proximity to the national grid network, will play a role in how high a mini-grid operator can set their tariffs. Moreover, national laws and regulations often do not permit a SPP to set the tariff high enough to be cost-recovering. To stay competitive, the cost-revenue gap should be avoided, by ensuring a low Levelised Cost of Electricity (LCoE) of the mini-grid.

Associated design criteria To avoid a cost-revenue gap, the PHS plant should be designed in an economical way, to ensure the lowest installation cost possible while still adhering to the remaining design criteria.

2.3. Socio-cultural

If rural electrification efforts fail to appropriately address the social and cultural challenges present in target communities, it can result in low or no acceptance of the project. A successful electrification project thus requires a holistic approach, and with the energy storage system being an integral part of the rural electrification, all socio-cultural factors influencing the functioning of the ESS should be considered to ensure successful operation of the entire mini-grid. Most socio-cultural design criteria affect the strategies of operation and maintenance.

There are several challenges which should be accounted for when implementing a Pumped Hydro Storage plant in a remote and rural mini-grid in sub-Saharan Africa. The trust and acceptance of the community is essential. Furthermore, local expertise and technical knowledge is limited. Issues can also occur with theft and vandalism of the system. Moreover, politically the vertical networks and regulations pose their own challenges. There is also the fact that unintended water use from the reservoirs is almost certain to occur, and in this lies another challenge. Finally, on an environmental level, a PHS plant can have significant impact if not designed correctly.

2.3.1. Community trust and acceptance

A significant involvement of the community can be observed in existing mini-grids which have proven to be successful [62]. This can be explained by the low-trust society which exists in many African countries [132], and trust is essential for the acceptance and adoption of a technology [38]. Community involvement is thus seen as an important factor in the level of acceptance. As the PHS plant would be an integral part of the mini-grid, acceptance of the PHS plant by the community is required for the success of the mini-grid. It could potentially even increase the success of the project, as satisfaction with one part of the mini-grid would increase the overall customer satisfaction. After all, the community consists of the end users, who use, pay for, and assess the mini-grid. Several issues can arise when the community does not trust and accept the technology of pumped hydro storage:

- *Neglectful operation and maintenance:* It is likely the community will be due to the need for day-to-day tasks and duties to keep the plant running. If members of the community are involved in the operation and maintenance of the PHS plant, a lack of acceptance will likely lead to an indifferent attitude towards the condition of the PHS plant. This can quickly result in a break-down of the system.

- *Lower revenue:* if the customers have no involvement, acceptance and trust towards the mini-grid, they might be unwilling to pay the tariff required to ensure financial viability of the system (likely higher than grid tariffs, see 2.2.2), or unwilling to pay at all. Existing electrification projects involving the community have shown higher payment rates and a less occurrences of electricity theft [246].

- *Load curtailment conflicts:* in the situation of drought, or when the demand exceeds the generation capability of the PHS plant, the load has to be curtailed. Demand response in itself is an important aspect of an isolated mini-grid, as explained in 2.1.1. Rejection or misunderstanding of the need for load curtailment can lead to conflicts.

- *Water regulation conflicts:* likewise, in cases of drought or lack of stored water, the community is less likely to accept the division of water if they are not involved in the water regulation. This can lead to unregulated water tapping, drying up the reservoirs and leaving the system useless. Moreover, proper involvement of the community paired with education will create understanding as to why such as basic need as water needs to be regulated in the first place, and can ensure the realization that following the water regulations is in the best interest of the entire community.

- *Increased corruption:* when no ownership/involvement toward the PHS plant is perceived by the community, there is much less resistance against mismanagement, misuse and theft by the operational personnel of the PHS plant. However, when the community feels a sense of ownership, anyone trying to bribe the personnel to receive favorable treatment, such as cheaper and more energy, additional water supply, etc. will directly impact the community in a negative way, and they will respond to it as such. With the strong-knit communities present in rural SSA, going against the community can lead to ostracism.

- *System sizing:* with no community involvement, there is much less awareness of the energy needs, leading to incorrect sizing of the system.

Associated design criterion A clear understanding is needed of the community which the mini-grid aims to electrify. A study by Terrapon [226] identified the need for community involvement in the project development and the formation of a sense of ownership amongst the user as key social issues to be tackled in order to establish a successful electrification project. Community involvement is an important aid in the required trust and acceptance mentioned in this challenge, and therefore part of the design criteria. To establish a sense of ownership, the community members must be viewed as stakeholders.

Involvement of the community would be desired in each stage: the initial planning, the installation and the operation. Community participation can be improved by making use of the existing hierarchical structure present in many African rural communities. A strong hierarchical social structure and the primacy of the group are cultural dimensions which are common throughout the whole sub-Saharan African region [55]. Employing this in the operation strategy of the PHS plant will help mitigate the problems mentioned in this challenge.

2.3.2. Local technical skills limitations

A rural electrification project, such as establishing mini-grids with PHS, requires apart from financial capital also human capital. If local people can be trained and employed to work on the electrification project, this increases its chance of success [150]. Especially if the employment of the local community members is replicable for others mini-grids, it ensures these projects will not just prosper on a pilot project basis, but are scalable to other sites as well. For the PHS plant specifically, the challenge thus lies in establishing a design allowing for the inclusion of local people during the installation and operation.

For the initial installation of a PHS plant, technical skills are required in the fields of civil, mechanical and electrical engineering. Since the installation is a one-time occurrence, expertise can come from outside of the direct surroundings. However, both the desire to contribute to the Sub-Saharan economy as well as the fact that local engineers have more experience managing a local workforce and local working conditions, lead to the goal of using engineers operating in the same region as the intended site of installation; these regions are divided into the Central, East, West, and Southern sub-regions of Africa (see Figure 2.8). However, due to the explained importance of involving the local population, the actual labour required during the installation should be fulfilled by a workforce coming from the target community itself. Likewise, the day-to-day operation should be executed by people living in the direct surroundings of the plant, to avoid the need for continuous outside support [220].

The assessment of accessibility to technical knowledge should thus be divided. Firstly, is sufficient technical knowledge available at the regional level, to bring in expertise of trained engineers, and secondly, the level of technical skill available in close proximity, within the local community.

The technical expertise available at a regional level is exemplified by the analysis of 62 recently (since 2000) constructed, renovated or upgraded hydropower plants in Sub-Saharan countries, ranging in capacity from 1 to 300 Megawatts. Almost all large hydropower projects are included in this. It was researched which companies were the main contractors for the civil works construction of these plants. Many of these companies have subsidiaries and offices in Sub-Saharan Africa; Figure 2.8 shows the office locations of some of the most recurring contractors. The Chinese *SinoHydro* and *CGGC*, as well as the Italian *Salini Impregilo* work on large hydropower projects, whereas *KSJ Construction* from Sri Lanka has constructed mainly mini-hydropower plants. Together, these 4 companies were responsible for the construction or renovation of 24 of the 62 assessed hydropower plants.

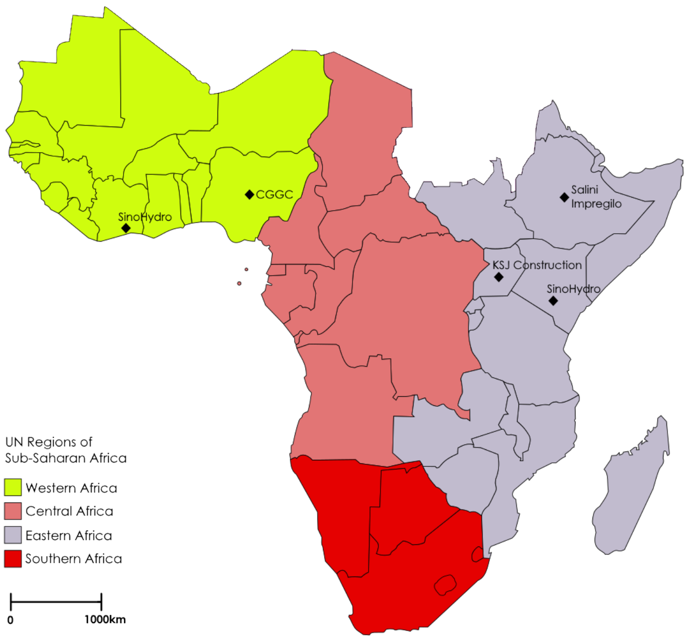


Figure 2.8: The 4 regions in Sub-Saharan Africa (Western, Central, Eastern and Southern), and the office locations of some of the most important contractors for the assessed hydropower projects.

Subsequently, the headquarters location for each main contractor for the 62 hydropower projects was researched. The existence of an office or subsidiary of the main contractor in the same region as the installation site was also assessed, and visualized in Figure 2.9. The goal of this research is to uncover the availability of civil engineering knowledge of large construction works related to hydropower, in Sub-Saharan Africa.

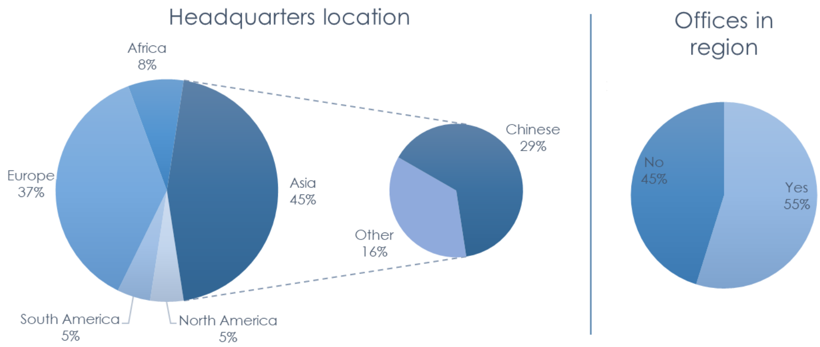


Figure 2.9: *Left:* of the 62 hydropower projects in Sub-Saharan Africa assessed, the percentage of the main contractors headquarter locations are shown. *Right:* for all of the main contractors of these hydropower projects, the percentage of which have an office or subsidiary in the same region as the project.

With only 55 percent of the main contractors having branches located in the same region as the project, it cannot automatically be assumed civil engineering knowledge with regards to hydropower projects is regionally available.

At a local level, in close proximity to the designated PHS site, the technical skills are also assessed. The target site for a mini-grid is in a remote and rural area. In rural Sub-Saharan Africa, 90 percent of rural households are engaged in agriculture [49]. While this is often combined with non-farm activities, rural enterprises are limited to those that do not require additional education. The lack of education among the rural population of Sub-Saharan Africa is further visualised in Figure 2.10, as obtained from research by the World Bank Group [56]. It has been mentioned the rural population is among the poorest in SSA (see Section 2.2), corresponding to the lower 80 percent of population by income in the Figure (orange columns).

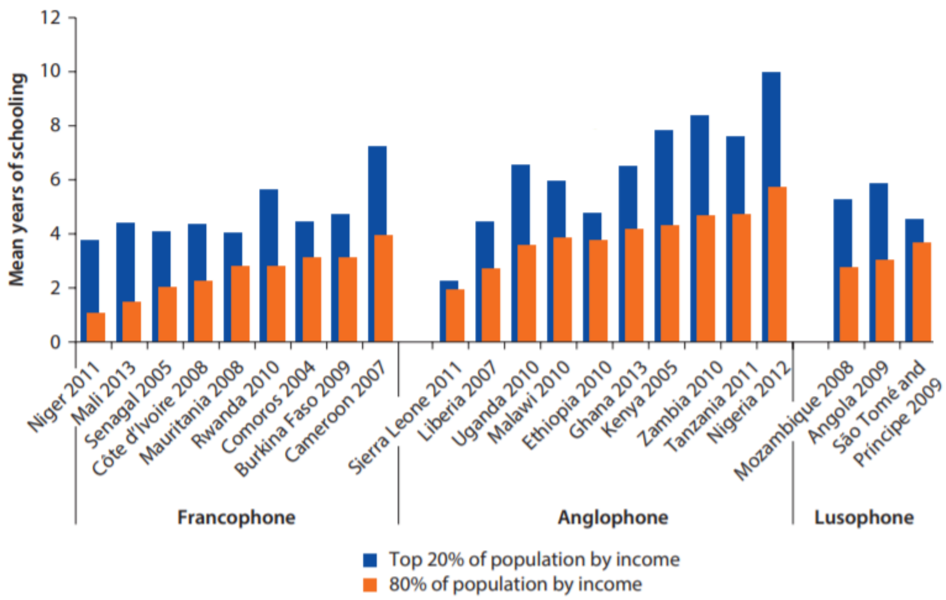


Figure 2.10: A comparison of mean years of schooling between the upper quintile of the population by income and the lower 80 percent. The rural population of Sub-Saharan Africa falls within the 80 percent and receives on average 3 years of education.

It can be observed that the rural population receives, depending on the country, on average 1 to 6 years of education. In most countries this is significantly less than the upper quintile. It can thus be concluded that the rural population has a low level of education. The fact that the target communities in rural areas are less educated, makes local and skilled human capital harder to come by [31].

From the technical skills available on the local and regional level, a challenge regarding the implementation, operation, maintenance and repair of a PHS plant presents itself. For the initial construction stage of the PHS plant, civil engineers designing and overseeing the project can be brought in from the region; it can however not be assumed regional civil engineers can be found to design and oversee the construction of complex civil structures, such as large concrete dams. For the actual labour however, a local workforce is required, due to the requirement of involving the local population and to save on mobilisation costs.

Moreover, it is important to note that many development projects fail because at some point, they arrive in a state of disrepair [181]. If continuous expertise and involvement from outside the community is required, it is likely the system will fall victim to operational malfunction due to a lack of local expertise. Therefore, for the operation, maintenance and repair of the PHS plant, locally trained operation personnel is required. The challenge lies however in involving the local population in all aspects of the PHS implementation and operation, including maintenance and repair, while their education and technical skills are limited.

Associated design criterion Due to the lack of a professional and educated local workforce, expertise required for the installation, operation, maintenance and repair of complex structures and equipment will make it difficult if not impossible to involve the target community to a high degree. As this is essential for a well-functioning mini-grid, the technical skills and expertise required for the installation, operation, maintenance and repair of the PHS plant should be obtainable by the rural population with rudimentary training and education. Moreover, the training of local technical personnel is an essential part of the implementation strategy, lest the system malfunctions and is eventually abandoned due to lack of support.

2.3.3. Theft and vandalism

An important factor in the failure of many electrification project is theft and vandalism [110]. For theft and vandalism to occur, three instigators can be identified:

- *Government inequality:* an unfair distribution of wealth is present throughout SSA, with income inequality even rising in many African countries [173]. This leads to frustration and anger among the poor, which often manifests itself in theft and vandalism of public works. Likewise a rural electrification project can be plagued by this instigator of theft and vandalism; the community itself might perceive it as unfair that they are not connected to the main grid, which without proper involvement and education of the community might seem like the better option. Indirectly, both other instigators can be influenced by this government inequality.

- *Crime to survive:* often a product of above-mentioned government inequality, there are instances reported of stolen components of rural electrification projects [110], which are then sold in order to earn money.

- *Sabotage:* the implementation of an electrification project in a specific community can lead to envy from a neighboring community [111]. With tight-knit communities and tribal factors prevalent in SSA [12], destruction of mini-grid components can occur without it benefiting anyone, just as an attempt to disrupt by a neighboring community.

Associated design criterion The design of the PHS plant should prevent the possibility of theft and vandalism. Community involvement can play an important role in a feeling of ownership, but this is only prevention from the community itself. Neighboring communities can still steal components or sabotage the PHS plant, which should be considered in the technical design.

2.3.4. Political vertical networks and corruption

In comparison to developed nations, a greater degree of corruption is present in SSA [165]. With almost any project or enterprise, the political vertical networks of Africa have to be navigated. Sometimes it is necessary to work together with state bureaucracy, although through establishing trust and cooperation between different groups (such as the target community itself) the state apparatus can be partly avoided [132]. However, for some essential aspects, such as permits and subsidies, the government can not be avoided. In many African countries, this is arranged through a Rural Electrification Agency (REA); In Sub-Saharan Africa, over 15 REAs have been created to promote rural electrification, which are responsible for the provision of subsidies for rural electrification projects [118].

The vertical networks make establishing a relatively large project, such as a PHS plant, difficult. While there will be a specific agency involved, so politics is partly avoided, shifting priorities and allegiances are always a major part of any governmental organization. Therefore, building up trust and cooperation within an REA will take time, and all progress towards collaboration could be nullified with a single election and shift in perspective on a certain project. Moreover, the large monopolist national utilities might work actively against SPPs and could use the vertical network to bring a negative attitude towards private SPPs using mini-grids, out of fear for loss of customer potential. This brings risks for a relatively large (large compared to e.g. solar home systems) electrification project, such as a PHS plant.

Associated design criterion The PHS plant should be implemented over time, to account for shifting priorities of the government, which brings risks for the implementation of a project on a relatively large scale. It would be best to make the PHS plant scalable over time, not only for political purposes but also to slowly build trust.

2.3.5. Regulations

On a national and regional level, political support from the government is of critical importance for a successful rural electrification project. In sub-Saharan Africa, the responsibility for the national electricity infrastructure is highly centralised and a part of the state apparatus [233]. This is because electrification is used as a political promise in order to attract voters, as its implementation is easily verifiable. This has led to the formation of governmental institutions to oversee rural electrification in most Sub-Sahara African countries. In many countries, these institutions have greatly increased the effectiveness of rural electrification.

There is a common institutional set-up for rural electrification in most SSA countries, influenced by a World Bank driven reorganization of the energy sectors [83]. At the top governmental level, the Ministry of Energy decides the overall energy policy, with often an additional regulatory body overseeing the implementation of energy laws and regulations. The aforementioned REA has a mandate to implement smaller off-grid electrification projects, which they can also subsidize using the Rural Electrification Fund.

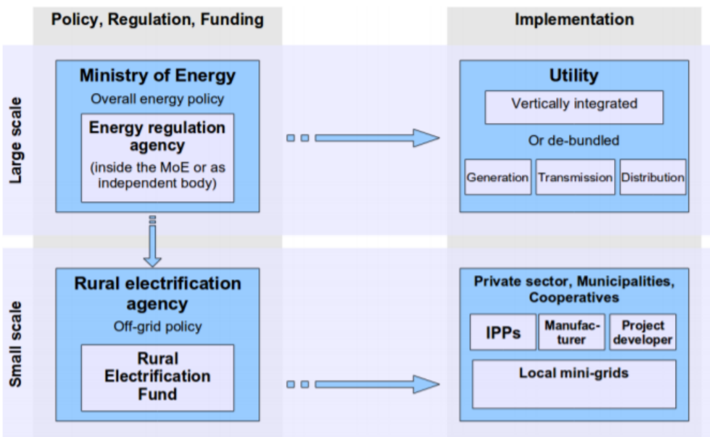


Figure 2.11: Institutions involved in rural electrification regulation [83].

While this structure seems clear, in practice electrification projects can run into regulatory problems. For example, in Kenya a Mini-Hydro Project (MHP), Thunga Kabiri, was at first not allowed to supply electricity directly to households due to legal requirements. And in Ghana, three different institutions have to give their permission to SPPs to allow them to generate and distribute electricity [83]. Especially a small-scale PHS plant, which is as of yet has not been implemented in any rural electrification projects, might encounter difficulties to receive the right permits. Land and water rights are governed by the state, and should thus be followed. Land and water rights are closely related, and while land rights are easier to obtain, water is considered a public good and its use is thus associated with more permits and regulations [218].

Water rights are legal rights, concerned with the removal and use of water from a natural source. Water rights come into play when a specified quantity water from a natural source is either used directly, first diverted and then used, or impounded behind a dam or other hydraulic structure. Using a natural source of water in any of these ways requires a formal right, obtained from the local government. Water rights regulate how much water can be stored in a reservoir.

Associated design criterion To avoid any regulatory or legal issues with the state apparatus, the PHS plant should be designed in a way that national regulations and laws are followed. For an unfamiliar project such as a small-scale PHS plant, it is thus best to follow existing regulation. This is related to land and water rights, to construct and fill the reservoirs.

2.3.6. Water balance

Rainfall fluctuations of varying lengths and intensities commonly occur in sub-Saharan Africa [87]. Associated with this are periods of drought in many regions in sub-Saharan Africa; half of the world's population will live in conditions of severe water stress by 2025, with conditions especially extreme in Africa [102]. A large water reservoir can make a huge impact during these times of drought. For this reason, reservoirs are often built in such regions to be used by the surrounding village inhabitants, and the majority of dams are constructed primarily for irrigation or agricultural purposes.

Large reservoir also need to be built for a PHS plant. It is thus only natural the surrounding community will start using these reservoirs for irrigation, as domestic water supply, or even for a fishery, effectively converting the stored water into a common-pool resource. However, a lack of water in the reservoirs can lead to a malfunctioning system, and a lack of water is more likely to occur in a dry season, when more water is tapped by the community and evaporation exceeds rainfall.

Associated design criterion Unintended water use by the community is almost guaranteed to occur, but when accounted for by the PHS plant design, can generate significant positive side-effects. Water use by the community for other purposes is then referred to as secondary water use. Apart from the fact that this secondary water use is almost unavoidable, using multipurpose reservoirs actually presents several advantages:

- The appeal of the system is increased, improving the chances to attract donors and subsidies (see 2.2.1).
- It increases the trust and acceptance of the community, who get additional uses out of the PHS plant. In fact, if efforts are made to avoid secondary water use, it can easily create opposition within the community, decreasing their trust and acceptance.

Therefore, secondary water use should be implemented as a part of the design. This means the water stored in the reservoirs must be considered as a common-pool resource.

2.3.7. Environmental/ecological impact

Small-scale PHS plants do not, unlike large plants, require the construction of large dams, mitigation of mass population, nor does it involve deforestation and silting problems [180]. However, directly or indirectly, the construction of dams affects land use. It can effectively turn land into aquatic ecosystems, and thereby reduce the amount of land available for farming. Moreover, flooding natural depressions or valleys has a significant negative influence on the environment. Likewise, using existing bodies of water or river systems as reservoirs negatively influences their aquatic ecosystems [253], and diverting too much water to a reservoir poses issues for the water levels in the surrounding area.

Agriculture is a major part of economic activity in the target regions [45]. Making adjustments to the terrain or the natural water cycle can thus damage or transform the surrounding environment in such a way that it destroys people's livelihoods, or it can cause ecological destruction.

Associated design criterion While land is required for the building of the reservoirs, several measures can be taken to reduce the impact on the surrounding environment and ecological systems. The PHS plant should be designed in a way that any environmental or ecological impact are minimized.

2.4. Program of requirements

Combining the technical, economic and socio-cultural challenges and their associated design criteria leads to a program of requirements. The design decisions should aim to fulfill this program of requirements as much as possible. The program of requirements of the PHS plant design is summarized as follows:

1. Ability to output a power ranging between 75 and 580 kilowatt and have a capacity ranging between 75 and 580 kilowatt and 1,440 and 12,200 kilowatt-hour.
2. Improvement of the quality of supply and power in the mini-grid.
3. Locally available components and materials, or or easily transportable from a location within reach, are used.
4. Compatibility with connection to the main grid network.
5. Increase the appeal of the mini-grid rather than degrade it.
6. Low operational and replacement costs through a durable design.
7. Low capital costs, such as installation and component costs.
8. Community involvement and participation to a high degree at every phase.
9. Required expertise and technical skills for installation, operation and maintenance is attainable by the rural population with rudimentary training and education.
10. Difficult to steal and vandalize the components.
11. Possibility for implementation over a longer time-frame, through a scalable design.
12. Adherence to land and water rights.
13. Considers the stored water in the reservoir as a common-pool resource.
14. Little environmental and ecological impact.

These design criteria work together to satisfy four core criteria for a successful energy storage installation: technical functionality, community trust and acceptance, economic viability and political approval. Moreover, several design criteria reinforce other design criteria. Figure 2.12 visualizes the design criteria assisting each core criterion, and which design criteria reinforce others.

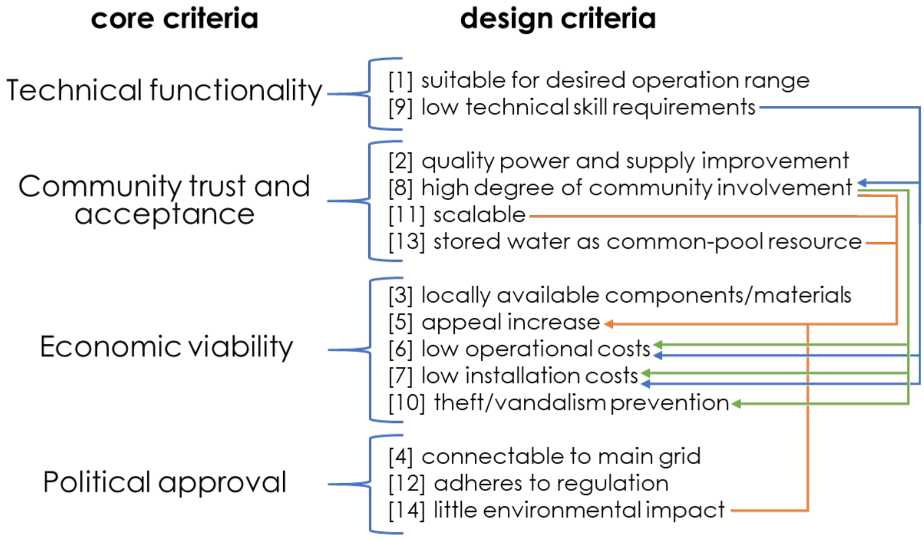


Figure 2.12: Core criteria are satisfied by a group of design criteria. Orange and blue arrows: several design criteria reinforce others.

In the next chapter, the technical design synthesis, the program of requirements decides the technical design of the Pumped Hydro Storage plant.

3

Technical design synthesis

The design synthesis eliminates possible design options if they do not comply with the design criteria established in Chapter 2. The technical design covers the physical design of the PHS plant; which materials, components and construction methods are used. While this primarily constitutes the design phase of the project, implications on the planning, implementation and operation phases are also discussed.

It is important to first get a general sense of the mini-grid architecture. Subsequently, the physical design of the three distinct PHS plant elements are discussed: the water storage system, the water conduit and the powerhouse. For each of these elements, the technical design options are discussed, after which a discussion will compare them with the program of requirements from Section 2.4. Finally, a decision matrix summarises whether the options meet the design criteria. A decision is then made on the most suitable design option for each element; which is the option or options satisfying the program of requirements as well as possible.

The design synthesis frames a provisional technical design in Chapter 4. With this in place, the focus shifts to the planning, the implementation and the operation of the PHS plant in Chapter 5.

3.1. Mini-grid architecture

To adhere to the design criterion which requires the PHS system to improve the quality of supply and power in the mini-grid, the isolated mini-grid requires service from the ESS at different time scales. Short-term energy fluctuations and balancing low power requirements cannot easily be accommodated by a storage system based purely on PHS, due to the limited range of a pump and turbine. The low power discrepancies can be better supplied by a Battery Energy Storage System (BESS). Batteries have complementing characteristics to the long-term usability of PHS; matching storage technologies with different attributes enhances the power quality and reliability. Such a system, utilizing multiple energy storage technologies, is known as a Hybrid Energy Storage System (HESS).

The proposed architecture of the mini-grid is presented in Figure 3.1.

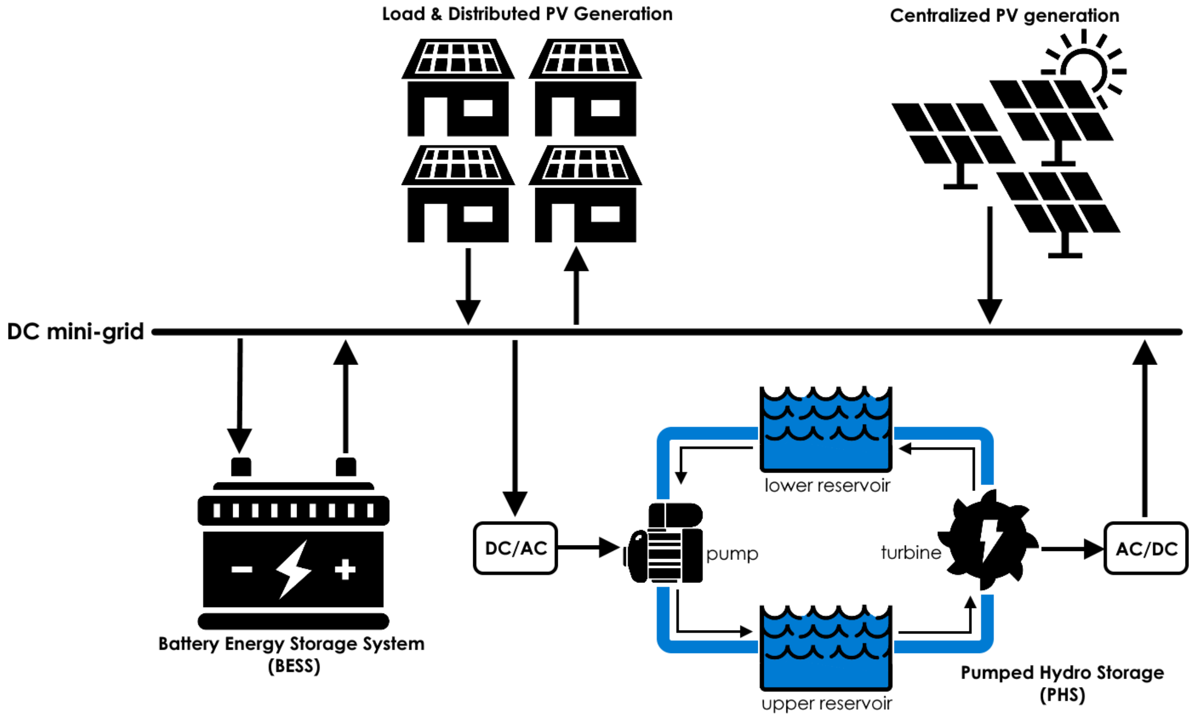


Figure 3.1: Proposed architecture of the assessed mini-grid.

3.2. Water storage system

The upper and lower reservoir, along with their intakes, form the water storage system of the PHS plant. There are several ways to construct such a reservoir, determined mostly by the desired capacity.

3.2.1. Design options

Two different kinds of PHS plants can be identified: pump-back or open-loop PHS, which acts similar to a conventional hydropower plant in the sense that it utilizes both stored water and natural inflows to produce electricity; the natural inflows from a stream or river replenish the reservoir. Alternatively, closed-loop pumped storage have, apart from precipitation, no natural inflows of water, and rely on reservoirs isolated from a free flowing water source. These reservoirs can be natural or artificially built. Natural reservoirs are identified as either natural lakes or sites where a depression in the terrain can be flooded with water. For a closed-loop PHS system, the only functionality is energy storage, whereas pumped-back storage can also provide energy generation similar to a conventional hydropower plant [130]. The reservoirs for both the pump-back and the closed-loop PHS schemes can be obtained in several ways.

Natural bodies of water Natural bodies of water are either rivers or naturally formed lakes, and can be used as a reservoir. Especially with rivers, where the water can flow freely, it must be ensured that they do not dry up in the drought season. For natural lakes, the pumping or generating operation can disturb the lake's ecosystem. Using lakes and rivers is cost-effective, since there is no need for the construction of a dam. The absence of choice in the reservoir placement however often leads to high civil costs due to a necessity for tunnel construction for the penstocks. An example of a PHS plant utilizing both a natural lake and a river, is Yamdrok Hydropower Station in Tibet. In this scheme, the upper reservoir is formed by the naturally formed Yamdrok Lake, and the Yarlung Tsangpo River functions as the lower reservoir.

Concrete dam Alternatively, when the terrain presents a natural depression or valley, or at the gorge of a river, a concrete dam can be constructed to impound water. Valleys can impound large quantities of water; the creation of a large body of water by building a dam leads to high pressure from the water reservoir, and concrete is needed as a material, often even reinforced with steel rebars. Most large hydropower or PHS plants have a reservoir with a concrete dam. Such a reservoir requires favorable terrain parameters with regard to the topology and geography, and advanced civil works.

Seawater As a lower reservoir, the sea itself can be used; this is referred to as Sea Pumped Hydro Storage (S-PHS). The salinity of the seawater presents several technical issues. Corrosion resistant materials are required for the penstock and hydrodynamic equipment, such as turbines and pumps. Moreover, a leakage of seawater from either the penstock or the upper reservoir can create serious environmental impact. Additionally, the powerhouse would need to be placed on the coastline; this is often the location of extreme meteorological conditions. While multiple seawater PHS projects have been proposed, the only one to be operational was the Okinawa Yanbaru Seawater Pumped Storage Power Station, which was opened in 1999 and dismantled in 2016 due to a lack of power demand in the area, causing the plant to become unprofitable.

Earth dam reservoir Earth dam embankments are the most common type of dams worldwide. Earth dam reservoirs are used to supply dry and rural areas with water for irrigation, conservation, drink water or fisheries [218]. They are constructed using material available at the site: either homogeneously of compacted earth or zoned with and impervious clay core. These dams can be built almost anywhere, whether the terrain provides natural depressions or is completely level.

Steel storage tanks An alternative to civil works, is to erect large steel storage tanks to function as reservoir. These large tanks are commonly used for agricultural and industrial purposes, and are designed in a modular way to facilitate transportation and giving the possibility to construct the tanks at more difficult to reach areas.

Underground reservoir Subsurface spaces, such as caverns or abandoned mines, can be used as a reservoir, known as Underground Pumped Hydro Storage (U-PHS). These underground reservoirs often need to be redesigned and reconstructed, but present less adverse ecological impacts than conventional pumped hydro storage [146]. While no underground PHS plants as of yet exist, several projects have been explored and proposed, all with high heads and large storage capacities.

3.2.2. Discussion

The discussion will determine to what degree the design options satisfy the relevant design criteria, as summarised and numbered in the program of requirements (2.4).

Operating range The potential of a PHS plant is very dependent on the site on which it is built. One of the biggest constraints on the construction of a conventional PHS plant is finding a suitable location. The existence of a suitable area to construct the lower and upper reservoirs plays a large part in the potential of a PHS plant at a location. A preliminary investigation on the selection of a suitable site for building the reservoirs includes a geographical and topographical analysis.

When deciding on a site to build the lower and upper reservoirs, the topography of the area needs to be considered. The amount of energy that can be stored per cubic meter of water is calculated in the following way:

$$E = \rho \cdot g \cdot V \cdot H_{gross} \cdot \eta \tag{3.1}$$

Here E is the stored energy in Joules, ρ is the density of water (1000 kg/m^3), g is acceleration due to gravity (9.81 m/s^2), V is the volume of water in m^3,H_{gross} is the gross height difference between the two reservoirs and η is the round-trip efficiency of the PHS plant. The term “cycle efficiency”, as defined by the ASCE [51], is the ratio of the generating output of the pumped storage plant to the generating input, including pump/turbine, generator/motor, and hydraulic losses. Dividing the energy output by the energy input provides the cycle efficiency.

When considering the size of the upper reservoir (in terms of cubic meters) needed to store one kilowatt hour of energy, the impact of the height difference is significant. This is represented in Figure 3.2 below. For the graphs below, a round-trip efficiency range of 60 to 70 percent is taken, as is common in small-scale PHS plants [205].

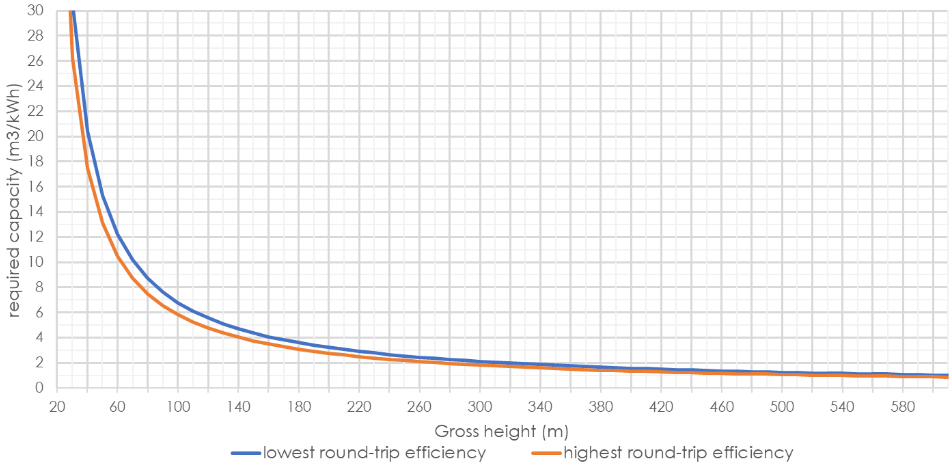


Figure 3.2: Visualisation of the required amount of cubic meters of water in the upper reservoir to store one kilowatt-hour of energy, relative to the gross height difference between lower and upper reservoir.

From Figure 3.2 it becomes clear that a larger head between the two reservoirs significantly decreases the required reservoir capacity. This is further visualised in Figure 3.3, where the total required cubic meters of storage capacity is shown for the amount of stored energy. In this graph, it has been estimated that 80 percent of the water in the reservoir can be used, since a reservoir can not be fully drained.

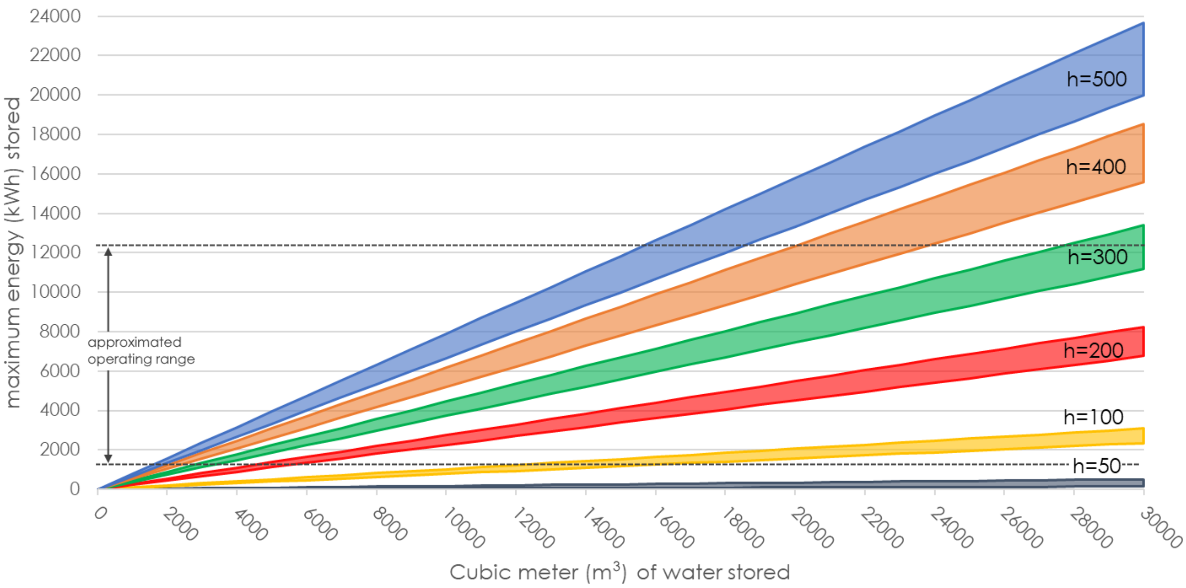


Figure 3.3: The maximum amount of energy in kWh that can be stored per cubic meter size of the upper reservoir, for the indicated gross height differences. The range is due to the consideration of round-trip efficiencies ranging from 60 to 70 percent.

Assuming the required capacity range from the program of requirements, as discussed in Section 2.1.1, up to 12,200 kWh could be needed. Storing this amount of energy can require a reservoir as large as 190,000 cubic meter for a head of 50 meter, or 10 times as small when the head is 500 meter. A site with very hilly or mountainous terrain where the lower and upper reservoir can be built with sufficient height difference between them is thus advantageous and preferred. Assuming thus a head of at least 100 meters, and a capacity range of 1,440 to 12,200 kWh, the assumed capacity range for the upper reservoir is 2,000 to 95,000 cubic meter. Since both reservoirs need to be able to store the same amount of water, the lower reservoir would be the same size. This capacity range influences the suitability of certain design options.

As mentioned, all U-PHS projects currently explored or proposed have large storage capacities. This is due to the fact that these underground cavities are large and require large amounts of water to be filled up. Moreover, valleys flooded by concrete dams are almost always larger than the maximum storage capacity required. Therefore, these two options do not meet this first design criterion. While natural lakes and rivers also have a larger capacity than the requirements, their entire potential does not need to be used since they require no construction.

quality of supply This design criterion is only relevant for natural bodies of water; on the other design options it has no bearing. For small lakes and especially rivers, the seasonal rainfall in sub-Saharan Africa makes the water supply unreliable [211]. Dependence on a free-flowing water source means the dry season does not allow for proper functioning of the PHS plant. Therefore, a closed-loop system is necessary.

Material availability For the reservoirs, this design criterion can be divided in the availability of construction materials, and the availability of geographical parameters.

Firstly, the material availability. It is advantageous to use materials available in close proximity to the construction site itself, to cut on the high transportation costs and avoid difficulties with hauling materials where the road infrastructure is lacking or absent. Otherwise, the materials used to build the reservoir must be lightweight and easily transportable. Construction materials used for conventional dams (which is mainly cement, with a density of 1,440 kg/m^3) do not satisfy this requirement. Cement is not assumed to be available in rural communities in large quantity; most rural buildings are constructed using locally available natural materials [162]. While steel storage tanks do require transportation of the steel plates, the modular construction method and limited thickness of the plates make them lightweight and less complicated to transport than cement. Most convenient are the earth dam reservoirs, which use materials obtained from the soil at the site itself.

With regards to the availability of geographical parameters, reliance on natural bodies of water, naturally occurring depressions or valleys, proximity to the sea, or the existence of nearby underground reservoirs significantly limits the number of available locations where a PHS plant can be constructed. Generally, it is unlikely that these geographic conditions will be present near a community in need of electrification. It can thus be said that natural bodies of water, valleys and underground reservoirs are, in general, not locally available.

Appeal The appeal for a mini-grid in the eyes of donors is increased if as a whole it positively affects the community. This design criterion is thus dependent on other criteria, such as community involvement, secondary water use, and little environmental impact, and if the design options satisfy those three design criteria, it can be said also the appeal is increased.

Operational costs Whichever design option is considered, an annual inspection is required. This inspection focuses on specific issues such as cracks, erosion, settling, corrosion (in the case of steel tanks) or other forms of damage. While in all reservoirs seepage occurs, it must be properly inspected in order to avoid a collapse due to excessive seepage. Both earthen dam reservoirs and concrete dams require continuous maintenance [175]. Inspection and maintenance of the water storage system do not require professional workers from outside the community, since this maintenance is considered uncomplicated. While very low expenses are expected for the continual maintenance works of the reservoirs, this does not include the major repairs, which need to be done by or under the supervision of a professional. The day-to-day maintenance of the embankments however can be carried out by members of the community [27], significantly reducing the maintenance costs.

While existing lakes require little maintenance, river systems still require a reservoir constructed in parallel. Their maintenance requirements are thus the same as earth dam or concrete dam reservoirs. While likewise for underground reservoirs little maintenance is expected, any seepage or erosion might demand a significant repair operation, due to the difficulty in accessibility with the reservoir below ground. Finally, steel water storage tanks, while not maintenance-free, can be sufficiently maintained with bi-annual inspections rather than day-to-day maintenance.

Using the sea as a reservoir for S-PHS, maintenance of other components is required as a consequence of the reservoir design choice. Due to the corrosive properties of salt water, S-PHS requires a significant amount of added maintenance to the system [123].

Capital costs Capital costs for a reservoir are discussed in relation to one another. While the costs are site dependent, an estimation can still be made. The costs of the reservoir is determined by the materials required, the amount and complexity of construction required, the expertise of the designing and overseeing engineers as well as the workforce, and the costs of land and water rights.

The construction requirements when using a natural water source depend on whether it is a lake or a river. Lakes mostly require underground tunnels for the water conveyance between upper and lower reservoir and thus have low costs associated with them, while rivers require dam structures for parallel reservoirs. Similarly, valleys and depressions to be flooded also require dam structures. For large reservoirs, the high water pressure demands for concrete dam structures. The complexity involved with concrete dams is demonstrated by the fact that planning and engineering are a major part of the total costs [171], demanding a professional workforce. Additionally, material costs are relatively high (with the average cost of cement approximately 110.00 €/m^3 in Sub-Saharan Africa [75]) and the heavy cement brings along hefty transportation costs. For these reasons, concrete dams are deemed, cost-wise, an unfeasible option for relatively small reservoirs. Likewise, underground reservoirs require technologically advanced and expensive excavation [234], which becomes economically unfeasible when the capacity needs are low. Thus it is concluded that these expensive, technologically advanced civil works required for concrete dams and underground reservoirs are not a cost-effective option in regions where structural knowledge and construction materials are scarce, and only a small reservoir needs to be constructed.

Earth dam reservoirs, steel storage tanks, some natural bodies of water and the sea do not necessitate complex labour. Therefore, a local workforce can carry out the construction, cutting on costs. Using the sea as a reservoir however brings significant extra costs due to the necessity of corrosion-resistant equipment and penstock. To estimate the costs for earth dam reservoirs and steel storage tanks, a more in depth analysis is required. In Appendix B and Section 3.5.1 a capital cost equation has been established for each option. From equation 3.23 for earth dam reservoir capital cost, the price per volume (€/m^3) decreases exponentially, while for steel tank reservoirs the price is around 10 €/m^3 according to equation B.5. For even the smallest required storage capacity, 2,000 m^3, this comes down to approximately 20,000 € if steel storage tanks are used and 18,000 € if earth dam reservoirs are used. Due to the linear equation for steel storage tank capital costs and the exponentially declining equation for earth dam reservoir capital costs, this gap in price will only increase with larger reservoirs. It can thus be concluded that earth dam reservoirs are a significantly cheaper option.

Finally, the dependence on geographic site condition again needs to be considered. The dependence of the existence of natural bodies of water, valleys, underground cavities or proximity to the sea limit the freedom in reservoir placement. Earth dam reservoir and steel storage tanks however, can be placed almost anywhere, as long as the topology and hydrology allow. This means they can be constructed in much closer proximity to the mini-grid and renewable energy sources, reducing the need for expensive transmission lines. Close proximity to the mini-grid is important due to the desire of minimizing the infrastructure.

Community involvement For socio-cultural feasibility, interaction with the community regarding installation and the subsequent engagement with the PHS plant are required. For a rural electrification project, community participation is an active process, in which beneficiaries not only receive the benefits of the project, but also influence the direction and execution of the project [232]. For the installation it is therefore important to involve the entire community in the decision making process of the installation site, as not to negatively impact certain community members by constructing a water reservoir on or too far from their farmland, or diverting water streams which they use for irrigation. Involvement in the planning and installation already ensures an initial feeling of ownership. Several barriers to community involvement and participation can be identified:

- *Unwillingness:* this barrier means the community is unwilling to participate in the planning and installation of the reservoir, and thus also the subsequent operation and maintenance of the whole PHS plant. Unwillingness is a result of negative side-effects, whether these are actually present or only perceived by the community. For example, diversion of water from a river can lead to adverse environmental effects downstream, such as habitat deterioration, reduction of environmental flow and wildlife disturbance [24]. This is an actual negative side-effect and will cause opposition amongst the local population. Another example is the flooding of a valley, which even on a small scale can come with the loss of valuable farmland. With regards to perceived side-effects, these are consequences of the reservoirs which do not actually have much impact, but are perceived as a substantial negative impact by the community. This can for example occur when a natural lake is used as a reservoir. While a small-scale PHS plant actually has little effect on the aquatic life of a small lake [253], the rural population of Africa living in proximity to these lakes is very much dependent on fishing [59]. So much so, that it would have dire consequences for food security, nutrition and health for these communities [19]. If this source of income and food is threatened, whether it truly is a threat or just perceived as such by the community, will likely cause opposition instead of participation.

- *Inability:* the community might be unable to participate, for two reasons. First of all, construction and planning could require technical expertise which they do not possess (see 2.3.2); this is the case for U-PHS and concrete dam construction. Moreover, involvement of the community in planning and siting of the reservoir location might be impossible, because for several design options the location is pre-determined (S-PHS, U-PHS and natural bodies of water). Even if only one of the reservoirs is for example an existing lake or the sea, there is much less flexibility in where the other reservoir is constructed. Siting flexibility is important, because it avoids conflicts with land rights, it can increase the potential for secondary water use (e.g. by constructing a reservoir near arable land, for irrigation) and the water diversion for the intake can be adjusted to minimize impact. To make the most out of these flexible siting advantages, the community should be involved in planning. Moreover, to ensure a sense of ownership, which is important for a successful project [226], it is helpful if the community can be involved in the maintenance of the reservoir.

- *Misunderstanding:* finally, it might just be that the community member do not completely understand how the system works. U-PHS for example is not visible, making it difficult to obtain a good comprehension of what actually happens. S-PHS makes use of salt water, making the water in the second reservoir useless for other purposes, which might be confusing. An advantage of earth dam reservoirs is that a mini-model can easily be constructed to demonstrate how the PHS system functions; a study by the Karamoja Productive Asset Program (KPAP) found that such mini-models have a positive impact and lasting effects [48].

Community involvement is thus best obtained when either a earth dam reservoir or steel storage tanks are used; these allow for flexible siting, demonstrative mini-models, community participation in the maintenance. Moreover, these reservoir options do not require expertise for the construction labor (except proper supervision) allowing the employment of local people, and they have no actual or perceived side-effects on the community (if planned correctly with community involvement).

Technical skills requirements The Technical skill requirements consider both the expertise require for construction and for maintenance. The knowledge requirements are tied to the installation costs, and have for a large part already been covered in the paragraph discussing the design criteria for low capital costs. As mentioned, earth dam reservoirs, steel storage tanks, some natural bodies of water and the sea do not necessitate complex labor. Therefore, a local workforce can carry out the construction. Moreover, earth dam reservoir are a common occurrence in the SSA region and the expertise required for construction is thus likely to be present locally. For concrete dams and underground cavities however, complex labor and a professional workforce are required. With regards to the maintenance, it has also been established that for the day-to-day upkeep of earth dam reservoirs, steel storage tanks, natural bodies of water and concrete dams can be performed by the community. However, as Berhane et al. observed, proper education and management on the maintenance is required if the responsibility falls on the community [27]. Training employed technicians on proper reservoir management is a requirement, allowing them to oversee any maintenance works.

Theft and vandalism No evidence could be found on the purposeful destruction of reservoirs or embankments. However, since steel tank reservoirs are made of steel plates, these can easily be dismantled and sold or used for structures and roofs.

Scalability Scaling the reservoir to a larger size, leads to a larger storage capacity. The construction works required for U-PHS and concrete dam reservoirs depend on the desired size of the reservoir. It is thus financially disadvantageous to build a larger reservoir than required. While this is the same for earth dam reservoirs, these can be expanded much easier due to the uncomplex construction of the embankments. For natural lakes and the sea, the reservoir already exists and the construction works do not influence the size of the reservoir. Therefore, the water used in these reservoirs can be easily extended without considerable additional construction.

Contact with steel storage tank suppliers has established a maximum capacity of 3,500 m^3 is possible with modular steel tanks. This means that multiple tanks should be placed together if the capacity requirements are larger. While this does increase costs, it allows for a scalable capacity.

Regulations Permits and regulations concerning construction of a reservoir is related to land and water rights. Land should be purchased if a reservoir is to be erected, however natural water bodies of water are considered a public good and can thus not be owned. It is thus difficult to use these as reservoirs unless there is a close collaboration with the local government; such a collaboration is however complicated due to the challenge presented by the vertical networks and corruption (see 2.3.4).

While the regulatory framework regarding water reservoirs is different for every country, a common guideline is present. A reservoir would need to satisfy the following demands in order to receive a permit [52]:

- Natural land and water resources should be optimally used and improve the quality of human environment.
- Natural resources require sustainable use, to not only meet the needs of the present generation but also preserve the ability to meet the needs of future generations.
- Environmental conservation and economic activities must be integrated.
- The international obligations regarding the conservation of bio-diversity and protecting the ecological balance should be met.

Clearly it is important to avoid environmental and ecological impact to satisfy regulations. Moreover, there should be an improvement of the quality of life for the community. Using a public good such as water purely to make profit, what a PHS plant in essence is used for, will thus bring legal difficulties. Therefore, the regulatory framework reinforces what was already a design criterion; secondary water use should be permitted and accounted for, as a common-pool resource.

While eventually for every design option a case could be made and permits obtained, the options with an environmental impact are more likely to receive resistance from regulatory instances.

Secondary water use The design of the reservoirs decides whether secondary water use is possible. As discussed, the importance of a multi-purpose reservoir becomes evident due to its ability to increase community trust and acceptance, and to improve the appeal of the system. Moreover, it makes it easier to receive permits and rights. Since secondary water use helps to meet multiple design criteria, it is seen as one of the most essential design criteria for the water storage system.

To get a better grasp of the influence of secondary water use, and how it will impact the size of the reservoir, the water balance in the reservoir should be considered. The water balance is shown with the following equation:

$$Y + P_r = E + L + Q_o \tag{3.2}$$

On the left side of the equation is the water inflow: Y is the catchment yield from runoff inflow and P_r is precipitation on the water surface. The right side of the equation represents the water outflow or water losses: E is evaporation from the free water surface, L is the losses due to water seepage, and Q_o is water outflow due to secondary water use. Due to the variability of rainfall throughout the year, this balance can will shift towards the left side in the wet season and to the right side in the dry season. Each variable of the water balance equation will be further explained, starting with the catchment yield.

To initially fill the reservoir and subsequently maintain the water level, an inflow of water is needed. To store enough energy for a community or village, at least a ten thousand cubic meter of water is needed (see Figure 3.2). Considering large tank trucks can hold at maximum 50 cubic meter of fluid, transporting the water in from elsewhere is unfeasible. Therefore either one of the reservoirs, most likely the lower reservoir, must be situated in a catchment area. Depending on the choice of reservoir design, the reservoir is initially filled in one of the following ways: either a natural inflow of free flowing water sources is already present, or diversion channels and cofferdams can be constructed to divert run-off water and rain collected in tributaries and streams to fill the reservoir [1]. Whether a reservoir is actually feasible, is determined by calculating the catchment yield. If this yield is too low, it might take years to fill up the reservoir initially and if the water is used for other purposes, the water outtake will exceed the intake. If the yield is too large however, the reservoir will require either an expensive spillway, or the excess water will need to be diverted. The catchment yield (Y) based on the expected annual run-off is calculated as follows:

$$Y = R_r \cdot A \cdot 1000 \tag{3.3}$$

In this equation, R_r is the annual run-off (mm); if this is not known, it can be estimated by taking 10 percent of the mean annual rainfall for the catchment area. A is the catchment area in square kilometer, located upstream of the proposed reservoir. The annual yield, Y, is calculated in cubic meter, and thus dependent on the annual rainfall. The total annual precipitation is visualized on a global map in Figure 3.4. Precipitation directly on the reservoir surface also adds to the water balance, as variable P_r in equation 3.2.

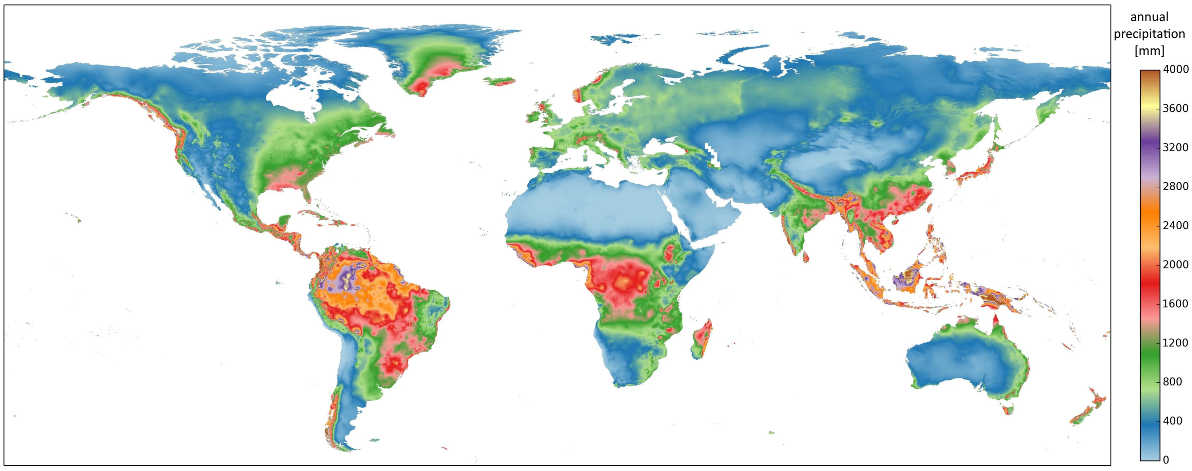


Figure 3.4: Global map of precipitation in millimeter over an average year, averaged over the period of 1970-2000 [72].

The yield determines whether a reservoir should be built at a certain site, and should be sufficient to fill the reservoir within a foreseeable time frame. Furthermore, the annual yield should be equal to annual water losses.

regarding the water outflow, the evaporation of the water surface is considered. Due to the geographic location and the associated climate of many countries in sub-Saharan Africa, temperatures are usually high. This can also be observed in Figure 3.5, where average annual global temperatures are indicated.

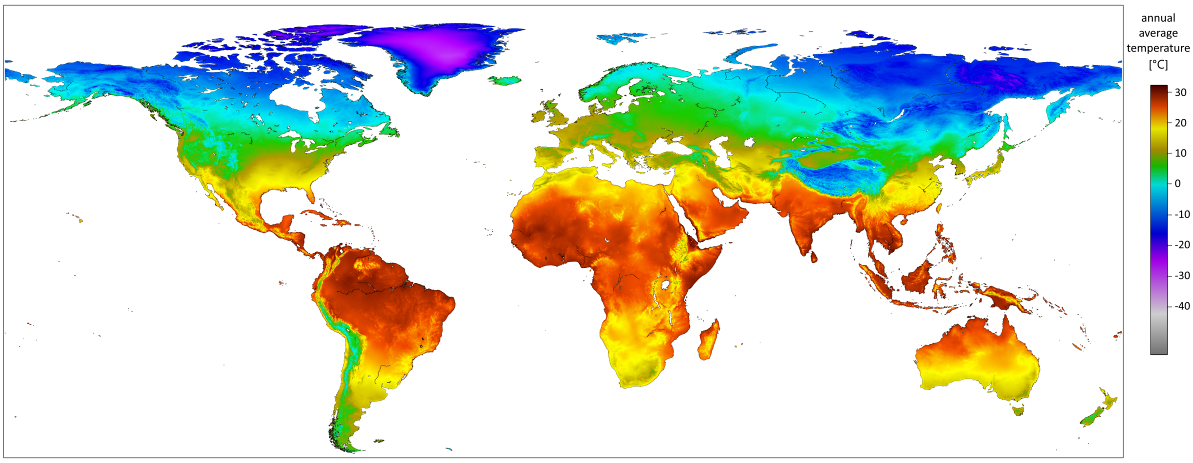


Figure 3.5: Global map of annual average temperature in Celsius, averaged over the period of 1970-2000 [72].

Taking these high temperatures into account, a simplified equation on Penman's evaporation formula [138] can be used to estimate the evaporation losses for a square meter of a free water surface, such as a reservoir.

$$E_0 = \frac{700 \cdot T_m/(100 - A) + 15(T - T_d)}{(80 - T)}(mm/day) \tag{3.4}$$

In this equation, where $T_m = T + 0.006h$, h is the elevation (m), T is the mean temperature, A is the latitude (degrees) and T_d is the mean dew-point. The equation indicates that higher temperatures lead to more evaporation losses, thus should especially for developing regions be considered in the water balance equation. The seepage losses losses, L in equation 3.2, will always occur but can be minimized is the reservoir is properly designed and constructed.

Finally, the secondary water use (Q_o) can be considered. To properly understand the requirements to satisfy this design criteria, it is necessary to establish likely manifestations of secondary water use. There are several additional uses for a large water reservoir: it can be used for irrigation of surrounding farmland, as a fishery, as a domestic water supply or conservation purposes.

- *Irrigation:* Rainfall variability has a huge negative impact on the rural poor of Sub-Saharan Africa. A key strategy of improving the food security in rural regions that are dependent on rain-fed agriculture, such as in Sub-Saharan Africa, is retaining and using the variable rainfall in an efficient manner. This can be done with small-scale reservoirs, which can provide a reliable supply of water under a variable climate. As of now, water storage capacity and irrigated area in Sub-Saharan Africa are the lowest of any region in the world [212]. There is however an increase in small-scale reservoirs for water retention and accompanying irrigation projects in Sub-Saharan Africa [84]. Irrigation requirements can be calculated by multiplying the gross annual irrigation requirement per hectare by the land area proposed.

  In general, reservoirs constructed in rural SSA purely for the purpose of providing a water supply in the dry season, are used only for spot irrigation (with buckets); it is more common to use the water reservoir for domestic and livestock water use. This is due to the large water requirements for crops, which is 1,500 to 3,000 cubic meter of water for a tonne of dry matter yield [152].

- *Livestock water supply:* Water from the reservoirs can be used to supply water to livestock, especially in periods of drought. Livestock water requirements can be determined through guidelines of the Food and Agriculture Organization of the United Nations (FAO) or local organizations [218].

- *Domestic water supply:* An important aspect of public health is the quantity of water available to households. 18 percent of the global population have no access to water, and are found largely in Asia and Africa, particularly in rural populations [104]. Distance from a water the water supply influences the amount of water used per capita, as shown in Figure 3.6. This is due to the increase in water use for hygiene purposes when it is more easily accessible.

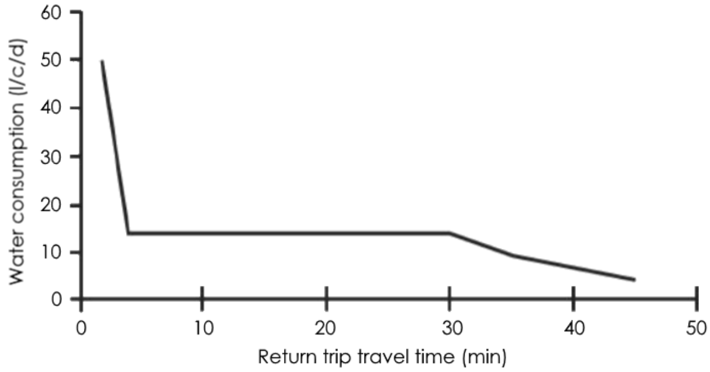


Figure 3.6: Water consumption in liter per capita per day, related to the distance in minutes from the water source. Obtained from [244].

Small-scale reservoirs can help secure this water supply [137], and this can thus also be provided by the same reservoir as is used for the PHS plant. Even after being cycled through the penstock and hydraulic machinery, the water remains potable [37].

- *Fisheries:* If organic matter is present in the reservoir, it will decompose and cause a build up of carbon dioxide and methane in the water. This has an undesirable effect, both for a reservoir used for hydroelectric storage and on the desired ecosystem required for fish production. If this is not the case, the water in the reservoir is a viable environment for fish production [218]. Furthermore, for small scale PHS the reservoir's depth will likely be limited, giving the reservoir the properties of a polymictic lake. Research shows that for these types of lakes, the water column properties do not significantly change when the turbulent kinetic energy (TKE) is low at the intake of the reservoir [13]. The TKE at the intake is determined by the rate the water flows from the reservoir from or into the penstock. This flow rate will be low, due to the small power output requirement as determined by the design criteria (2.1.1). The biggest concern is entrainment of planktonic animals during pump or generation operation. This can be avoided with filter curtains.

With regards to domestic and livestock water supply, the water must be potable, which is not the case for S-PHS and often not for U-PHS using abandoned mines [194]. To be used for irrigation, the salt water of a S-PHS plant can also not be used. Moreover, the additional water requirements for irrigation are significant if proper irrigation with pumps is implemented. With spot irrigation, less water is required but the impact on yield increase is also reduced. Due to the limited capacity of steel storage tanks, new tanks would have to be installed just to account for secondary water use. Regarding fisheries, for an earth dam reservoir design all vegetation is removed prior to construction and the reservoir is lined with a polymeric geomembrane. This makes them suitable for fish production, since no organic material remains to decompose. Finally, for the purpose of facilitating secondary use of the reservoir, easy accessibility is favoured. This is obtained with earth dam reservoirs and steel storage tanks; due to the freedom in situating these reservoirs, they can be placed more conveniently (e.g. close to arable farmland for irrigation, nearby the community for domestic and livestock water supply, etc).

Environmental and ecological impact There are several ecological and environmental impacts to be considered when deciding on a reservoir design. These can be divided in the following:

- *Ecological impact:* For S-PHS, in case of dam failure or a penstock rupture, the salt water brings considerable damage to the environment. Moreover, U-PHS using abandoned mines can contaminate the groundwater [194].

- *Inundation:* For several reservoir design choices, land must be flooded. If this happens on a large scale, for example when constructing a concrete dam, it can lead to loss of land.

- *Natural water cycle:* The natural water cycle is impacted when e.g. the river flow is adjusted, bringing environmental issues further downstream. Furthermore, for earth dam reservoirs, steel tank reservoirs, U-PHS and concrete dams, rainwater must be diverted to collect a water inflow in order to maintain the water balance. However, if there are not too many reservoirs constructed in the same catchment area, this will have little impact [48]. However, if the reservoir helps to prevent flash floods in the wet season and improves water flow in the dry season, it actually has a positive impact on the natural water cycle.

- *Public health:* Construction of a reservoir can cause adverse effects to the public health, due to water-related diseases, mainly malaria and schistosomiasis [34]. There are however ways to prevent and mitigate these problems through community participation.
- *Dangers:* A reservoir might increase the chance of flash floods, or dam failure can leads to damage to property. Loss of life is unlikely for small reservoirs.

3.2.3. Decision matrix

Based on the discussion in Section 3.2.2, a decision matrix gives an overview of which design criteria are satisfied by each design choice for the water storage system, as presented in Table 3.1.

Table 3.1: A decision matrix, which shows whether a design option satisfies a certain design criterion.

criterion	**Design option**					
	natural bodies of water	**concrete dam**	**S-PHS**	**U-PHS**	**earth dam reservoir**	**steel water tank**
[1] suitable for desired operation range	yes	no	yes	no	yes	yes
[2] quality power and supply improvement	no	yes	yes	yes	yes	yes
[3] locally available components/materials	no	no	no	no	yes	yes
[4] connectable to main grid	not applicable	not applicable	not applicable	not applicable	not applicable	not applicable
[5] appeal increase	no	no	yes	yes	yes	no
[6] low operational costs	yes	yes	no	no	yes	yes
[7] low installation costs	yes	no	no	no	yes	no
[8] high degree of community involvement	yes	no	no	no	yes	yes
[9] low technical knowledge requirements	yes	no	no	no	yes	yes
[10] theft/vandalism prevention	yes	yes	yes	yes	yes	no
[11] scalable	yes	no	yes	no	yes	yes
[12] adheres to regulation	no	no	no	yes	yes	yes
[13] accounts for secondary water use	yes	yes	no	no	yes	no
[14] little environmental impact	no	no	no	yes	yes	yes

This decision matrix makes it clear that earth dam reservoirs have the potential to meet all design criteria. Several design criteria do however require a correct maintenance and management strategy, as explained further in Chapter 4.

While steel storage tanks are likewise a viable option, steel storage tanks and Earth dam reservoirs have such a large gap in capital costs that the design criterion to design an economical system does not justify using steel tank reservoirs. Furthermore, geographical constraints for natural bodies of water, S-PHS and U-PHS have negative effects on the costs, complexity, environmental and ecological impact and secondary use potential of the reservoir. Secondly, concrete dam structures and underground reservoirs are deemed too advanced and too expensive to use in the proposed setting.

3.3. Water conveyance system

The water conveyance system is responsible for the transportation of water between the upper reservoir to the powerhouse. The main component is the enclosed conduit, called the penstock.

3.3.1. Design options

When considering the design of the water conveyance system, several aspects are of importance. The material of which the penstock is made, the method of installation of the penstock, and the flow control components within the penstock. The flow control is however very dependent on the powerhouse configuration, discussed in Section ...

Penstock material The selection of material for a penstock is usually based on parameters such as surface roughness, design pressure, method of jointing, weight and ease of installation, availability, and maintenance [135]. The penstock can be made of several materials [88]:

- Concrete: pre-stressed concrete pipes are used in favor of reinforced concrete. These concrete pipes contain wires of high-tensile steels and are compressed during production to improve their concrete's resistance to tensile forces. They are used for low to medium head applications (up to 150 meter) [26].
- Plastic: plastic penstocks are made of either polyvinyl chloride (PVC) or high-density polyethylene (HDPE). As there is little difference between the two, only HDPE is assumed. With pipe pressure resistances available up to 32 bar, these pipes are used for medium to medium-high head applications (up to 300 meter).
- Steel: mild steel (MS) is most commonly used for hydropower penstocks, due to a wide applicability and availability [214]. These are the only penstocks to be used for high head applications of more than 300 meter.
- Wood staves: penstocks constructed of wood staves held together by steel rings can prove very economical and useful for developing regions, but their applicability is limited to low head PHS installations [170] (up to approximately 100 meter).
- Fiberglass: Glass Reinforced Plastic (GRP) is a lightweight and strong material which is increasingly used for hydropower penstocks. With nominal pressure ratings up to 32 bar, it can used for medium to medium-high head applications, similar to HDPE.

The penstock materials are summarized in Table 3.2.

Table 3.2: Commonly used materials for the penstock of small-scale hydropower projects [230].

Material	absolute roughness (mm)	Young's modulus (GPa)	density (kg/m^3)
Concrete (pre-stressed)	3.00	30	2400
Wood stave	0.18-0.91	8-12	600-1000
HDPE	0.0015	0.8	940
GRP	0.02	17	1200
Mild Steel	0.05	200	7850

Penstock installation Apart from the penstock material, the installation method must be considered. The penstock can be either buried or exposed, depending on several factors: the ruggedness of the terrain, the penstock material, ambient temperatures and environmental requirements. An exposed penstock rests on confined supports, so there is no contact between the ground and the pipe. A penstock can be buried by digging a trench to lay the pipes, which are then covered with soil.

3.3.2. Discussion

Both the penstock material as the installation method (buried or exposed) are separately discussed for the relevant design criteria.

Operating range The hydraulic head and the flow rate of the water through the penstock determine the power that can potentially be harnessed by a hydro turbine. The power is calculated in the following way:

$$P = Q \cdot (H_{gross} - H_{losses}) \cdot \rho \cdot g \cdot \eta_g \tag{3.5}$$

In this equation, P is the power (Watts), η_g is the generation efficiency of the turbine and generator combined, H_{gross} is the gross head between the outlet of the upper reservoir and the turbine inlet and H_{losses} is the loss of head.

The energy losses in a penstock due to friction are represented in the loss of head, H_{losses}. These losses can be subdivided in major losses and minor losses. The major losses are due to friction over a length of pipe, which is dependent on the diameter of the pipe and the velocity of the fluid through the pipe. A higher velocity leads to a more turbulent flow, thus increasing the major losses. The minor losses are the losses due to turbulence of the fluid at a change of section, valve, bend or other interruption. The hydraulic head losses are calculated with the Darcy-Weisbach equation [40]:

$$H_{losses} = \frac{V^2}{2g}\left(\frac{fL}{D} + \sum K\right) \tag{3.6}$$

Which can be subdivided in equations for both the major ($H_{losses,major}$, equation 3.7) and minor ($H_{losses,minor}$, equation 3.8) losses.

$$H_{losses,major} = f \cdot \frac{LV^2}{2Dg} \tag{3.7}$$

$$H_{losses,minor} = \sum K \cdot \frac{V^2}{2g} \tag{3.8}$$

In these equations, D is the diameter of the pipe (m), L is the length of the penstock (m), V is the average velocity of the fluid in the penstock (m/s). K is a dimensionless factor defined as the loss coefficient, which depends on the type of interruption.

The friction factor (f) is a dimensionless number which is used to determine the friction losses. It can be estimated with a Moody chart, or otherwise several formulae have been developed to approximate the friction factor. In this thesis, the formula as determined by Haaland [97] will be used:

$$f = \left[1.8log\left(\frac{6.9}{Re} + \left(\frac{\epsilon/D}{3,7}\right)^{1.11}\right)\right]^{-2} \tag{3.9}$$

In this formula, ϵ is the absolute roughness of the pipe (m) which is a determined constant for every commercial pipe material. The Reynolds number, Re, is dependent on the velocity of the fluid:

$$Re = \frac{\rho VD}{\mu} \tag{3.10}$$

Where μ is dynamic viscosity of the fluid ($Pa \cdot s$), which is 0.001 for water at 25 degrees Celsius.

The diameter of the penstock influences the friction losses significantly. A larger diameter leads to less friction losses, but at the same time it increases the cost of the penstock. The previous equations can be used to determine how the diameter of the penstock influences the losses in potential power due to the reduction in hydraulic head. In current literature this is done by using a determined flow rate (Q). However, this flow rate is assumed to be controllable by means of a valve, so the objective is to relate the flow rate to the height and desired power output. Therefore the equations 3.5, 3.6 and 3.9 have been rewritten in *Python* to be used in a vector function, as can be seen in equations 3.11 and 3.12, for which the optimization library *Scipy* can be used to find the roots or zeroes.

$$Q - \frac{P_{generated}}{(H_{gross} + H_{losses}) \cdot \rho \cdot g \cdot \eta_g} = 0 \tag{3.11}$$

$$H_{losses} - \left(\frac{fLV^2}{2Dg} + \frac{\sum KV^2}{2g} \right) = 0 \tag{3.12}$$

This leads to the corresponding flow rate and head losses obtained when certain site-specific parameters, such as the desired power output (P), penstock length (L), penstock material used (ϵ) and gross head (H_{gross}) are known.

In order to visualize the effect of the diameter on the flow rate, head losses in meters and percentage of lost power, the Python code as used in the model discussed was used to plot Figures 3.7 and 3.8. The percentage of head losses was calculated as follows:

$$Head\ \ losses(\%) = \frac{H_{friction}}{H_{gross}} \cdot 100\% \tag{3.13}$$

Here $H_{friction}$ are the head losses due to frictional forces in the penstock. The optimal flow rate and head loss in the penstock for the set parameters of penstock diameter, gross head, and desired power output are thus determined with a root function.

Several assumptions were made for the plots: the fluid is water, the penstock material is a commercial steel pipe with an absolute roughness (ϵ) of 0.045mm and the penstock length is 5 times the gross height difference (which corresponds to a slope with an average angle of 10 degrees). Furthermore, the losses are constricted to major losses to simplify and reduce the assumptions made in the pathway of the penstock. Lastly, the efficiency of the hydroturbine and generator combined, η_g, is assumed to be 83 percent. Figures 3.7 and 3.8 show the influence of the diameter and gross head on the head losses for the desired output of 75kW, 150kW, 300kW and 600kW, respectively. The green area is seen as suitable diameter and gross head combinations, where the head losses are acceptable. The combinations falling in the red area are not able to reach the desired power output, and are thus unfeasible.

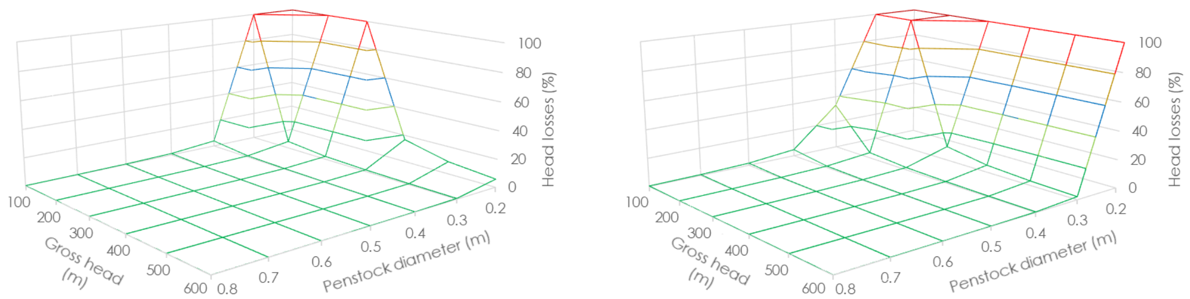


Figure 3.7: The head losses with respect to the gross head difference, ranging from 100 to 600 meter, and the diameter of the penstock, ranging from 0.2 to 0.8 meter. *Left:* With a desired output of 75kW (lower limit of determined range in 2.1.1), an available gross head of 0 to 300 meter requires a penstock diameter of at least 30 centimeter. *Right:* A desired output of 150kW does not allow for penstocks with a diameter of less than 30 centimeter; for low heads, it should even be at least 40 centimeter.

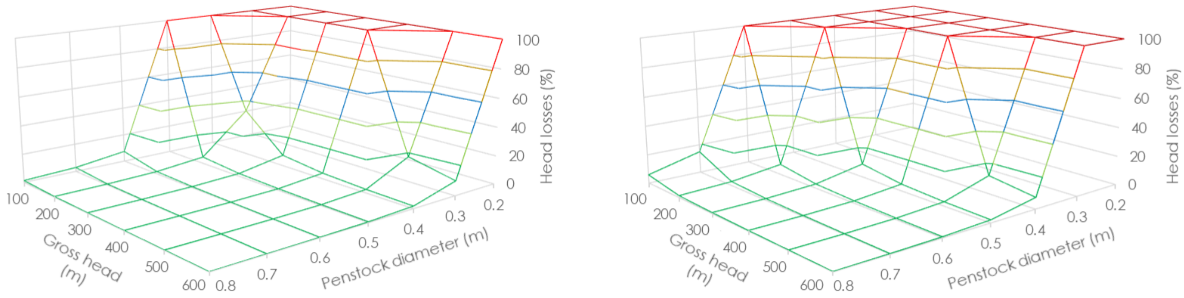


Figure 3.8: The head losses with respect to the gross head difference, ranging from 100 to 600 meter, and the diameter of the penstock, ranging from 0.2 to 0.8 meter. *Left:* a desired output of 300kW leads a required penstock diameter of at least 40-50 centimeter for heads higher than 200 meter; below this a diameter of at least 60 centimeter is needed. *Right:* If the desired output is 600 kW (upper limit of determined range in 2.1.1), the penstock diameter should be at least 70 centimeter for a range of 100-200 meter, 60 centimeter for 200-300 meter, and 50 centimeter from 300 to 600 meter.

The power output of a PHS plant is largely dependent on the flow rate entering the turbine, as seen in equation 3.5. As a design criterion, the power output ranges from 75 to 600 kW. it can be observed from Figure 3.7 that even at the low limit of 75kW power output the head should be at least 100 meter; otherwise the required diameter becomes significantly larger. While it is not visualized, analysis shows that for a head of 50 meter for example already needs a pipe of at least 50 centimeter to get a power output of 75kW. Therefore, the PHS design should focus on medium to high heads PHS plants, of at least 100 meter head.

Consequently, due to the hydrostatic pressure, the applicability of wood stave penstocks is limited to low head PHS installations [170], it is regarded as an unsuitable material for the setting. Concrete can only be considered for heads up to 150 meter, GRP and HDPE for heads of 100 to approximately 300 meter and heads exceeding this require mild steel penstocks. The upper side of the operating range, nearing 600kW, would benefit from high heads, since the diameter of the penstock becomes significantly smaller (see Figure 3.8. These high heads require Mild Steel penstocks. Clearly, with increasing power requirements, there will be a trade-off between either increasing the head (and thus the penstock length) and the pipe diameter.

Component and material availability The only material available at the installation site itself, is wood to construct wood stave penstocks. The materials concrete, HDPE, GRP and Mild Steel are available worldwide; however, there are few manufacturers in Sub-Saharan Africa, and it can be assumed pipes made from these materials will need to be transported from a city with a significant industrial sector present.

Building a pre-fabricated and pre-stressed concrete penstock on site is expensive, and the heavy weight of standard concrete pipes confines their use to sites close to the manufacturer. Pre-stressed concrete pipe sections weigh about twice to three times as much as the alternative steel pipe sections [136]. This high weight leads to difficulties in transportation. While mild steel pipes require less thickness and diameter, and consequently less material, their density of around 7,859 kg/m^3 still makes the pipes a substantial weight to transport. GRP and HDPE pipes have a much lower weight, making them more transportable over long distances and poor roads than either mild steel and especially bulky concrete pipes.

Operational and replacement costs The operational costs of the water conveyance system consist of replacement and repair costs, as well as inspection by operating personnel. Inspection of the entire water conveyance system should occur with regular intervals, which requires professional technicians. However, this thorough inspection is only required every 1 to 5 years. A more frequent inspection can occur every month to a year, where a simple visual observation of exposed penstocks suffices, and the required expertise only necessitates basic training. The maintenance costs associated with each penstock material option is shown in Table 3.3.

Regarding the replacement and repair, the durability of the material should be considered. Durability is the property to resist erosion, material degradation and subsequent loss of function due to environmental and other service conditions. An effective way to evaluate the durability is by looking at the service life of each penstock material. These are again presented in Table 3.3.

Table 3.3: The expected service life and maintenance costs for each material.

Material	Service life (years)	Maintenance cost
concrete	>75 [88]	low [88]
wood staves	35 [239]	high [88]
HDPE	>50 [9]	low [135]
GRP	>50 [10]	extremely low [135]
mild steel	>50 [135]	above average [135]

Wood stave penstocks degrade quickly when exposed to sunlight, which is abundant in most of the targeted regions (see Figure 3.5), necessitating frequent and expensive replacements and repairs. It requires maintenance such as tar spray coating every 5 years and constant undergrowth control. Steel, plastic and concrete pipes have a significantly longer lifetime, where repairs are required much less frequently due to a better resistance against degradation.

Apart from the penstock material, the choice for burying the penstock or keeping it on the surface affects the maintenance. For buried penstocks, surrounding earth provides inwards pressure, making the structure stronger and more durable. Additionally, the surrounding soil provides protection from temperature variations. However, a buried penstock is difficult to access for inspections and maintenance/repairs. Moreover, pipes can slide on steep slopes, as there are no supports, causing ruptures and water leakage.

Keeping the penstock exposed allows for continuous inspection during operation, and easy maintenance/repair access. It also provides safety against sliding due to the supports. However, an exposed penstock is unprotected against temperature variations, natural hazards, and degradation due to environmental conditions. In fact, these conditions are such a major influence of the degradation of the penstock, that a buried penstock needs little to no maintenance [88].

Capital costs and technical skill requirements These two design criteria can be joined for the penstock discussion; the technical skill requirement refers to the expertise required for installation, which in turn influences the installation costs.

The capital cost of wood stave penstocks is relatively the lowest, since transportation is not required due to its assumed local availability. Moreover, simple erection with unskilled labor is possible, lowering labor costs. Building a pre-fabricated and pre-stressed concrete penstock on site is expensive and requires skilled laborers. The heavy weight of standard concrete pipes confines their use to sites close to the manufacturer. Pre-stressed concrete pipe sections weigh about twice to three times as much as the alternative steel pipe sections [136]. This high weight leads to high transportation costs, along with logistical issues such as requirements for heavy equipment to lay the penstock segments in place.

To assess the costs of the remaining materials, quotes have been obtained from several manufacturers: Metline Industries (India), FlowTite, Truco (South Africa), Savoypiping Inc, Apex Steel (Kenya), Tana (Ethiopia) and JuNeng (Nigeria). The acquired prices per kilogram have been averaged for each material, resulting in a price of 2.06 €/kg for HDPE pipe segments, 3.10 €/kg for GRP pipe segments and 0.92 €/kg for Mild Steel pipe segments. However, for a corresponding pressure rating, mild steel pipe segments have by far the largest weight per meter, followed by HDPE pipes and finally GRP pipes. Due to this, when the head is below 300 meter, GRP pipes are most cost-effective, followed by HDPE pipes and lastly mild steel pipes. This is further reinforced by the transportation costs, which favor the lower weight of GRP pipe segments. The penstock is separated into pipe segments, which have manageable weight and can be carried and installed by unskilled laborers; however, the handling of GRP and HDPE pipe segments is much easier than steel pipe segments due to the difference in weight.

Regarding the installation method of the penstock, keeping the penstock exposed circumvents the additional digging costs, which can especially increase with hard and rugged ground.

Theft and vandalism Theft of the pipe segments of the penstock is unlikely to be an issue, whichever material is chosen [228]. The pipe segments are too heavy and/or not worthwhile to sell or re-use. Moreover, the pipe segments are secured as one large penstock unit, and thus difficult to dismantle. Vandalism for an exposed penstock is however made more difficult with tougher material such as steel and concrete. The opportunity for vandalism is however more effectively reduced with a buried penstock, as has been exemplified with the burying of oil pipelines [109]. Destruction of the penstock is the most likely form of vandalism: either water might be tapped for convenient irrigation, or purposeful harm to the structural integrity of the penstock might be done out of envy by unserviced surrounding communities.

Scalability Wood stave penstocks are constructed from individual parts on site, and the diameter can thus be customized. For all other pipe materials however, the dimensions are standardized. Pipe dimensions are, depending on the material, determined by international codes: ASTM F714 (HDPE and GRP), ASME/ANSI B36.10 (steel) ASTM C-76 (concrete). Therefore, inside and outside diameter, as well as wall thickness, are globally identical for pipes of a certain material and pressure grade. The pressure grade depends on the pressure a pipe can withstand; for Mild Steel pipes the pressure grade is called Schedule, for HDPE and GRP pipes it is known as Pressure Nominal (PN), and for standard concrete pipes this is divided in classes. An increase in desired power output will thus result in the decision to either keep the same pipe diameter and thus increase power losses, or stepping up to the succeeding standard nominal diameter and increasing the price by a significant margin.

The optimal pipe diameter would be based on the desired maximum power output, so this can still be reached without losing all power due to friction in the penstock. When this power would be scaled up however, either the entire penstock must be replaced to conform to the new maximum power output, or a second penstock can be laid alongside the first. The practice of laying new penstocks next to each other thus allows to scale up the power output operating range of the PHS plant. Furthermore, transport and installation issues can limit the size of possible pipe segments, since it is easier to transport smaller and lighter pipe segments. Additionally, separated penstocks leads to a more convenient arrangement with better operational facility; when a single penstock serves to provide all water flow to the mechanical equipment, damage to this penstock forces closure of the entire PHS plant. With multiple penstocks, the PHS plant can remain operational when one penstock is damaged, albeit with a lessened capacity. There is however a significant drawback to using multiple penstocks from an economic viewpoint. When the same discharge is passed through multiple penstocks, the capital cost will be greater compared to a single penstock. However, in the case of a short penstock length, adoption of individual penstock for each machine may be more economical [133]. The economical effect of scaling up a PHS plant with the addition of a penstock is further explored in Section 5.4.3.

Environmental and ecological impact The environmental impact of using a certain material over another can be assessed through the carbon footprint when producing a certain material. This is visualized in Figure 3.9.

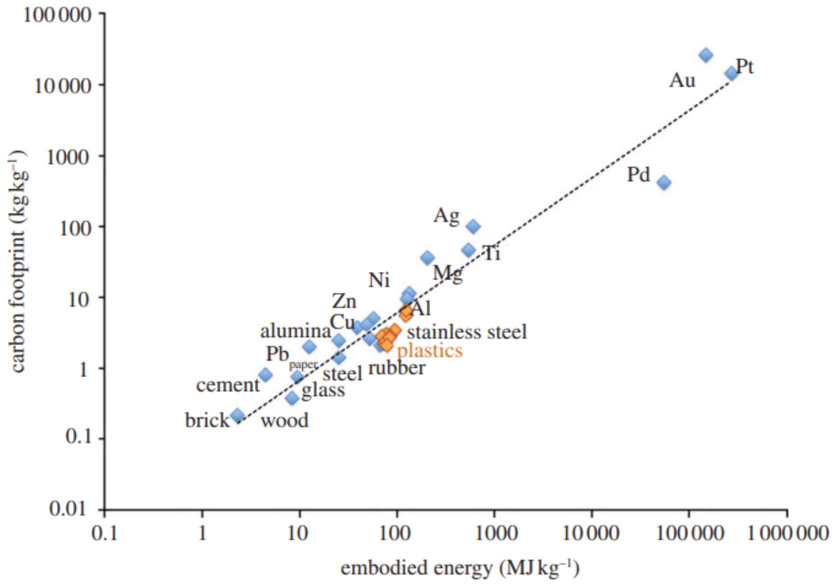


Figure 3.9: The carbon emission (kg/CO_2) per kilogram of material produced versus the embodied primary energy. Obtained from [96].

It can be observed that the lowest carbon footprint is obtained by using wood, followed by steel, cement, and plastics. However, since a wood penstock is more susceptible to leakage and has a much shorter lifetime, its environmental impact is larger than estimated through this image. Furthermore, plastic pipes require much less material than cement penstocks. Likewise, steel penstocks are much heavier per pipe segment, which closes the gap in the total carbon footprint.

3.3.3. Decision matrix

For the decision of the suitability for penstock material, it has been determined that for medium-high head application (more than 300 meter) only mild steel penstocks can be used. For lower head applications, a multi-criteria decision matrix is used, as seen in Table 3.4. For this matrix, the weight for each criterion is equal, and a score of 0 to 4 is given.

Table 3.4: The multi-criteria decision matrix for penstock materials suitable for low and medium head applications.

criterion	concrete	plastic (HDPE)	mild steel	wood staves	fiberglass (GRP)
locally available materials	0	2	1	4	2
low operational costs	4	3	1	0	4
low capital costs	0	2	1	4	3
low technical skill requirements	0	3	2	4	3
theft/vandalism prevention	2	1	2	0	1
little environmental impact	2	2	2	3	2
	8	13	9	14	15

GRP penstocks come forward as the best material to use for low, medium and medium-high head applications (up to 300 meter) due to their low weight and associated ease of transportability, low capital costs and low maintenance requirements. While wood staves come close in score, they have a very limited head range and are thus ranked as a lesser option than a GRP penstock. For higher heads, mild steel penstocks are required.

Regarding the choice for a buried or an exposed penstock, there is no best practice; rather, it depends on site-specific conditions. These conditions are:

- Consistency of the soil: hard or rocky soil makes digging more difficult and expensive.
- Attitude of neighboring communities: hostile tribes or communities could sabotage the penstock out of envy, which is avoided by burying it.
- Length of the penstock: if the penstock is rather long, a longer trench must be dug to bury it, leading to higher costs.
- Expertise of the supervising engineers: the engineers responsible for the design and installation should have experience with installing a penstock if it is to be buried. Otherwise, if mistakes are made in the installation and the penstock starts leaking or fails, a buried penstock is difficult to access.
- Environment: if there is a high chance of environmental damage, due to falling trees, rocks, animals, or weather conditions, it is best to bury the penstock. Likewise, if it obstructs wildlife, it should be buried. There is less maintenance involved with a buried penstock, due to the added pressure of the soil and lessened wear by environmental factors.
- Slope: if the penstock follows a steep slope, burying it not only becomes more difficult but also brings the risk of the penstock sliding, due to the absence of supports. An exposed penstock is more stable.

Above conditions should be assessed to determine whether a penstock is to be buried or remain exposed above ground.

3.4. Powerhouse

The machinery of a PHES plant consists of four important components, which can be used in a variety of configurations to form the powerhouse of the plant. These components are the hydro-mechanical machinery (pump and hydro turbine) and the electrical machinery (motor and the generator). This electro-mechanical machinery, together with the electrical equipment, is grouped together as the powerhouse unit.

3.4.1. Design options

Generally, three different configurations can be employed: binary, ternary or quaternary [54]. The type of configuration chosen affects the quantity of electro-mechanical machinery required. In this section alternatives for a PHS powerhouse configuration are presented.

Binary unit This configuration is most common in large hydroelectric plants; new plants in particular almost always consist of a binary unit [224]. A binary unit has a single hydraulic machine, a pump-turbine, which can both operate as a pump and as a classical water turbine by reversing the flow. Furthermore, it consists of a single electrical machine, the motor-generator.

Pump-turbine units are specifically designed for large PHS plants, by a relatively small number of manufacturers. Most commonly, these pump-turbines are based on the Francis turbine design and have proven very cost-effective due to a more compact power house, saving on equipment and civil costs. The design however is a result of compromises between the pump and turbine operation; many of the requirements for each operation contradict one another.

For small-scale hydropower schemes, a centrifugal Pump as Turbine (PAT) can be used as an efficient and cost-effective alternative. By running the pump in reverse operation, a higher volume of water than when run in conventional pumping mode can be handled, and the power output is higher than the pump input power at its best efficiency [126] [183]. However, a pump run as a turbine has a lower maximum overall efficiency. This efficiency is on average around 60 percent, whereas a conventional hydro turbine has an efficiency of 75 to 85 percent [161]. Additionally, it is however not efficient to have a single installation over a wide range of flows [156]. A pump has, unlike conventional turbines, no hydraulic control devices and thus no flow regulation. Therefor, performance away from the Best Efficiency Point (BEP) will be poor and even pose issues (see Figure 3.12), so a constancy of flow and load conditions is required. While the design criteria require the PHS system to account for a large range of excess and deficit power, a pump run as turbine can not provide this.

There is thus a trade-off between costs and efficiency. The limited range of the pump in turbine mode can however be mitigated. Three methods can be used to vary the input and output power of the storage system:

- First, a battery energy system can be employed to be combined with the PHS plant. As discussed in Section 3.1, a BESS will be required in any case; the BESS size must however be much larger when it must level the power discrepancy. The control scheme behind this alternative is further explained in Chapter 5.
- Secondly, equipping a centrifugal pump with a Variable Frequency Driver (VFD) allows the PAT to spin at different rotational speeds in both pump and turbine mode. Due to the changing rotation speed, the pump can supply a larger range of loads (as low as 30 percent of the rated power). A VFD does however add significantly to the capital costs of the machinery; generally, a VFD has the same price as the pump itself [158].
- Finally, several PATs of different sizes, each optimized for a different flow and suited for specific flow regimes, can be installed in parallel. This increases the costs of the hydraulic equipment, as well as additional penstock costs due to the need for branching the penstock near the PATs. To limit the additional costs, two PAT can be installed, of which only one is equipped with a VFD. The PAT with driver can then modulate the power output.

Ternary unit Alternatively, the pump and turbine can be detached. A ternary unit consists of a separate pump and turbine coupled on the same shaft, together with a motor-generator. The turbine can be either a Kaplan, Pelton or a Francis turbine; this depends on the hydraulic characteristics of the site. These hydro-turbines have high efficiencies, up to 90 percent; moreover, they have a wide operating range, allowing them to efficiently generate energy with much lower flow rates than what they are rated for. The unit is switched between pump and turbine operation by either a clutch (operable at standstill), a starting turbine or a synchronizing torque converter.

For a ternary unit, the penstock usually splits near the powerhouse, with one pipe leading to the pump and another to the turbine. While a ternary unit can have both a horizontal and a vertical shaft configuration, a vertical shaft allows for the pump to be installed below the water level of the lower reservoir, to avoid cavitation. The turbine is then installed above the water level. Pump start up is achieved with the help of the turbine, which synchronizes the motor-generator to the grid.

Quaternary unit In a quaternary configuration the pump and turbine are not mechanically coupled. There are thus separate powerhouses for both the pump and the turbine, with respectively a motor and a generator coupled. Motor start up is can be carried out with the help of a frequency converter.

The possible configurations can thus be summarized as the following 3 configurations each with different equipment options, totalling 10 options:

- Binary unit using a reversible pump-turbine or a Pump-as-Turbine (PAT).
- Two binary units using differently sized PATs, to extend the operating range.
- Ternary unit using a Kaplan, Francis or Pelton turbine.
- Quaternary unit using a pump and a Kaplan, Francis, Pelton or PAT as turbine.

Electro-mechanical equipment As part of the powerhouse, an electrical machine is chosen. The electrical machines, a synchronous AC machine or an induction machine, are discussed below.

Synchronous AC machine For a synchronous AC motor the rotation of the shaft is synchronised with the waveform of the AC grid voltage (in an AC grid, usually 50 or 60 Hertz). Its most important parts are the rotor, which contains either permanent magnets or electromagnets, and the stator, which contain multiphase AC electromagnets. When the stator is excited by a three phase AC supply, producing a rotating magnetic field in the stator windings, at synchronous speed. The rotor has a constant magnetic field. The opposite poles of the rotating magnetic field and the constant magnetic field attract, which will rotate the rotor at synchronous speed. The rotor's constant magnetic field can be produced by either permanent magnets, or by a field coil electromagnet excited by a DC power supply. However, permanent magnet synchronous machines require a variable-frequency, variable-voltage, electronically controlled source to start, to decrease the stator's initial frequency so the rotor's torque is enough to speed up and catch up with the stator's magnetic field [116].

While generating, the rotor is rotated by the external prime mover, in this case the hydro-turbine; every peak of the sinusoidal output waveform corresponds to a physical position of the rotor. Again, the field coil windings in the rotor have to be excited by a DC source or permanent magnets have to be used; a major disadvantage of using permanent magnets however, is an uncontrollable air gap flux, and thus the voltage of the machine can not easily be regulated.

The frequency is of an AC synchronous machine is determined by the formula:

$$f = \frac{RPM \cdot p}{120} \quad (3.14)$$

Where f is the frequency (Hz), RPM is the rotor speed (revolutions per minute) and p is the number of poles formed by the stator windings.

Induction machine Almost all industrial motors are induction machines. An induction motor can be used as an AC generator. For normal motor operation, 3 phase AC power is supplied to the stator, which then creates a rotating magnetic field rotating at synchronous speed. This induces an electric current in the rotor, which produces an electromagnetic field with polarity opposite to the stator's rotating magnetic field. The rotating magnetic field produced in the stator pulls the rotor to run behind it, with the currents in the rotor induced at the slip frequency. As a motor, an induction machine is self-starting.

In generation operation the rotor is accelerated to a speed exceeding the synchronous speed by means of a prime mover (in this case, a hydroturbine), and the slip becomes negative. A rotor current is then generated in the opposite direction, and this generated rotor current produces a rotating magnetic field in the rotor. This magnetic field pushes onto the stator field, and an active current is produced in stator coils. Now the motor operates as a asynchronous generator. An induction machine working as an induction generator is not self excited. For stand-alone installations, reactive power needs to be supplied by capacitors which provide the magnetization current required to begin producing voltage. These capacitors can be charged by a DC source, such as batteries or PV panels. An induction generator is asynchronous, which means they cannot provide synchronised power; the output frequency will be 2 or 3 percent lower than synchronous speed (as is calculated by equation 3.14). The frequency of the grid to which the induction generator is connected regulates the output voltage frequency. They tend to decrease the frequency stability of the grid, because they add an inductive load. However, connecting the machine to a DC grid through a rectifier would circumvent this problem. Induction generators are frequently preferred over synchronous generators for small hydroelectric sites, since they have no loss of synchronism when transient changes in the power system occur.

These induction machines could be used in a ternary unit. However, a binary unit using a PAT generally uses the pump's induction motor as an AC generator [182].

3.4.2. Discussion

The optional configurations can be judged through the relevant design criteria.

Operating range The power output of a turbine is calculated through equation 3.5, where the gross head (H_{gross}) and water flow rate (Q) determine whether a turbine can be used. A turbine selection chart can aid in determining the suitability of a turbine. Considering the case of small-scale hydropower with the option to use a PAT, a new turbine selection chart covering all requirements has been established (Figure 3.10), based on information of the manufacturers Voith and Andritz [91] [90], as well as literature on tested PATs [216].

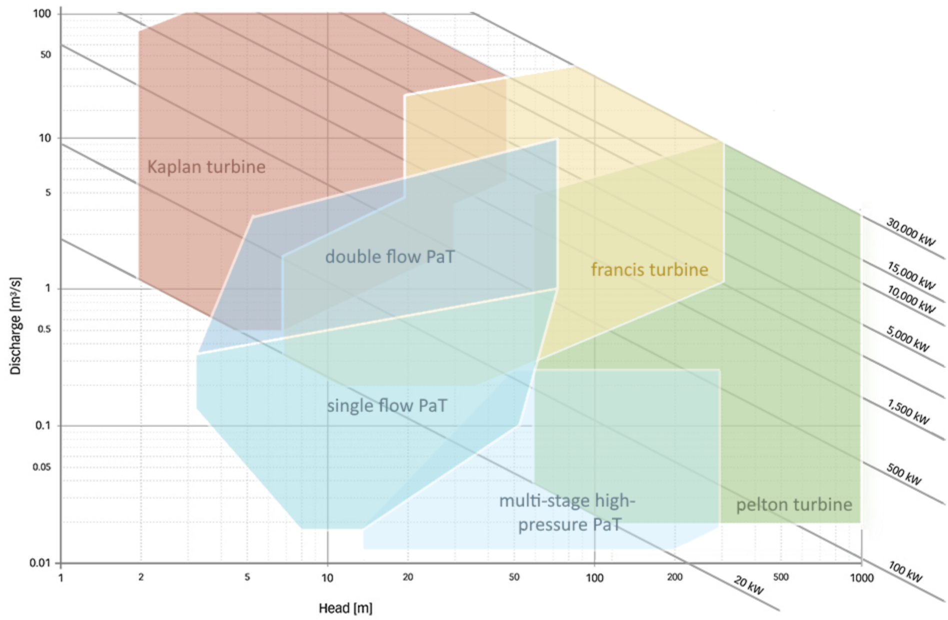


Figure 3.10: Turbine selection chart for mini-hydropower. Information for mini-hydroturbines is gathered from [91], and for the Pump as Turbine (PAT) from [90]. The chart shows that for high heads, a Pelton turbine is needed. Single-stage pumps used as turbine, both double and single flow, have a very maximum head, up to about 80 meter. Francis turbines for mini-hydro purposes have a maximum head similar to multi-stage pumps used as turbine, but can handle much more flow and thus give a much larger power output. Kaplan turbines are only used for low heads applications.

Since the minimum gross head has been previously set at 100 meter, equation 3.5 can be used to estimate the required flow rate for certain power outputs. Assuming a minimum gross head of 100 meter and a maximum power output requirement of 580 kilowatt, the combination of flow rate and gross head will never fall within the area for either a Kaplan turbine, a Francis turbine or a double or single flow PAT according to Figure 3.10. Moreover, contact with Voith and Andritz Group, both major manufacturers of reversible pump-turbines, established that these units are not available for capacities of less than 5 megawatt and thus are not suitable for the scope of small-scale pumped hydro storage.

Due to the fact that reversible pump-turbines, Kaplan turbines, Francis turbines, double and single flow PATs are out of the operating range and completely unsuitable for the setting, there is no motivation to discuss these options further. These options are thus henceforth eliminated, with the following 4 options remaining:

- Binary unit with a PAT.
- Ternary unit with a Pelton turbine.
- Quaternary unit with either a Pelton turbine or a PAT.

Quality of power and supply The powerhouse plays an important role in the improvement of quality of power and quality of supply within the mini-grid. To guarantee this, the configuration should have a wide operating range, to account for a wide range of fluctuations in the power discrepancy, which is the difference between generation and demand. As discussed in Section 3.1, a supporting BESS will take care of small power transients. The pumping and turbine mode of the PHS plant should however balance the majority of the power discrepancies; this is only possible with a wide operating range.

Whether a synchronous AC machine, an induction machine or the induction motor of a PAT itself is used, the input and output power is AC. As discussed in Section 1.1, DC mini-grids present many advantages of AC mini-grids. Therefore, for this thesis a connection to a DC mini-grid is assumed. This has an influence on the deliberation for the applicability and suitability of the configurations discussed. A converter between the DC mini-grid and the AC electrical machine is required. The circuit of the aforementioned VFD, which increases the operating range of a PAT, is visualised in Figure 3.11. With a DC mini-grid, the rectifier circuit can be discarded. Therefore, with a DC mini-grid, "half" a VFD can function as the converter, which is needed in any case, while also controlling the speed of the electrical machine. Equipping a PAT with a VFD thus brings no additional costs which were not required anyway. Moreover, ternary units also need a converter, increasing their costs.

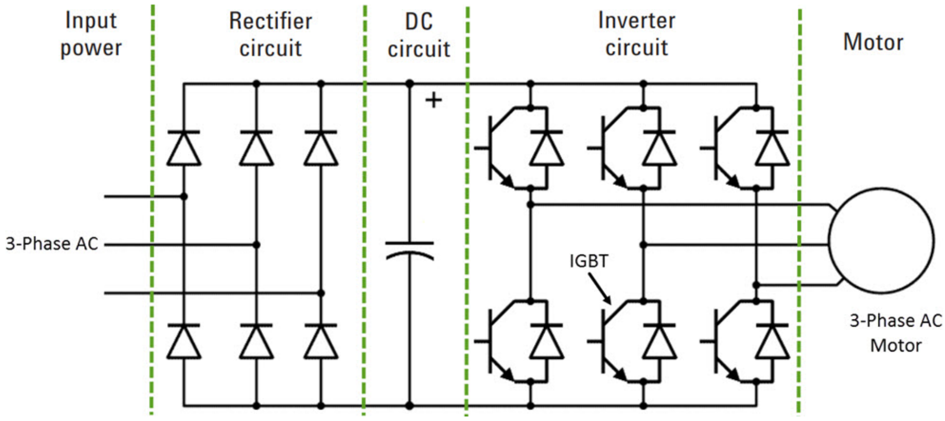


Figure 3.11: Circuit of a Variable Frequency Drive (VFD), converting power from AC to DC, and back to AC. Obtained from [197].

The addition of a converter allows for the extension of the operating range of every configuration; for the ternary and quaternary units not only the turbine operating range, but likewise the pump operating range. Operation during pump mode influences the quality of power and supply just as much as the turbine mode. The pump of a ternary unit, as well as a PAT in pumping mode without VFD, can only provide a flow around their Best Efficiency Point (BEP). Moving away from the BEP can cause instability and damage to the pump, as can be observed in Figure 3.12. The flow rate provided by the pump is determined by the power input; for this reason, the power input range is limited, even with a VFD. For pumping, the flow should not fall out of the range of 60 to 125 percent of the pumps rated flow at BEP.

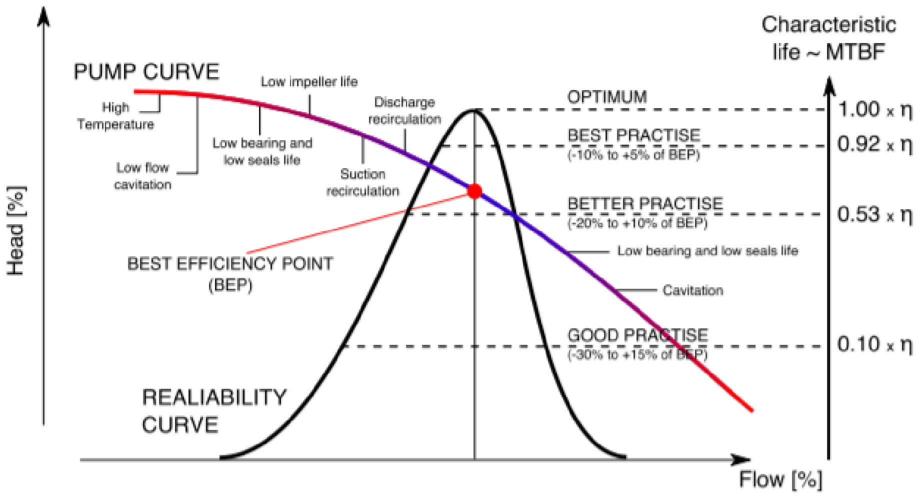


Figure 3.12: Damage and instabilities which can occur when running the pump too far from its BEP [157].

There is thus a difference in the operating range of the turbine mode and of the pump mode. Due to this, quality of power and supply is greatly improved if both the turbine and the pump can be optimized for efficiency. This is possible for a ternary and a quaternary unit, but for a binary unit using a PAT it is a compromise to allow for operation as either a pump or a turbine. There is thus a guaranteed mismatch between the optimal turbine and pump characteristics, and the actual turbine and pump characteristics of a PAT, leading to less efficient operation and a narrower operating range than a ternary or quaternary unit.

Moreover, the rotational direction of the motor-generator is the same for both operational modes for a ternary unit, so there is no change in the direction of water flow to change from pump to turbine mode or vice-versa. Since the motor-generator of a ternary unit does not need to change direction, there is only a short changeover time between modes, leading to a much faster response time. With a quaternary unit, the motor and generator are separated, giving an equally short response time. It can thus be said that the ternary and the quaternary configuration are better equipped to improve the quality of the power and the quality of the supply in the mini-grid.

Component availability Centrifugal pumps are a common occurrence around the globe, including in rural areas for the purpose of irrigation. Therefore they are readily available for a wide range of heads and flows, also in most developing countries [199]. This makes a PAT a popular option for mini-hydropower in developing regions, such as sub-Saharan Africa; similarly, this makes PAT an interesting option for small-scale PHS.

In contrast, the more complex hydraulic equipment for ternary units, such as small hydro turbines, are manufactured by a few companies and in some cases even needs to be custom designed. Potentially, importation of the equipment might be necessary, although large manufacturers such as Voith and Andritz Group do have offices and manufacturing facilities in Sub-Saharan Africa. Nonetheless, it is very likely a Pelton turbine would need to be transported over a long distance, from a hub of one of the manufacturers.

Main grid connection Whether the electro-mechanical machinery can easily be connected to the main grid network, depends on which of the scenarios describes in Section 2.1.4 becomes reality. There two scenarios where the PHS plant remains a part of the grid: either the mini-grid operates as it used to but with the main grid as an energy supply during a generation-demand mismatch, or the PHS plant becomes an entity by itself, providing energy arbitrage.

In the first scenario, the mini-grid will be connected to the main grid network with a Voltage Source Converter (VSC). There are three operating modes for a grid connected DC mini-grid [200]:

1. *Grid-connected (daytime):* During the daytime, the PV modules generate enough electricity to meet the demand, and surplus energy can either be used to charge the ESS or it can be sold to the main grid. To ensure a supply of smooth power to the utility grid, the voltage of the common DC bus is controlled by the ESS by absorbing the power surplus or supplying the deficit. The bus voltage control is thus still handled by the ESS.

2. *Grid-connected (nighttime):* During the nighttime, the PV modules do not provide any power. The mini-grid receives power from the main grid to meet the demand. The bus voltage is thus controlled by the VSC, in the case there is not enough storage capacity.

3. *Islanded:* In islanded mode, the VSC is disconnected and the mini-grid works autonomously; the ESS thus controls the bus voltage.

For this first scenario, the PHS plant will clearly retain an important role in balancing and stabilizing the mini-grid. The connection of the electro-mechanical machinery to the mini-grid will remain the same, through a converter, since the power will still be DC. However, an implication of this connection is the reduced need for storage capacity. This amplifies the need to incorporate secondary water use, since this can start playing a bigger role in the operation of the PHS plant is less storage capacity is needed for mini-grid power balance.

For the second scenario, the PHS plant will be directly connected to the AC main grid. Due to the change of connection from a DC grid to an AC grid, the converter will need to be either removed or replaced with a Variable Frequency Drive. Removing it will significantly limit the operating range of the PHS plant, but installing a VFD adds substantial costs. For energy arbitrage using a small-scale PHS plant, which has in relation to the power in the main grid a very small capacity, a wide operating range is not required. If excess power is available in the main grid, it is likely a large amount of power, so the strategy can be to run the PHS plant at its best efficiency when energy arbitrage is deemed economical. This means the BESS will also no longer be needed.

Appeal When installing a PHS plant, a major part of the appeal is that the negative implications of batteries (chemical waste, short lifetime, etc) are avoided. If however a substantial supplementary BESS is still required due to a limited operating range, the appeal of the PHS plant diminishes. Therefore, a ternary or quaternary unit with a Pelton turbine seems a more attractive option to potential donors.

However, using PATs is very pragmatic, which give the PHS plants a sense of ingenuity. This can likewise appeal to donors, who like to see widespread technology used in new applications.

Operational and replacement costs The costs of the powerhouse during its lifetime are determined by the costs for machinery replacement, maintenance and operation. Replacement is necessary if the electro-mechanical machinery fails, and assessed by the technical lifespan of a piece of machinery. Pelton turbines have a lifespan of 40 to 70 years [73], with 40 years a very conservative estimation. However, the technical lifespan of a pump is only around 25 years [77]. This means a PAT would have to be replaced approximately every 25 years, however a ternary and quaternary unit also use a pump so while their turbine need less frequent replacement, the pump is still replaced every 25 years. A binary unit uses the same machinery, the PAT, for the turbine and pumping operation. This will likely degrade the pump faster, and thus a binary unit is assumed to require more frequent replacement of equipment.

Moreover, the maintenance of the machinery changes depending on which configuration is chosen. Both Pelton turbines and PATs require little maintenance [214] [79]. However, if more electro-mechanical equipment is installed, more maintenance is required. This implies that a quaternary unit has the highest maintenance requirements, followed by the ternary unit and lastly the binary unit. Moreover, proper hydraulic equipment selection, especially the material used, can significantly decrease the maintenance requirements of the powerhouse [134]. Finally, to reduce on maintenance requirements, the pump should, even with a converter providing variable operating speeds, remain within the limits of 60 to 125 percent of its rated flow. Staying within this limit results in longer pump seal life, reduced impeller wear, less system vibration and noise, and less chance of cavitation, making maintenance and replacement less frequent.

Apart from replacements and maintenance, the operation of the machinery itself is considered. The power control depends on the PHS system. For many micro-hydropower installations used for rural electrification, automatic control systems and protection equipment are excluded due to economic constraints [4]. However, due to the need of an ESS in an isolated mini-grid to quickly respond to load fluctuations, the PHS system is assumed to have automatic control. While this increases costs, it is deemed a necessity for proper balancing of generation and demand. In this case, the operators do not always have to control equipment except in cases of starting, stopping and emergency. Moreover, if an automated system is installed, operators do not have to be present at the power plant continually.

Capital costs The capital costs associated with the powerhouse configuration encompass the equipment and machinery itself, as well as the civil costs of the building containing the machinery.

Pumps are significantly cheaper than micro-hydro turbines. Up to a capacity of 500 kW, PATs can be 6 to 8 times cheaper than custom-made turbines [185] [255]. Furthermore, due to the extra equipment for a ternary unit, the capital costs increase, and more complex and thus costly installation is required [129]. A quaternary unit has even more machinery, increasing the capital costs even further.

As discussed, a converter between the AC electrical machine and the DC mini-grid is required in any case. Since this converter incorporates the function of a VFD, a PAT will be controllable without additional costs compared to a Pelton turbine. This increases the costs-effective advantage of a PAT even more. Moreover, a quaternary unit has two separate electrical machines (a generator and a motor), which means two VFDs are needed. This is a substantial addition to the capital costs.

To protect the machinery from weather, theft and vandalism, it is placed within a powerhouse building. The size of this building depends on the amount of machinery, how large the machinery is, and how it must be installed. A binary unit requires less machinery than a ternary unit, which in turn requires less than a quaternary unit. Furthermore, a Pelton turbine is significantly larger than a PAT, extending the space requirements even further. Finally, the position of the machinery relative to the lower reservoir must be considered. The position of the pump in relation to the lower reservoir water level is critical. The pump must be installed below the water level to avoid cavitation, which can damage the pump [20]. This is determined by the Net Positive Suction Head (NPSH), where the available NSPH ($NPSH_A$) should exceed the required NSPH ($NPSH_R$). The $NPSH_R$ is the head value at the inlet of the pump required to keep the fluid from cavitating, which is provided by the manufacturer. The $NPSH_A$ can be calculated with the following formula:

$$NPSH_A = \frac{p_0}{\rho g} - \frac{p_v}{\rho g} - (z_i - z_w) - h_f \tag{3.15}$$

Here p_0 is the atmospheric pressure, p_v is the vapor pressure of the fluid (water) and h_f are the friction losses in the inlet pipe. $z_i - z_w$ is the static head difference between the center line of the pump and the water level in the reservoir, respectively. If there is suction lift, in instances where the pump is elevated above the water level, this value becomes negative. When the pump is below the reservoir, this becomes suction head and the value is positive; subsequently, placing the pump sufficiently below the lower reservoir increases the $NSPH_A$ leading to a lowered chance of cavitation. Conclusively, the ternary unit should have a vertical shaft, since the turbine should be above the lower reservoir and the pump below. Equally, for the binary unit using a PAT, the pumps should be installed below the water level of the lower reservoir. So while for both these configurations digging must occur, a ternary unit is much taller and bigger, requiring a larger building. This means increasing civil costs for ternary units and even more so for quaternary units.

Technical skill requirements With regards to PATs, pumps are relatively simple and robust machines, making installation and maintenance uncomplicated and cheap. However, pump manufacturers usually do not provide the characteristics of a pump run in reverse. There have been several studies to predict the operation of a pump run as turbine, which can be used to estimate its efficiency [117] [255] [167] [79]; nonetheless, without experimental validation these methods are unreliable, and it remains impossible to accurately predict the functioning of the PAT in turbine mode without experimental data. This complicates the sizing and the prediction of how the PHS plant will function. Especially with a pump purchased regionally, it is unlikely this knowledge will be present.

Operation of the machinery must be automated, as discussed in the operational costs discussion. Only initial installation, repairs and replacements require technical expertise. This is unavoidable with electro-mechanical equipment, and while preventative measures can be taken to reduce the chance of failure, there are few continual maintenance measures which can be taken [231]. This means a permanent technician trained to handle electro-mechanical machinery is not required, but there must be technicians available on a regional level in case of machinery failure.

Theft and vandalism Theft is a challenge for RES projects in SSA, with solar panels and other electrical infrastructure commonly stolen. Fortunately, the electro-mechanical machinery, the most valuable element of the PHS plant, can be housed completely inside chambers, mitigating both vandalism and theft [140]. All powerhouse components should thus be contained and locked away in a safe building, only admissible to operating personnel.

Scalability The power output and input of the PHS plant are determined based on estimations of the demand and generation profiles, leading to a power discrepancy profile. This in turn determines the size in terms of power output and input of the electro-mechanical machinery, and a turbine, pump and motor-generator rated for this power are chosen. Similarly, the penstock diameter is determined on the power output. If the power demand and generation profiles increase, due to more energy-intensive loads or new household connections, the power discrepancy profile will likewise have larger fluctuations. Thus the power output and input of the PHS plant change; the electro-mechanical machinery is however not rated for these larger power requirements, and thus are not able to absorb all surplus power and provide all deficit power in the expanded mini-grid. Consequently, an entirely new powerhouse unit, including all electro-mechanical machinery, must be built alongside the first. Thus, with growing energy needs in the mini-grid, an additional powerhouse unit can be installed in order to account for the larger power requirements. This will be referred to as the powerhouse extension.

This ability to scale the system according to changing power demand provides huge benefits, as are further explained in 4.2. However, significant costs are attached, since it requires an entirely new PHS plant to be built alongside the first. The operating range of the powerhouse extension however does not need to be as wide, since both powerhouses will work in conjunction with one another. For example, the turbine of the powerhouse extension can run around its rated power, while the turbine of the original powerhouse unit modulates the power output, and balances low power demand. Consequently, together the powerhouse units cover a large operating range.

3.4.3. Decision matrix

Due to a quaternary unit presenting almost no advantages compared to a ternary unit, and significant economic disadvantages, this option is eliminated. Thus, the options of a binary unit with a PAT and ternary unit with a Pelton turbine are considered.

Table 3.5: A comparison between a binary unit with a Pump-as-Turbine and a ternary unit with a Pelton turbine. The cross indicates the most favorable option for the design criterion.

criterion	Binary unit (PAT)	Ternary unit (Pelton)
suitable for desired operation range		X
quality power and supply improvement		X
locally available components/materials	X	
connectable to main grid		X
appeal increase		X
low operational costs	X	
low capital costs	X	
low technical skill requirements	X	
scalable	X	

- PAT has many advantages - main disadvantage is limited operating range, which is partly extended with VFD

This independence on operating range requirements when scaling up the system, leads to a preference for a binary configuration with a PAT for the powerhouse extension. This is because the operating range is the main barrier for using a PAT, while

3.5. Provisional technical design

The technical design synthesis leads to a combination of suitable design options, which are brought together in the provisional design. The provisional design is however not a single design. Due to the dependence on site conditions, the design of the water conveyance system changes. And since the choice between powerhouse configurations can not be made without further investigation, there are multiple powerhouse configurations considered in the provisional design. All aspects of the technical provisional design, as well as an estimation of their capital costs, are discussed below.

3.5.1. Earth dam reservoir

The reservoir will be constructed as an earth dam reservoir. Earth dam embankments are built from locally available materials, which can usually be sourced from the reservoir site itself, reducing costs and complexity. The construction itself is an accessible process, with only basic equipment and design procedures required. Due to the broad base of an earth embankment, the load is spread across the foundation, making it a sturdy structure without much structural engineering involved. Moreover, earth dams have a better resistance to settlement and movement than more rigid structures, making them more qualified for areas where earth movements occur regularly. The maintenance associated with earth dam reservoir is considered minimal, provided the initial construction is done correctly; while this initial construction is not a sophisticated procedure, a civil engineer should nonetheless be present to guide the construction. Additionally, while the maintenance does not require much technical skill, it is a continual process necessary to avoid tree growth, erosion, subsidence, animal/insect damage and damage due to seepage. As a final advantage, earth dam reservoirs can easily make use of the terrain, by utilizing naturally occurring slopes and depressions.

The overall construction of earth dam reservoirs is discussed in this section. Firstly, the building materials for the dam embankments are discussed. Then, the dimensions of the dam embankment itself in relation to the required reservoir capacity. Thereafter, the possibilities of capitalizing on favourable terrain conditions. Finally, the necessary construction equipment, workforce and associated costs and expertise are discussed.

Building materials A major advantage of earth dam reservoir is the ability to use local natural materials; material excavated from within the reservoir perimeter can be used to build the dam embankments. There are two types of dams that can be used: a homogeneous earthfill dam or a zoned earthfill dam. The distinction is that the zoned earthfill dam has an impervious core, thus reducing the seepage through the dam. Whether it is possible to construct this impervious core, depends on the material availability at the site, or otherwise, albeit less favourable, at a reasonable haul distance. It is important to conduct a site survey and test the soil, to investigate the feasibility of building an earth dam. Soil can be classified on the proportion of particles it contains. Stephens (1991) showed which soil can be used for the construction of earth dams, based on the soil classes as determined by United States Department of Agriculture (USDA). This is summarized in Table 3.6.

Table 3.6: Soil suitability for the construction of homogeneous and zoned earth dams [217].

Textural Class	% Sand	% Clay	Soil suitability for earth dams		
			Homogeneous dam	Zoned dam	
				Core	Shell
Sand	>85%	-			
Loamy sand	70-85%	-			√
Sandy loam	50-70%	<20%			√
Sandy clay loam	45-80%	20-35%	√	√	√
Clay loam	<45%	25-40%	√	√	
Sandy clay	45-65%	>35%	√	√	
Clay	<45%	>40%		√	

While there are a number of preliminary visual and field tests which can be conducted on site, to determine whether the soil might be suitable, soil samples should thereafter be tested in a laboratory in order to determine the suitability completely before construction of an earth dam. The following laboratory test should be performed:

- Particle Size Analysis: this tests what the type of soil is. By passing the soil sample through sieves of an increasingly smaller mesh, a Particle Size Distribution Curve is achieved.
- Atterberg Limits: this test determines the water content of the soil and thus whether it exists in the liquid, plastic, semi-solid or solid state. The test places the soil sample on a Plasticity Chart.
- Proctor Compaction Test: used to determine the optimal moisture content of the soil, for which it reaches its maximum dry density.

After these tests, a conclusion is made: ideally, a zoned dam can be built with the material available on site, along with sufficient clay to cover the bottom of the reservoir. Otherwise, it might only be possible to construct a homogeneous dam. In this case, seepage can be avoided lining the reservoir with a liner [127]. These polymeric geomembranes and are commonly available in developing regions, due to the frequent occurence of earth dam reservoirs, and are usually manufactured from recycled PVC or HDPE (for larger reservoirs) plastics. With liner thicknesses of 400 to 800 micron, and a HDPE density of 970 kg/m^3, the geomembrane will have a weight of approximately 0.4 to 0.8 kg per square meter, and is thus not too heavy to transport to the reservoir site.

If however, it is concluded that the soil on the site can not be used as material for the foundation and construction of any earth dam, the material has to be transported to the site from a different location. This adds logistical issues to the dam construction, as well as additional costs, and an alternative location for the reservoir should be considered.

Dam dimensions An earth dam should be designed and constructed in such a way that it is safe and stable. Therefore, the following aspects should be considered:

- Overtopping should be avoided, because this can seriously damage the structural integrity of the dam. Providing sufficient outlets and spillways, as well as allowing for enough freeboard (the vertical space between the dam crest level and the reservoir water level when it is filled up) prevent the dams from overtopping. The minimum freeboard is normally determined according to design standards, with respect to the fetch (the length of water surface over which a given wind blows, thus generating waves). But since relatively small reservoirs are considered, the fetch will be short and the dam should have a freeboard of 10 to 15% of its height [39].
- The earth dam should be stable and contain the water without breaching. This is established with a sufficient crest width and slope height/width ratio. For a zoned dam, the impervious core should constitute 30% of the cross-sectional area of the dam.
- The seepage through the dam should be minimal. Either an impervious core should be constructed, or a plastic liner should be placed to separate the soil from the water. As a reservoir is normally built by excavating earth from within, the excavated part of the reservoir should also be lined with either locally obtained clay or a plastic liner.

The values of the dam dimensions are summarised in Figure 3.13.

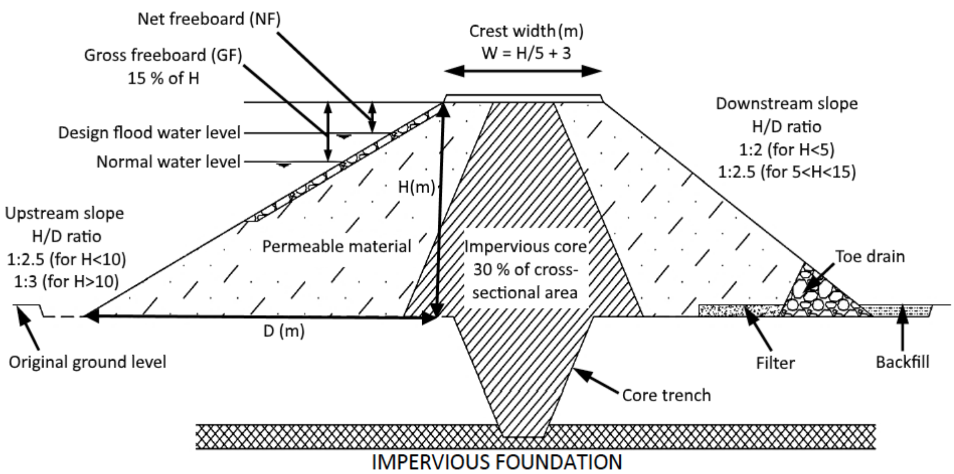


Figure 3.13: Cross-section of an earth dam with impervious core. All equations for the dimensions are taken from [163], [176] and [177].

With the equations for crest width, freeboard height and slope height to width ratio, an equation for the volume of earthwork in the dam in relation to the height of the water level can be established. The conditions of the slope ratio differ according to the dam height, therefore two equations are set up:

$$V_{dam} = \left(\frac{2,45}{0,7225}H_w^2 + \frac{3}{0,85}H_w\right)L \qquad for\ 0 < H < 5 \qquad (3.16)$$

$$V_{dam} = \left(\frac{2,7}{0,7225}H_w^2 + \frac{3}{0,85}H_w\right)L \qquad for\ 5 < H < 10 \qquad (3.17)$$

In this equation, V_{dam} is the volume of the dam, H_w is the height of the water level, and L is the length of the dam. Dams higher than 10 meter are not recommended.

The length of the earth dam depends on the required volume of the dam, but also on the site. Two different kind of sites for an earthwork reservoir can be differentiated, a dry gully site and a turkey's nest site, depending on the terrain characteristics of the site.

Terrain When the slope of a hill or mountain features a gentle gully, the terrain can be used to create a reservoir, contained on one side by the natural slope and on the other side by a constructed earth embankment. This is called a dry gully site, as illustrated in Figure 3.14. Using a naturally occurring depression and the slope as containment on one side greatly improves the storage/excavation (S/E) ratio. In some instances, natural slopes can even surround a potential reservoir site on two or three sides, meaning less dam construction and thus less excavation is needed, improving the S/E ratio and decreasing the construction costs. The lower reservoir is more likely to be built at a dry gully site, since these sites occur mostly at the foot of a hill or mountain. A reservoir at a dry gully site will also be able to collect run-off water through diverting the catchment streams.

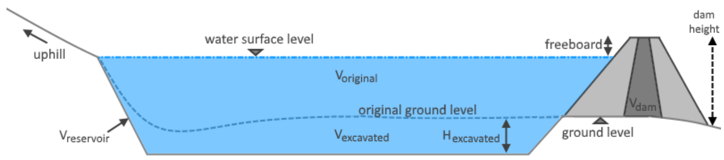


Figure 3.14: Representational cross-section of a reservoir constructed on a dry gully site.

For both Figure 3.14 and 3.15, $V_{original}$ is the volume of water stored if no additional excavation was performed, $V_{excavated}$ is the volume of excavated earth, which creates additional volume for water storage, and $V_{reservoir}$ adds these two volumes together and represents the total capacity of water storage in the reservoir. Ideally $V_{excavated}$ and V_{dam} are equal, since that means all excavated soil can be used for the construction of the dam. $H_{excavated}$ is the excavation depth, used to calculated the total volume of soil excavated.

On flat land, where no natural slopes can be utilized, a turkey's nest dam can be built. Here earth is excavated from the center and moved to the edges, to help form a continuous dam creating a reservoir within. This type of reservoir also has an S/E ratio exceeding 1, since the excavated soil is used to form a surrounding dam which contains water above the original ground level. See Figure 3.15. A turkey's nest reservoir can also be located in a catchment area, but water inflow other than precipitation is more difficult since the diverted run-off water streams need to come from natural slopes.

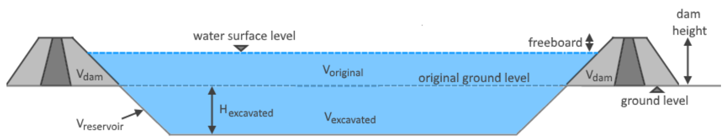


Figure 3.15: Representational cross-section of a reservoir constructed on a turkey's nest site.

Again, $V_{excavated}$ and V_{dam} should ideally be equal. Earth dam reservoirs are usually rectangular in shape.

Reservoir dimensions All equations defined in this section relate the dimensions of the complete reservoir (including dams) to one another. To compare costs, the dam height (H) should be minimized since this implies less excavation work is needed. However, the available area for building a reservoir is dependent on the site location, and this constrains its size. In addition to this constraint, water evaporation is directly tied to the the water surface area [128], as can also be seen from equation 3.4 where the evaporation is measured in mm/day per square meter. Therefore, a deeper reservoir will have the same capacity but less evaporation; it does however require more excavation work, as observed from equations 3.16 and 3.17 which indicate the volume of the dam is influenced more by dam height than dam length. This leads to higher initial construction costs, and a dam height and length ratio must thus be found to balance excavation work and water evaporation. Therefore, the length of the dams should be a free variable to be adjusted according to the site conditions and requirements.

We can relate the two variables of length and dam height to the total volume of the water in the reservoir, $V_{reservoir}$, differentiating between dry gully and turkey's nest sites. To simplify, the assumption is made that the soil is suitable to use all excavated earth for the construction of the dam, and the reservoir is assumed to be rectangular as this is common practice. Taking these assumptions in mind, the following equations are needed:

$$V_{reservoir} = V_{original} + V_{excavated} \tag{3.18}$$

$$V_{excavated} = V_{dam} \tag{3.19}$$

Where for the calculation of V_{dam} the equations 3.16 and 3.17 are used; here the values of the length (*L*) are dependent on the area. If the site allows for a rectangular reservoir, the length is determined by sides *a* and *b*.

The values for $V_{original}$ are the same for both site types and can be approximated as follows:

$$V_{original} = a \cdot b \cdot H_w \tag{3.20}$$

These equations, together with the relation between water level and dam height $H_w = 0,85H$, as taken from Figure 3.13, can be used to relate the reservoir surface area and the volume of excavated earth to one another, depending on the total reservoir capacity required. A code has been written in *Python*, to easily obtain and compare several alternatives for a proposed site. This differs for turkey's nest sites, where a dam embankment must be built on each side, or a dry gully site, where natural slopes confine 1 or 2 sides of the reservoir and only 3 or 2 dam embankments must be constructed. This has been implemented in the code, by relating the total dam length to the amount of natural slopes present, represented as *n*:

$$L = 2(L_1 + L_2) \quad for \quad n = 0 \quad (turkey's\ nest)$$

$$L = L_1 + 2L_2 \quad for \quad n = 1 \quad (one\ natural\ slope)$$

$$L = L_1 + L_2 \quad for \quad n = 2 \quad (two\ natural\ slopes) \tag{3.21}$$

In these equations, L_1 is the short side of the rectangular reservoir and L_2 the long side; a natural slope will be used for the long side to capitalize on its usefulness and in case of two natural slopes these are assumed to be adjoining.

The relation between the surface area of the proposed reservoir compared to the required volume of excavated earth for reservoir capacities of 1000, 2000 and 3000 cubic meter are graphically represented in Figure 3.16.

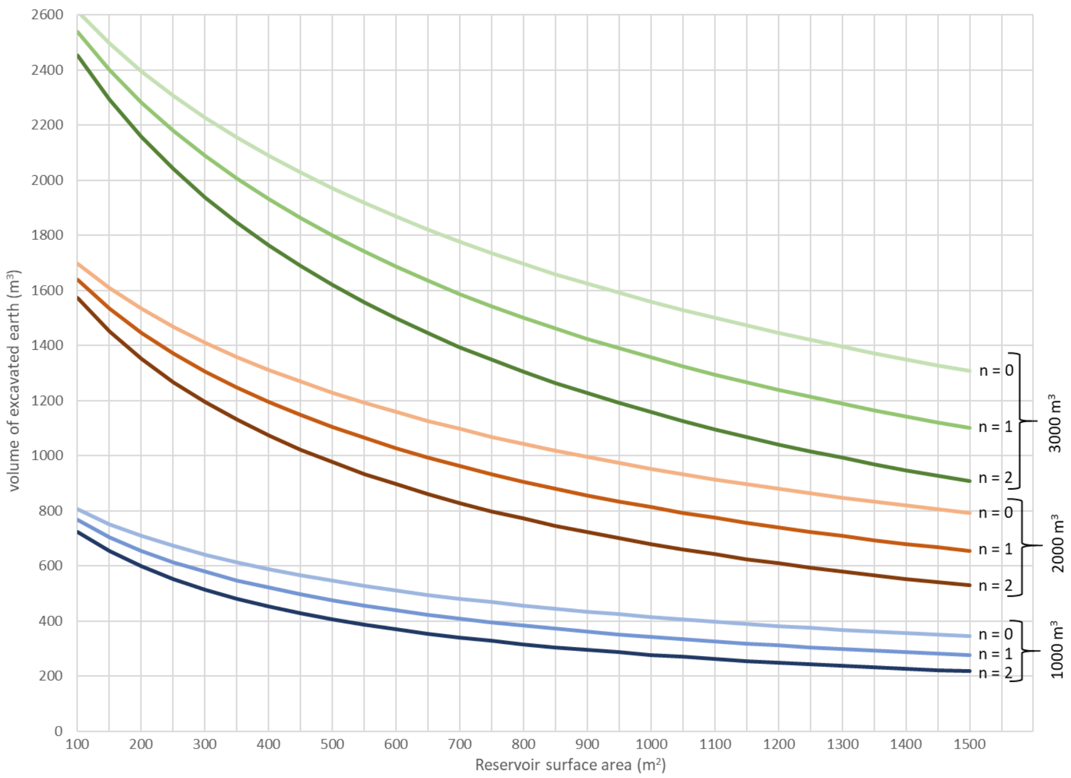


Figure 3.16: Relation between surface area and excavated volume of soil. Each blue line represents a proposed total reservoir capacity of $1000m^3$, each orange line $2000m^3$ and each green line $3000m^3$. for each of these reservoir capacities, the relation between reservoir surface area and required volume to be excavated is represented if no natural slopes are present (n=0), if one natural slope can be used as confinement on one side (n=1), and if two natural slopes can be used (n=2).

From the figure, it can be observed that especially for reservoirs of larger capacities, an existing natural slopes to confine one or two sides of the reservoir significantly reduces the volume of earth that needs to be excavated. Moreover, based on the relation visualized in Figure 3.16, a trade-off between reservoir surface area (linked to evaporation) and excavation requirements (linked to higher construction costs) can be made.

Reservoir expansion An earth dam reservoir can be expanded should the need arise, for example with growing storage capacity needs or an expansion of the entire PHS plant. This is however not an easy process because of the following reasons:

- A large part of the water impounded in the reservoir can be transported through the penstock to the second reservoir. However, it is assumed 20 percent of the water in a reservoir can not be drained, as it is 'dead storage'.
- Larger reservoirs require more depth to avoid excessive evaporation. However, to obtain this, the reservoir must be completely empty if it is to be expanded. The embankments can however be raised without completely draining the reservoir.
- Dam dimensions are scaled to the size of the original reservoir. The dams thus need to be strengthened to withhold the pressure of a larger water impoundment.
- Likewise, the spillway is constructed for a smaller size reservoir, and a new spillway is thus required.

To successfully expand an earth dam reservoir, a new reservoir be attached to one of the embankments of the original reservoir, with a new spillway built. Meanwhile, the embankments of the original reservoir are reinforced from the outside and raised. Up until this moment the reservoirs does not need to be drained; this is only done when the reservoir attachment is finished to keep the PHS plant functional for as long as possible. Subsequently, the embankment separating the original reservoir and the reservoir attachment is removed, uniting the two reservoirs as one. This is visualized in Figure 3.17.

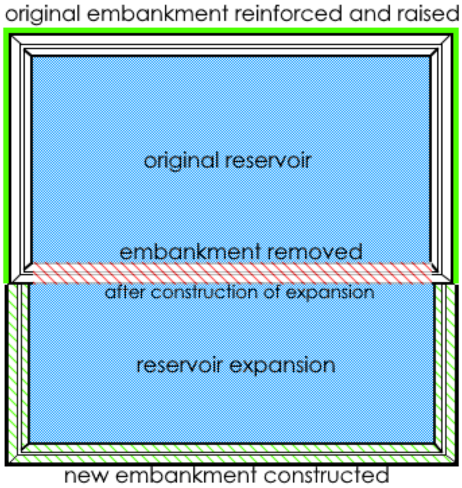


Figure 3.17: Visualization of the expansion of an earth dam reservoir

Capital costs The construction of the reservoir can be divided into several stages. Each stage has its own associated costs and technical skill requirements. While reservoir construction costs are dependent on the region and site conditions, a general cost curve will be established based on generalized costs for each stage. For the cost of unskilled workers, the mean of the average daily wage in low-income and lower-middle-income economies in Sub-Saharan Africa is assumed to be representative. This information is obtained from data of the Worldbank and the International Labour Organization (ILO) [32] and comes down to approximately 4.20 € per day per worker (or per worker day). The productivity norms for every aspect of construction, such as site clearing, excavation, hauling, etc. are obtained from the medians as researched by ILO in collaboration with ASIST [219]. The construction stages are the following:

- Site evaluation: this initial stage requires a qualified civil engineer experienced with the construction of earth dam reservoirs, to find a suitable location, as well as test the soil and make a design for the earth dam reservoir. Since these reservoirs are commonplace in developing regions, a regional civil engineers are likely to be available. Regardless of the proposed reservoir capacity, the site analysis will be similar and requires the same tests and effort. Therefore, this initial survey is assumed to have an associated base cost of 10,000 €, as based on a earth dam reservoir construction project in Zambia [218].
- Site clearing: before construction can begin, all obstacles need to be removed, such as vegetation. This manual labour can be performed by unskilled workers, and while it depends on the obstacles present, assuming an equal distribution of light, medium and dense bush, approximately 110 m^2 per worker day can be cleared; this comes down to $4.20/110$ = 0.038 € per m^2.
- Excavation: while the full extent of this stage depends on whether a zoned dam or homogeneous dam is constructed, for the sake of simplifying a cost equation it is assumed the soil is moved from within the reservoir to the outer edges to form embankments. Heavy earth-moving machinery are not necessary or thus not recommended for this process; instead, manual labour and dam scoops drawn by tractors or draught animals can be used, depending on the availability. With dam scoops 120 m^3 per worker day can be moved, and manual workers can excavate up to 5 m^3 per worker day. The soil moved to the embankment must be compacted with rollers. Due to unavailable data on the cost an availability of farm equipment and draught animals, the costs from the above mentioned Zambia project are used 3.22 € per m^3.
- Additional construction: a spillway, along with diversion channels and cofferdams need to be constructed. This is difficult to put into direct costs, but it is assumed additional construction

is an extra 25 percent added to the total cost of reservoir construction. Apart from additional construction, this also includes engineer supervision fees. Again, this factor of 25 percent is obtained from the Zambia project.

- Liner: lastly, the price for a polymeric geomembrane is included. Several quotes obtained from Kenyan and South African companies estimate the price for a liner at approximately 5.00 € per m^2; the square meters required is the surface area plus the height of the dams; an additional 10 percent should also be added to account for joining and overlap of the liner.

These costs are added to formulate the total cost:

$$C_{reservoir} = C_{evaluation} + C_{clearing} \cdot A + C_{additional} \cdot (C_{excavation} \cdot V_{excavated}) + C_{liner} \cdot A$$

$$C_r = 10000 + 0.038A + 1.25(3.22V_{excavated}) + 5 \cdot 1.1(A + H_{dam}) \tag{3.22}$$

It should be noted that the dam height, H_{dam}, is in this equation the height of the dam from the reservoir floor to the crest of the dam. There is no clearly defined relation between the surface area and the depth of the reservoir (see previous section). This is very dependent on the situational conditions. To calculate the costs per cubic meter of reservoir in relation to the reservoir capacity, several likely reservoir dimensions have been calculated, along with their estimated costs per equation 3.22, and are summarized in Table 3.7.

Table 3.7: Realistic reservoir dimensions, based on construction guidelines, and their associated costs.

Capacity (m^3)	A (m^2)	$V_{excavated}$ (m^3)	H_dam (m)	C_r (euro)	euro/m^3
1000	300	639.54	3.55	14255.04	14.26
2000	500	1225.16	4.27	17723.78	8.86
3000	750	1729.05	4.30	21136.59	7.05
4000	1000	2271.81	4.30	24705.71	6.18
5000	1200	2696.95	4.51	27525.61	5.51
6000	1400	3162.49	4.64	30507.76	5.08
7000	1600	3617.92	4.75	33449.04	4.78
8000	1800	4065.61	4.83	36359.05	4.54
9000	2000	4507.24	4.90	39244.55	4.36
10000	2200	4924.27	4.95	42031.05	4.20
11000	2400	5335.35	5.00	44793.50	4.07
12000	2600	5741.44	5.04	47535.82	3.96
13000	2800	6143.30	5.08	50261.09	3.87
14000	3000	6541.54	5.11	52971.79	3.78
15000	3200	6936.67	5.13	55669.94	3.71

These reservoir costs are visualized in Figure 3.18, and a trendline is established to find the reservoir construction costs, in $euro/m^3$ for a desired reservoir capacity:

$$\frac{C_r}{V_r} = 331.3 \cdot (V_r)^{-0.474} \quad €/m^3 \tag{3.23}$$

The result of this equation multiplied by $V_{reservoir}$ gives the total cost of a reservoir, which can also be calculated by the following equation:

$$C_r = 331.3 \cdot (V_r)^{0.526} \quad € \tag{3.24}$$

This cost equation is for the situation where no natural slopes are available; in case the terrain can be used, the costs will be lower.

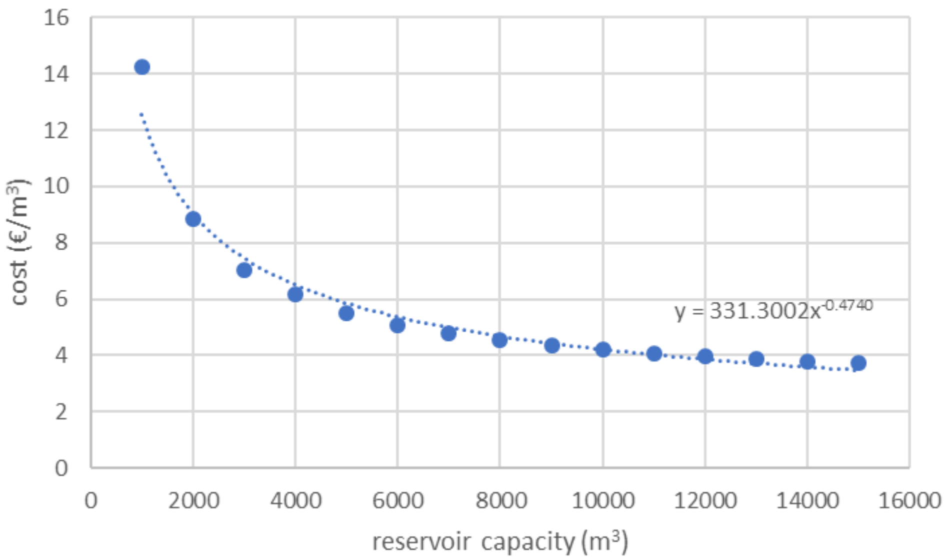


Figure 3.18: Visualisation of the relation between reservoir cost (euro/m^3) and the desired reservoir capacity. The trendline and its associated equation makes it possible to estimate the costs for any reservoir size.

3.5.2. Penstock

Dimensions of pipe segments made from GRP or Mild Steel are globally standardized. The thickness of the pipe wall and thus the weight of a pipe segment, and the inner and outer diameter of the pipe depends on the material, the nominal diameter and the pressure grade (PN for GRP, and Schedule for mild steel). A pipe of a certain material, pressure grade and nominal diameter is hereafter referred to as a pipe type. An example of several pipe types and their associated characteristics are presented in Table 3.8.

Table 3.8: An example of pipe types; the type is characterised by the material, pressure grade and nominal diameter, and has an associated wall thickness, actual inner diameter, weight and allowed internal pressure.

Pipe type			Characteristics			
Material	Pressure grade	Nominal diameter (mm)	Inner diameter (mm)	Wall thickness (mm)	Weight (kg/m)	Allowed pressure (MPa)
GRP	PN25	300	301.6	4.7	5.43	2.5
MS (Mild Steel)	S80	400	363.52	21.44	203.54	32.44

All pipe types, along with their characteristics, have been added to a database. This database contains the following information for each pipe type: Nominal diameter, material, pressure grade, inner diameter, wall thickness, weight per meter, price per meter (as obtained by quotations, as explained in Section 3.3.2). With this database of pipe types, the most cost-effective pipe type can be chosen for certain site-specific conditions, as discussed in the paragraph on ’capital costs’ below.

Flow control To control the flow through the penstock, a valve is required. Which valve is used, is dependent on the desired control of the PHS output power. Butterfly or spherical valve are usually used as turbine and pump inlet valves, or as safety valve. They shut the flow off completely, and thus are used in systems to either let the maximum flow or no flow at all run through the penstock.

Cone valves are used to control the flow rate from 0 to 100 percent. These valves however only allow an unidirectional flow. Usually, they are combined with a butterfly or spherical valve, to shut the flow off completely in case of emergency or maintenance.

At short valve closing times, as well as in case of operational failure, the pressure in the penstock may increase excessively. In order to avoid penstock eruptions, a pressure relief valve can installed, which automatically open in case of a sudden turbine stop, to re-route the water directly to the tailpipe. Alternatively, a surge tank can be installed to dampen excess variations in pressure. The surge tanks functions by storing excess water when the flow in the penstock is stopped. They are usually provided in medium to high heads schemes, where the penstock has a considerable length.

Capital costs Due to the length of penstock required for most PHS sites, the penstock constitutes a significant part of the total cost of the PHS plant. As indicated, the required diameter of the pipe depends on the available head, the length of the penstock and the desired maximum power output.

With the equations presented in the paragraph 'operating conditions' in Section 3.3.2, a pipe selection tool is programmed which decided the required pipe type for a specified power output and head. All pipe types in the above mentioned database are put through the program, which calculated for each pipe type whether the system can reach the desired maximum power output (this is not possible if the diameter is too small), the head losses, and the maximum pressure occurring in the penstock, which is defined as the hydrostatic pressure summed with the water hammer pressure. The water hammer pressure occurs when the valve is closed, and is calculated as indicated in equation 3.25.

$$P_{wh} = \frac{\rho L V}{t} \tag{3.25}$$

In this equation, P_{wh} is the water hammer pressure in Pascal, L is the length of the penstock (m), V is the speed of the water in the penstock derived from the required flow rate (m/s), and t is the valve closing time. For the water hammer effect in the penstock selection tool, the fastest valve closing time is assumed to be twice the critical closing time, T_c; the critical time valve closing time is defined as the time in which the pressure waves would reflect and is calculated with equation 3.26. It is assumed in the case of instant valve closure, during an emergency or a technical defect, the pressure relief valve will negate the remainder of the water hammer effect.

$$T_c = \frac{2L}{c} \tag{3.26}$$

In this equation, the pressure wave velocity, c, is calculated as follows:

$$c = \left(\frac{E_W}{\rho}\right)^{0.5} \cdot \left(\frac{1}{1 + \frac{E_w D}{E_m e}}\right)^{0.5} \tag{3.27}$$

After the penstock selection tool calculates the required values for each pipe type, the following pipes are discarded:

- Those that do not meet the requirements of being able to supply the desired power output.
- Those that have more than 5 percent head losses.
- The pipe types that can not withstand the hydrostatic and water hammer pressure.

After this, all remaining pipe types are considered feasible, and are ranked by price per meter. The pipe type with the lowest cost per meter is deemed most suitable.

To obtain an understanding of the price (euro/m) of the penstock, with respect to the head and power output, the model was used to find the required pipe type for certain values. For the length of the penstock, a ratio of 5:1 with respect to the head was used. For lower heads, of 100, 200 and 300 meter, GRP from several pressure grades were indicated by the model as the most economical pipes. For higher heads, of 400 meter and up, mild steel pipes become necessary due to an increase in hydrostatic pressure, although the lowest pressure grade (S5) is already sufficient. The price per meter decreases with higher heads, due to the decrease in required diameter.

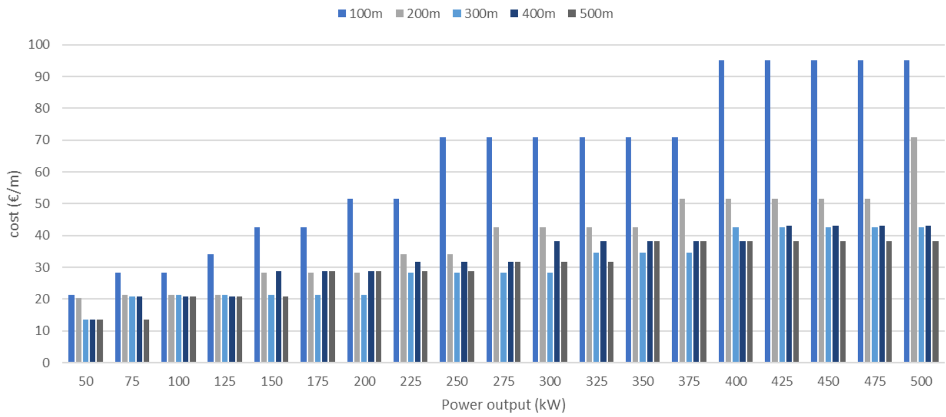


Figure 3.19: Indication of the price (euro/m) of the most economical pipes to be used for a certain gross head and desired power output (kW). It can be observed that the price generally becomes lower with higher heads; there is however a spike in price between 300 and 400 meter head, due to the change from GRP to Mild Steel pipes.

Figure 3.19 shows that a trendline for the cost per kW can not be established. The changes in pipe price do not change gradually but with sudden jumps, due to the predetermined pipe types. Conclusively, to get an idea of the costs of a small-scale isolated PHES system, a model is required where the costs are based on site conditions.

3.5.3. Powerhouse configuration

It has been established in Section 3.4.3 that both a binary unit with PAT and a ternary unit with a Pelton turbine are determined as the most suitable. However, neither of these options comes forward as the optimal choice, as they both have their advantages and disadvantages. The binary unit with a PAT for example satisfies the design criteria for low operational costs, capital costs, and technical skills, as well as local availability. However, it has a limited operating range, which a ternary unit using a Pelton turbine does have, providing more reliable power. Further inquiry in the implications of using either one of these configurations is required to make a deliberate comparison between the two options.

Scalable PHS plant When a mini-grid is installed, the demand of the customers is estimated to determine the amount of generation and energy storage required. As discussed in 1.2, the step to a mini-grid is made when a majority of households in the targeted community advance to electrification tier 3 and above. The rate of electrification of the community, and thus the increase in demand, can vary a lot after this point. While generation can easily be scaled up, through the installation of additional PV panels, a PHS plant is sized with a certain demand in mind. There are several approaches to account for increasing demand:

- The PHS plant can be sized for a ”future demand”, meaning the trend of the electrification rate in similar projects is observed and applied to to the mini-grid. The PHS plant is then thus sized for a demand higher than the actual demand at the time of installation. This approach has the drawback that predicting demand is not precise, which can lead to an oversized and thus too expensive PHS plant for an extended period. The challenge 2.2.2 indicates revenue is expected to be low, meaning if the PHS plant is oversized for too long this financially jeopardizes the entire project.

- The PHS plant can also only function as a large storage plant, and batteries can start playing a larger role with increasing power demand. In this approach, the storage capacity and peak power from the ESS expanded through the installation of additional batteries.

- Alternatively, only the storage capacity can be expanded, through expansion of the reservoirs. A growing demand however also leads to higher peak power requirements, especially since the peak power is already estimated with demand response in mind. Therefore, this approach, while useable for a medium increase in demand, is not suitable for large demand increases.

- Finally, the entire PHS plant can increase in scale when the electrification rate and the demand have increased significantly. The scaling can be done in steps: first the storage capacity is expanded through reservoir expansion, as in the previous approach, and subsequently the power output is increased through extension of the powerhouse. Since the penstock and machinery are designed for the initial power input and output, a completely new penstock and powerhouse need to be installed.

While the first two approaches work with the design options of a one-time installation of a binary unit with PAT or a ternary unit with Pelton, the last approach, which is the only one focusing on an actual scalable PHS plant, requires new design options. A smaller PHS plant is installed initially, and with increasing demand, the reservoir is expanded, and an additional penstock and powerhouse are installed. This powerhouse extension does not require a wide operating range, since the initial powerhouse can modulate the power output and input. the operating range is the main barrier for using a PAT, so this independence on operating range requirements when scaling up the system, leads to a preference for a binary configuration with a PAT for the powerhouse extension. The initial powerhouse configuration can still be a binary or a ternary unit.

All powerhouse configurations are summarized in Figure 3.20. For all configurations, a BESS accompanies the PHS plant, for small power fluctuations or to mitigate any power discrepancies which fall out of the PHS pumping or turbine power range.

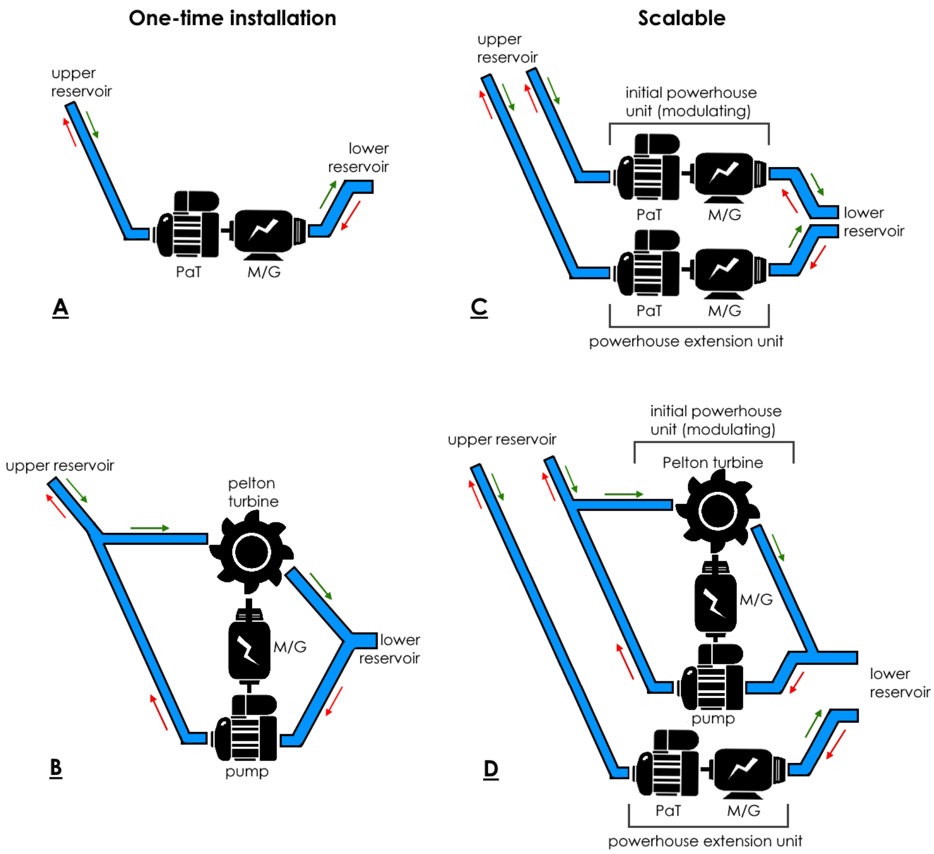


Figure 3.20: Feasible configurations for a PHS system, when considering the design criteria. All configurations are accompanied by a BESS. *A:* A one-time installation of a binary unit with a PAT. *B:* A one-time installation of a ternary unit with a Pelton turbine. *C:* A modular configuration with an initial binary unit with a PAT, and a powerhouse extension of a binary unit with a PAT. *D:* A modular configuration with an initial ternary unit with a Pelton turbine, and a powerhouse extension of a binary unit with a PAT.

Power output control As for the control of the turbine power output, a PAT is mostly controlled by adjusting the rotation speed by means of a VFD, while the flow rate is managed by a cone valve. For conventional turbines the control of the power output is regulated in a different manner. While the flow can be partly controlled in the penstock itself, by means of butterfly, spherical and cone valves, most of the power output control is performed by a hydro governor [164]. The governor controls the power output of a Pelton turbine by varying the nozzle discharge, by adjusting a needle shaped spear valve. For a Francis turbine, the power output is controlled by means of wicket gates or adjustable guide vanes.

3.5.4. Capital costs

The total capital costs of the powerhouse are dependent on which configuration is used. Moreover, even with the configuration established, the costs of the machinery depends on the site conditions as well as on the desired power output, requiring a specific quotation for a scenario. There are however certain cost functions to be found in literature, to generalize the expenses of hydraulic and electrical machinery, specifically for turbines under 2 MW [179]. The cost equations for the turbine also incorporate the capital cost of the electrical machine (motor-generator). For a Pelton turbine, the costs can be calculated as follows:

$$C_t = 17,693 P_t^{-0.3644725} H^{-0.281735} \quad (€/kW)$$

$$C_t = 17,693 P_t^{0.6355275} H^{-0.281735} \quad (€) \tag{3.28}$$

In the above equations, P_t is the rated power output in kW and H is the rated head in meter. For the centrifugal pump, the total capital cost is defined by an equation established by Caralis et al. [43]. Multiple pumps might be needed, therefor a factor N_p is included to indicate the number of pumps. The rated power of the pump is indicated as P_p.

$$C_p = N_p \cdot 1814 \left(\frac{P_p}{H^{0.3}} \right)^{0.82} \quad (€) \tag{3.29}$$

The costs of a Pelton turbine and a centrifugal pump are graphically represented in Figure 3.21.

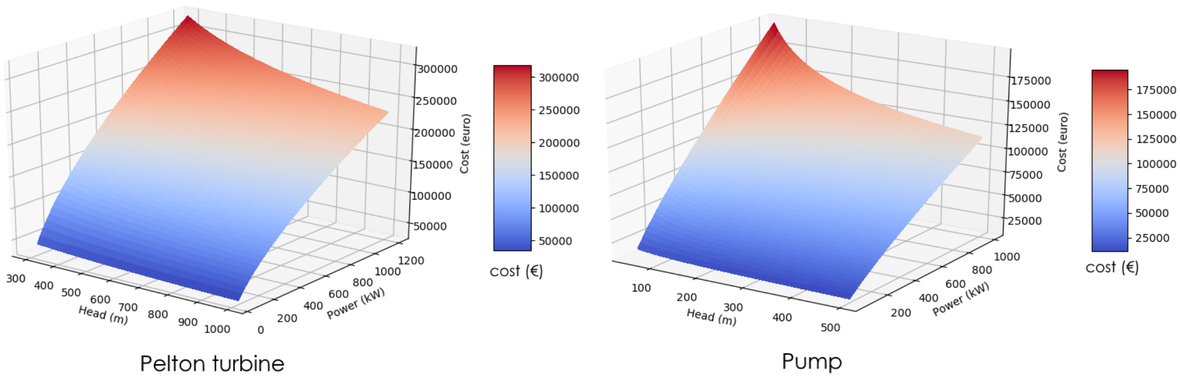


Figure 3.21: Graphical representation of the total capital costs of a Pelton turbine (left) and a centrifugal pump, in relation to the net head and desired power output/input. Costs become especially high with low head and large power output/input.

Additionally, the costs of the converter, which takes on the function of the VFD, are determined at approximately 620 €/kW [169] [168], leading to the following cost equation:

$$C_c = 620 \cdot P_c \tag{3.30}$$

The capital cost for the hydraulic machinery of a ternary unit is calculated by utilizing equation 3.28 in combination with equation 3.29. For a binary unit employing one or multiple PATs, only equation 3.29 needs to be used; since the induction motor of the pump can generally be used as the motor-generator, the electrical machinery is already included in the cost equation. For both the binary and a ternary unit, the cost of the converter can be added using equation 3.30.

These cost equations thus encompass all the hydraulic and electrical machinery, however, the total powerhouse cost also consists of other electrical equipment expenses, as well as civil works required to provide cover and protection to the machinery. Finally, the control system (hydro governor) is estimated to add 1.6 percent of the combined cost of the system, according to research of Caralis et al. [43].

4

Organizational design synthesis

In Chapter 3 a technical design has been established through a synthesis. During this synthesis it already became clear that the technical design by itself can not satisfy all design criteria. This is due to the fact that technological and societal change are interrelated, and just installing a PHS plant, even with a technical design adapted to the local conditions, is guaranteed to be a failure. The technical design focuses more on 'hard' issues, meaning technological, financial, physical and material. However, the so called 'soft' issues, such as community involvement, decision making procedures, the establishment of efficient social compacts, organizational development capacity building and empowerment, are just as important for an electrification project [35]. Crucial success factors for sustainable small-scale energy systems in poor rural areas are community ownership, capacity development, and stakeholder engagement [125]. This can only be reached through the addition of an organizational structure involving the local population, to properly embed the PHS plant into the community.

In this Chapter, a strategy for each phase of the project is discussed to satisfy the core criteria of obtaining community trust and acceptance, as well as reaching economic viability. With the basis of the initial design phase discussed in Chapter 3 and 4, the planning, implementation and operation phases are investigated. Each phase should work toward forming a sense of local ownership and creating a communal responsibility, as this is essential to the success of a rural electrification project [226] [30] [213]. Moreover, to establish a community-based project, participation in the decision-making processes is required. To properly implement this however, existing theory on community-based projects is to be explored; which challenges are encountered, and how can these challenges be navigated when installing a PHS plant in a sub-Saharan African community.

4.1. Theoretical approach to community-based projects

The importance of community involvement and participation in the project has been established, as this increases the trust and acceptance of the target community. To get a deeper understanding of the implementation of community participation, it is necessary to explore existing community-based development projects and the challenges they face. Community-based projects refers to projects actively including beneficiaries in the design and management. Participation is defined by the World Bank as 'a process through which stakeholders influence and share control over development initiatives, and the decisions and resources which affect them' [6]. With the community members as stakeholders, this implies their knowledge should be involved in the decision-making processes if community participation is to be reached. The expectation is that this participation in the decision-making processes not only leads to more trust and acceptance of the community, but also to several additional advantages. These include better designed and more cost-effective projects, better targeted benefits, more equitable distribution of the benefits, and less corruption [148]. However, community-based projects present several challenges; if these challenges are not tackled sufficiently, the project is likely to fail. These challenges and potential solutions are presented in this Section.

Poor implementation Institution building costs more time than direct control. It is for example much faster to distribute food than teaching people how to grow it themselves; however, in the long term a well-functioning local organization is worth the investment [81]. Care should thus be taken not to take the work out of the hands of the community to obtain faster results. Often however, those responsible for the implementation of a development project, have misaligned incentives, and may favor easily deliverable and measurable outcomes over the hard work of institution building [100] [160]. This means they could choose to discard relations and the power structure within the community, which could easily lead to an inequitable division of the project benefits. There are several reason why project facilitators might take this 'easy route': there might be a strict timeline, enforced by financial constraints and donors, or it could just be due to inexperience of the implementing organization employees.

Furthermore, many projects with seemingly high levels of participation, have in reality a superficial involvement of the entire community [160]. This is due to several factors. For one, participation is through public events, making them political. The result of these public meetings is thus often shaped by local relations of power, authority and gender. Secondly, the needs of the community are shaped towards what the project can deliver by the implementing organization, instead of the actual needs. Thirdly, initial planning with community participation allows certain beneficiaries to direct the program to their personal interests, instead of the communal interest. This is especially the case in heterogeneous communities with strong local elites (see 'Capture by local elite' below). And finally, participation is included initially to attract donors and legitimize the project, while it in reality had little support from the local population.

As a potential solution to poor implementation of community-based projects, institution building should become a core deliverable. If this is directly communicated as an essential part of the project to the donors, there is more leeway for longer timelines and less pressure to deliver timely. Furthermore, experienced and involved project facilitators are required. Only with a committed integration of local participation in the project the PHS plant can be embedded into the community. In the case of the three stage electrification plant of DC Opportunities, this community participation should be integrated from the start, and over time the local relations of power, authority and gender can be gradually understood. The gradual electrification by a single project facilitator, DC opportunities, should thus be used as an advantage, since a constrained timeline is often the cause of rushed and ineffective implementation of community-based development projects [148].

This also allows for a clear definition of what the 'community' actually is. While community is a term often labeled by the project facilitators or by administrative boundaries [53]. This however means that often ethnic and religious affiliation, and economic and social power structures are glossed over. However, gradual integration in the community, through involving the local population from the beginning, at the first stage of electrification, allows to gain insight on the community in an organic form. This results in a much better picture on what the actual cohesive community is, whose members share a feeling of unity because they internalize the ideology of the community, and will thus abide by its rules and work together. In this way, the social and cultural context within which beneficiaries live and organize themselves is not ignored.

Capture by local elite The PHS plant is installed in a region where resources are scarce due to poverty. This may result in a struggle to control the new resource, electricity. While the chance of success of an electrification project is increased with the approval of the leaders and influential members within a community [237], it is precisely these people who constitute the local elite of the community, with a superior political and economic status relative to the other members of the community. Due to their influence, this local elite is likely to take control of a community-based organization and the information channels between the low income community members and the utility [35]; this is known as elite capture (Araujo). Elite capture occurs when established local elites take a dominating role in the decision-making processes of the project, through affecting the project from the outside or taking key positions in the organization. The heterogeneity in a community in terms of social and economic status is context-specific. However, even in the most egalitarian societies, local elites will almost always dominate community involvement in planning, construction, and management of a public good (mansuri). A distinction should however be made between malevolent and benevolent elite capture, as indicated by research.

The elite capture can be considered malevolent in several scenarios. Firstly, the interests of the community, specifically those of the socially and economically disadvantaged segment of the community (the non-elite), can become subordinate to the interests of the local elite. When malevolent elite capture occurs, and the information channels between beneficiaries and project agencies are manipulated by local leaders to serve their own interests, the beneficiaries are no longer fairly represented. This has occurred in several World Bank projects, as observed by Paul [191], and can reinforce the existing social inequality even further.

Secondly, the local elite in leadership positions might not involve the non-elite in decision-making processes, but instead make these decisions on behalf of the community. Only when they want to sell a particular idea, public meetings are called [229].

Finally, genuine participation of the non-elite may require taking positions that are contrary to the interests of the dominating local elite, which can lead to psychological or physical pressure on the poor. In development projects in Africa participation has even been described as a form of forced labor, with the poor pressured into making far more substantial contributions than the rich [203].

However, often elite capture is misconstrued as malevolent, while in reality it presents advantages. In these instances, it is referred to as benevolent elite capture. This arises in several scenarios; for one, local elites might have genuine motivation to improve the community as a whole, and pursue the communal interests that have a generally positive impact [201]. It could also be the case that the interests of the local elite just happen to align with the interests of the non-elite [240]. Moreover, due to the strong hierarchical and tribal society present in rural SSA, the village bodies are often composed of the local elites. As Wade [241] argues, these village bodies can exercise more effective control due to their social standing; rules made by the powerful carries more legitimacy in the eyes of the majority of the villagers. Furthermore, since these local elites are likely to obtain the largest net benefits from successful implementation of the project, it is in their best interest to ensure the organization functions well. Finally, if the non-elite cheats the project, it can be checked by the sanctions of the village's power structure, making penalties from the project organizational board more effective. It might thus be necessary to structure the project organization around existing power structures in the community, implying a major role for the local elite.

If the project imposes negative net benefits on the non-elite of the community, it is likely the local elite will benefit at the expense of the majority of the community members. However, when costs and benefits of the project are the same for both the elite and the non-elite, capture of the local elite can easily be benevolent. For a PHS plant, this is true; malfunction due to a water deficit or poor maintenance affects both groups equally. Furthermore, energy theft by any member of the community, also the local elites, results in a loss of revenue which in turn reduces the treasury from which maintenance, operation and repair must be paid. This thus negatively impacts the whole community, and most of all the local elite who receive the most net benefits from the system. One decision which could benefit the local elite while negatively impacting the non-elite, is to bestow their own with more water for secondary water use. This can however by circumvented with checks and balances, both top-down and bottom-up. Top-down, a system of transparency can be implemented, by having the balance of the excess water division over a certain time-frame ratified through a public meeting. From the bottom-up, the non-elite could decide to discontinue voluntary maintenance on the PHS plant, resulting again in a more substantial negative net benefit for the local elite. Therefore, each project should be approached in a context-specific manner, instead of finding a wholesale best-practice application. The degree of impact and frequency of public meetings, depends on local conditions. Sometimes, the local elites pursue more their own interests and these public meetings are of more importance, while often they are motivated by the communal interest. Conclusively, the local power structure should be utilized, with some essential checks and balances in place.

Exclusion of women In sub-Saharan African societies, a gendered social structure is present, and it has been argued that the prevalence of gender inequality acts as a significant constraint to growth and development in sub-Saharan Africa [33]. The implementation of a PHS plant has perhaps the most significant effect on women in the rural community. For one, they are responsible for the household, meaning a nearby domestic water supply gives them a lot more free time [229]. Furthermore, electrification allows small farmers to set up small enterprises, which are often household-based, owned and managed by women [122]. However, the gender inequality present in the rural communities makes it unlikely women will have an active participatory role in the project.

As an answer, a quota for the inclusion of poor women in the organizational structure could be implemented. However, while this facilitates participation, it does not deliver it; after all, it does not guarantee these women are listened to [245]. Since the PHS plant aims to embed itself into the community, it is not advisable to immediately seek societal changes, and enforce these upon the community. To win the trust and acceptance of the community, existing social structures should be used. Inclusion of women in public meetings of the community should however be actively encouraged by the project facilitators.

4.2. Planning phase

As explained in Section 3.5.3, there are two ways of planning the implementation of the PHS plant in the mini-grid. The first way is with a one-time installation, where the demand reaches a certain level where it becomes worthwhile to install a PHS plant. The second way is to already install the PHS plant at a lower level of electrification, with less demand, and when the demand grows, the storage capacity and power of the PHS plant is scaled up by expanding the reservoir and installing an additional penstock and powerhouse unit. This scalable design is thus a more gradual implementation.

Both a one-time installation and a scalable system have their benefits. The consideration on how to approach growing energy demand requires a clear overview of the implication of each option. For a one-time installation, the benefits are the following:

- *Cheaper:* for a one-time installation, only a single powerhouse unit is installed, and thus less components are needed. Moreover, the power output is dependent on the flow rate through the penstocks. While the same power output can be reached with multiple penstocks of a smaller diameter, a single large diameter penstock is a more economical choice [133]. Further, due to the economy of scale penalty for PHS technology, a one-time installation of a larger PHS plant will be more economical.

- *Less maintenance:* due to the fact that there is only a single powerhouse unit, less maintenance is required, leading to less operational costs.

- *One-time installation:* the initial installation is the only large-scale construction required. With a scalable system, further down the line another large construction needs to be set up, which requires a second mobilisation, preparation of a construction site, etcetera.

- *Easier control:* When only a single turbine provides the deficit power and only a single pump absorbs excess power, control is much more straightforward than when two powerhouse units need to work in conjunction.

Likewise, a scalable design has its benefits:

- *Earlier implementation:* a one-time installation PHS plant requires a community well on its way to a higher level of electrification; if installed at a too low level of electrification, there is a good chance that power demand will increase in a short period, rendering the PHS plant insufficient. This is because electrification brings development [103] [63] [89], leading to a quicker rate of demand growth. When scalable, the PHS plant can already be installed when a lower level of electrification is present, since it can then later be expanded.

- *Easier initial installation:* due to the initial installation taking place at a lower level of electrification, the demand is lower, so smaller pipes are needed for the penstock and the size requirements of the reservoir are smaller. This decreases the threshold for installation.

- *Trust building:* successful implementation of a technology requires the acquisition of acceptance and trust of the target community, as explained in 2.3.1. Slow implementation help to build trust over time.

- *Trial period:* due to the earlier implementation of a scalable PHS plant, the initially installed PHS plant will be smaller in scale and thus the capital costs will be less. This allows for a 'trial period' for a smaller investment, to see at which rate the demand grows, how the community embraces the system, and whether the project is technically and financially viable.

- *Easier circumvention of vertical networks:* the vertical networks discussed in Section 2.3.4 are easier to circumvent with a gradual implementation of a project.
- *More resistant to failure:* for a scaled up PHS plant with two or more penstocks, the failure of one penstock or powerhouse unit does not mean the shutdown of the entire PHS plant. The plant can stay operational using the other penstock, albeit with a lower capacity.
- *Conforms better to demand:* instead of estimating the demand and demand growth, as with a one-time installation, a scalable system can conform to observed demand and demand changes.

Hence, a scalable design satisfies the core criterion of obtaining community trust and acceptance more than a one-time installation. It is however difficult to assess its economic viability compared to a one-time installation. In order to do so, the difference in costs is further explored in the case study in Chapter 5. The technical design options and the manners of implementation are summarized in Figure 4.1 below.

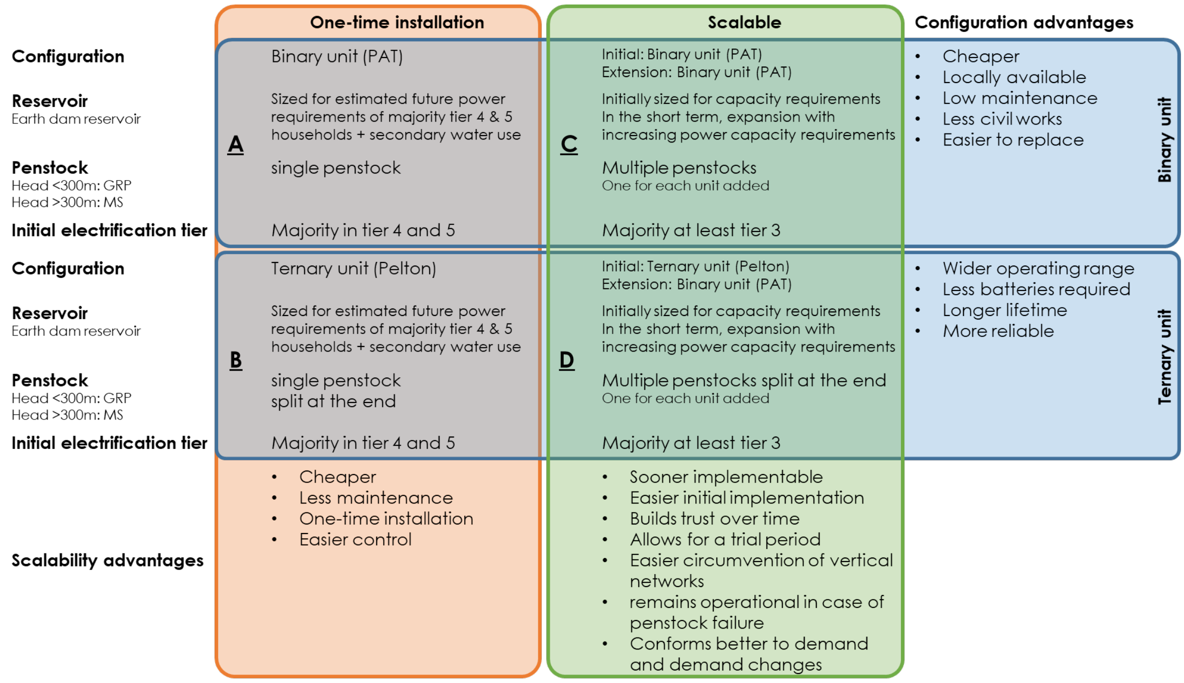


Figure 4.1: Summary of design options and their implementation, their characteristic and advantages.

4.2.1. Community involvement

Community involvement in the planning phase already ensures an initial feeling of ownership. The involvement of the community in the planning phase consists of their input on energy and water needs, expectation management, and installation site determination.

An overview of the energy needs of each household and business (existing or planned) is needed. This requires the identification of the decision-maker of every household, business owners and entrepreneurs. Their indication of energy needs should form the basis for the demand estimation; the organization or company installing the PHS plant (in this case, DC Opportunities) should be aware of their status as an outsider and not assume they know better than the beneficiary community itself [35]. The seasonal economy and locally distinct social practices can lead to unexpected energy demand [5]. Moreover, since the reservoir is multi-purpose, the water demand should be assessed, likewise with input from the intended users.

Additionally, the abilities and limitations of the system needs to be clearly communicated to the intended users. Their expectations might exceed the ability of the system; there is often not a realistic sense of the differences in energy usage of different appliances. With the electrification process evolving step by step, these expectations should have been tempered to realistic levels before the mini-grid is implemented. However, the appearance of a mini-grid might bring renewed unrealistic expectations. Even before installation the expectations should be aligned with the PHS plant abilities [68]. An approach to managing user expectations, with documented success [48], is the construction of a mini-model of the project. This can demonstrate the functioning of the system, the limitation and requirements, in an easily surveyable manner. This also assists in demonstrating the need for water management and proper maintenance.

Finally, preceding the installation the entire community should be involved in the decision making process of the installation site, as not to negatively impact certain community members by laying the penstock or cables on their land or diverting water streams which are used further downstream. The reservoirs should be positioned at an accessible location to satisfy secondary water use needs. In existing electrification projects, the participation of rural communities in decision-making has added value to the planning process and given communities a sense of ownership [187]. All community involvement in the planning phase can take place through public meetings and rural committees. It should however be considered that local knowledge might not be adequate for detailed and technical planning. In the case of a PHS plant for example, it could be that the community prefers the reservoirs at a certain site, while technically and economically a different site is much more beneficial. While it should be avoided, some directing of project facilitators might be necessary.

4.3. Implementation

After the planning stage, the PHS plant need to be implemented. The actual installation is one step of the implementation. An organizational structure needs to be implemented to ensure the PHS plant can function without perpetual outside involvement, but instead due to the community itself. This self-sustainability is further ensured through the implementation of an operational structure.

4.3.1. Installation

Participation of the local population during all project stages, including the construction and installation of the PHS plant, ensures the community take ownership [251]. The provisional technical design is focused to allow for this participation in the installation, by reducing the technical skills required to a minimum. The design, tailored to the site and the energy needs, is designed by professional civil and electrical engineers. Likewise, these engineers supervise during construction and installation.

The labor used in earth dam reservoir construction requires, apart from an overseeing engineer, little technical skill. The physical labour required is part of daily life for the members of an agricultural society. Besides, the construction of these earth dam reservoirs is common in the SSA region [218]. It is thus possible the local population has had experience building one of the reservoirs. A previously constructed earth dam reservoir could even be used, renovated and expanded if it is situated conveniently. Additionally, draught animals can be rented from local livestock farmers.

While the the pipes for the penstock need to be transported from outside the community, the local population can still be employing for the laying of the penstock. Clearing of the penstock path, digging a trench and carrying pipe segments from the transport truck to their designated spot are all considered low-skilled labour. For the reservoir construction and the penstock installation, local community members can thus be employed, giving the advantage of lowered installation costs and community participation. This community participation provides an immediate opportunity for income for several community members, as well as an immediate sense of ownership.

The powerhouse installation however, requires professional technicians. While this will be people from outside of the area, the technicians can still educate the intended operating technicians (see 4.3.3) while installing the equipment.

4.3.2. Organizational structure

The organizational structure of the PHS plant is in charge of the energy and water management. It can not be separated from the organizational structure involved in the management of the entire mini-grid system; the PHS plant is inherently tied to the generation and distribution of the mini-grid, and both are thus part of the same entity. Organization and management of the complete energy system (including the distribution, the generation and the energy storage) should be embedded in the community, by creating a community-based utility. A successful example of such a local utility, LUMEMA, is found at a small hydropower plant in the Ludewa District in Tanzania [5]. They have taken on the role of management organization, overseeing the distribution and setting fees. This last role, the decision on fees, is present because the project was set up by a non-governmental organization, which had no profit motive and was only interested in recovering operational costs. However, in the case of a for-profit organization, the community-based utility must have representatives of the organization on the board. The rest of the community-based utility board are elected community members, with elections being held every few years to avoid corruption. Furthermore, the board contains advisory members from the organization implementing the project and members from the district government to encourage powerful institutions to invest in the continuation of the utility. Additional roles for the utility would be to manage the distribution of water and the personnel responsible for operation and maintenance of the PHS plant, and implementing a maintenance schedule. The project facilitator should work towards capacity building of the community through this community-based utility.

As discussed, local elite capture is almost guaranteed, but the local power structure can be used as an advantage. Community-based organization should be structured to actively include the vulnerable and poor of a community, while taking care to not exclude influential members and leaders of the community, as their favor or opposition to the project can mean success or failure. The board of the local utility consists of elected local community members, which are likely to be part of the local elite. However, since the project is local and focused on a specific community, it is possible to have public meetings with all customers, giving them an arena to participate. Since a large part of the customers would be present at these assemblies, complaints and worries can not be ignored. Furthermore, checks and balances curtail corruption, such as the ratification of the water management plans through public meetings. The project facilitators should strive for the inclusion of women during these meetings, as they are a major stakeholder and gender equality should be encouraged, while not enforced, in community-based decision-making processes.

4.3.3. Operational structure

To operate and maintain the PHS system, certain expertise is required. In many countries in Sub-Saharan Africa however, there is no education available for operation and maintenance on a technicians' level, due to a decline in hydropower plant construction in recent years. Operators of hydropower stations instead recruit electro-mechanical technicians from technical secondary schools or from polytechnical schools. These technicians are subsequently trained on the job. Research by the Africa-EU Renewable Energy Cooperation Programme (RECP) indicates that at least 3 technicians and 1 part-time engineer are required for hydropower plants up to 1 MW [101].

The operating personnel of the PHS plant thus requires specific on the job training, and the technicians thus might as well be local community members. These technicians are trained throughout the planning and implementation phase, with temporary guidance at the first stage of the operation phase. While employing local community members as technicians improves the local ownership, the rest of the community might question their technical skills, seeing the technicians as 'uneducated' [5]. This is however a trade-off that can not be avoided.

4.3.4. Theft/vandalism prevention

To prevent theft and vandalism of PHS plant components, security is required [110]. Four types of security can be identified:

- *Human security:* individuals or groups are accountable for the guarding and protection of the equipment, for example a security agency. This is an undesirable approach to security, as it adds extra costs and creates an atmosphere of distrust between the security personnel and the community, which in turn leads to a lessened acceptance and trust of the community towards the technology.

- *Societal security:* when a technology or project is implemented in a community, and embeds itself, any wrongful action undertaken towards the project becomes an offence to the community itself. Communities play an important role in sub-Saharan African rural societies [55], and the group takes precedence over the individual. While a feeling of responsibility towards ones community might already be enough deterrence, any transgressions harming the group may lead to ostracism which is an efficient prevention method in tight-knit communities.

- *Technological security:* equipment can be protected with the use of technology, such as sensors, camera's, etc. Similar to human security, this creates an unwanted feeling of distrust and adds extra expenses.
- *Physical security:* components can also be secured by locking valuable equipment away in buildings, or protecting material with physical barriers. This would also add expenses but a lessened feeling of distrust.

For the PHS plant, a combination of societal and physical security should be used. Human and technological security add too much expenses and damages the much required trust between utility and customer. Mainly societal security will play a role, by creating a sense of ownership and as such make the community members stakeholders. Physical security is employed for the powerhouse, to lock the machinery and electrical equipment in a enclosure, not just for the sake of security but likewise to protect against environmental damage. If there is a concern of sabotage by a hostile neighboring community, the penstock can be buried to protect it from vandalism. With these measures, the PHS plant and its components should be sufficiently protected from the theft and vandalism as presented in the design challenges (2.3.3).

4.4. Operation

The operation of the electro-mechanical equipment is automated through a control system. The operation of the plant itself thus requires little from the operational personnel, apart from the occasional stop or startup, and check-ups. As mentioned, local people can be trained to be permanent technicians, and as PV panels require little maintenance, the same technicians can be responsible for the entire mini-grid. Part of their training is to gain knowledge on how to assess the water levels in the reservoirs, to give advice on the management and distribution of energy and water.

4.4.1. Energy and water management

Due to the intermittency of the generation in the mini-grid, the PHS plant balances the generation and demand. With a solar mini-grid, this means after sunset or on cloudy days the PHS plant becomes solely responsible for supplying the demand. Limitations to the capacity and especially peak power output of the PHS plant lead to the necessity for demand response. Rather than forcing customers to limit their demand or risking a blackout, collaboration with the customers is preferential. Locally embedding the mini-grid facilitates people voluntarily agreeing to manage the load. This once again proves it is essential to involve the community, making them stakeholders through participation.

It has been established in the design criteria that secondary water use is not just a desirable, but even an obligatory feature of the PHS plant.

Domestic and livestock water use, irrigation and potentially fisheries are forms of secondary water use. The sub-Saharan African region copes with seasonal weather patterns, which leads to periods of rainfall alternating with periods of drought. While during the wet season rainfall is plenty, and secondary water use is thus only needed in small quantities, the dry season poses a challenge. While secondary water use will increase in quantity, so will the evaporation of water, decreasing the water levels of the reservoirs at an even faster pace. Moreover, research has shown that high water availability can lead to less efficient irrigation schemes [70]. The amount of water in a reservoir employed for the multipurpose of secondary water use plus pumped hydro storage will significantly exceed the water demand for irrigation, since a large proportion of the stored water is meant for the purpose of energy storage. This can be wrongly perceived as a high availability of water, and thus lead to the use of negligent irrigation methods. To avoid all water being used for irrigation, it is important to establish efficient irrigation methods and a schedule for the distribution of the water. The water distribution strategy is ultimately decided by the embedded community-based utility, as advised by the trained technicians who have a better understanding of the water needs for energy storage. The community is involved in the utility through representatives and public meetings, and as stakeholders the community members will feel responsibility towards following the water distribution schedule.

4.4.2. Maintenance and repair

The maintenance and repair requirements of the PHS plant are divided in the three elements of the water storage system, water conveyance system and the powerhouse.

Water storage system A statistical analysis by Berhane et al. [27] on earth reservoir dams showed that 61% have siltation problems, 53% suffer from leakage, 22% from insufficient inflow, 25% have structural damages and 21% have spillway erosion issues. Moreover, they observed a lack of proper water management and maintenance in most of the reservoirs with irrigation practices. An earthen dam reservoir requires continuous maintenance: removal of vegetation, animal and insect burrows, and restoring eroded parts of the embankment. To assist in the maintenance and inspection, all parts of the dam should be kept clean with a low grass cover, which also helps to protect against erosion. This is unskilled work which needs to be carried out at regular intervals. As the necessity for good maintenance is already communicated to the community in the planning and implementation phases, a sense of responsibility towards the rest of the community creates an incentive for each individual member to take on maintenance tasks voluntarily [235]. Since the secondary water use is distributed as a gratuitous, public good, some community members are will benefit more than others; for example farmers which larger tracts of land, and in closer proximity to the reservoir, and livestock farmers. As compensation, these community members reaping the most benefits should have a larger responsibility for the maintenance of the reservoirs, and since they would be most affected by reservoir failure, their inclination to take on this responsibility will be higher. A maintenance scheme should be implemented to schedule the maintenance tasks by community members, who should perform these tasks on a voluntarily basis. This schedule is decided by the utility board, whose authority, as granted by the community, will help to enforce the maintenance schedule. However, proper education and management on the maintenance is required if the responsibility falls on the community [27]. Training the employed technicians on proper reservoir management is thus a requirement, allowing them to oversee any maintenance works on the reservoirs.

While voluntary community participation handles continual maintenance works of the reservoirs, this does not include the major repairs, which need to be done by or under the supervision of a professional. An advantage is that during major reservoir repairs, a large portion of the water can be transported through the penstock to the second reservoir, after which the PHS operation will be temporarily discontinued until the repairs are done. These major repairs require expertise from outside the community, which is provided by the implementing organization.

4.4.3. Water conveyance system

Inspection of the entire water conveyance system should occur with regular intervals. A thorough inspection consists of the following procedures [154]:

- an initial visual inspection of all components and an assessment of the penstock thickness (whether it has not corroded too much).
- a simulation of the emergency control, where the closing of the valves is observed.
- performing load rejection tests.
- readjusting the governor.
- evaluation of the data collected during the inspection.

Clearly, this inspection requires professional technicians. However, this thorough inspection is only required every 1 to 5 years. A more frequent inspection can occur every month to a year, where a simple visual observation of exposed penstocks suffices. This can be performed by the trained operating personnel.

4.4.4. Powerhouse

The power control depends on the PHS system. For many micro-hydropower installations used for rural electrification, automatic control systems and protection equipment are excluded due to economic constraints [4]. However, due to the need of an ESS in an isolated mini-grid to quickly respond to load fluctuations, the PHS system is assumed to have automatic control. While this increases costs, it is deemed a necessity for proper balancing of generation and demand. In this case, the operators do not always have to control equipment except in cases of starting, stopping and emergency. Moreover, if an automated system is installed, operators do not have to be present at the power plant continually.

The local technicians should conduct daily inspections to check if there are any issues at waterway facilities, electric equipment, transmission and distribution lines, record the results of these inspections and take measures if necessary. if the issue can not be solved locally (e.g. replacement is required) or is out of the scope of knowledge of the local operating personnel, the utility board should be informed who will in turn consult the implementing organization, which can send professionals.

4.5. Provisional operational design

The organizational structure as proposed is summarized in Figure 4.2. The feasibility of implementing this structure is dependent on the site and the local social and cultural conditions. It serves however as a basis for a strategy for the planning, implementation and operation phases for a small-scale pumped hydro storage plant in a remote and rural mini-grid.

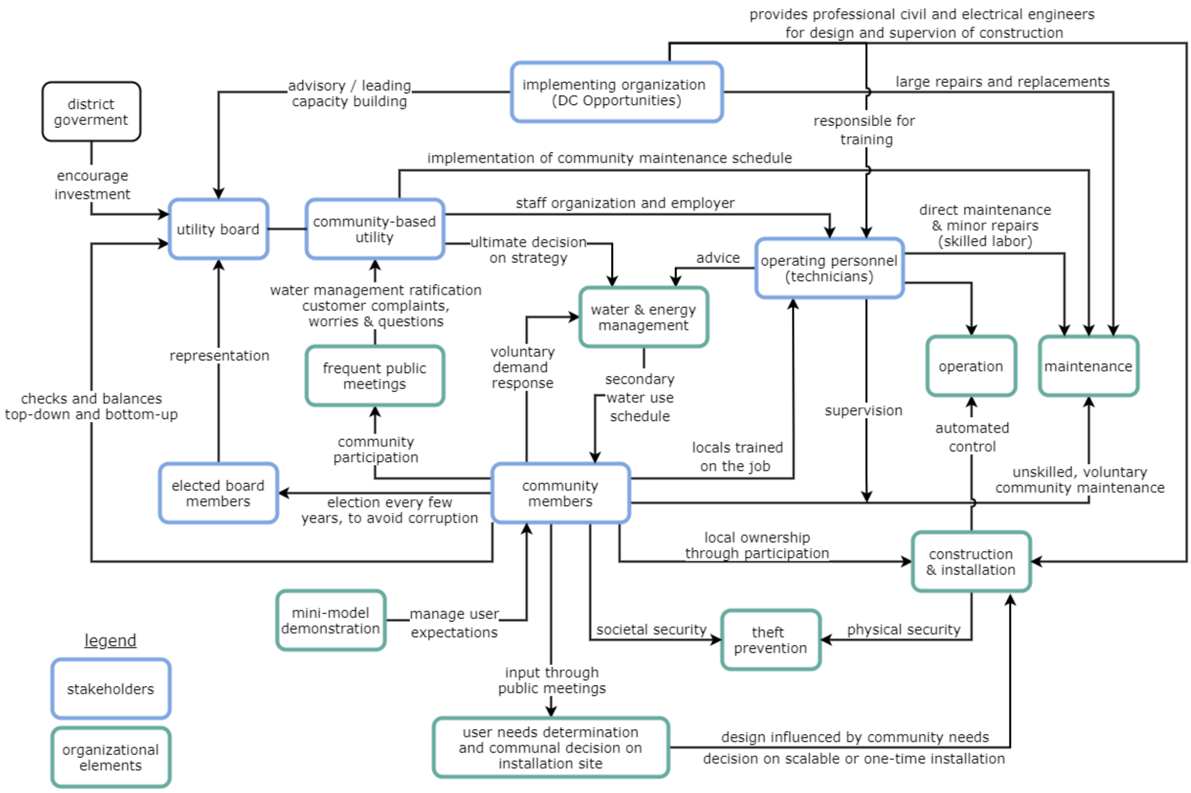


Figure 4.2: An overview of the organizational structure as discussed in Chapter 4.

5

Case study: Adi Araha, Ethiopia

A complication with drawing a general conclusion on the feasibility arises with the Pumped Hydro Storage system dependence on site-specific parameters, such as topology, energy needs, distance from major cities, local prices, local socio-cultural factors, etc. In an effort to draw a conclusion on the feasibility of the PHS plant, a case study is used, the village of Adi Araha in Ethiopia. For this case study, the provisional technical design discussed in Section 3.5 is simulated through a developed model. This results in the sizing of the components of the Hybrid Energy Storage System (HESS), which can then be used to determine the financial aspects such as capital cost and Levelized Cost of Storage (LCOS). Since multiple provisional designs are presented, all four alternatives (binary and ternary unit, one-time installation or scalable) will be considered to make an economical comparison. Subsequently, the suitability of the provisional operational design, and the possibility of successfully implementing the organizational structure discussed in Chapter 4 will be discussed based on local factors. Finally, an attempt is made to give a conclusion on the general feasibility of the PHS plant.

National background Since the case study is situated in Ethiopia, a background on the country's situation is given. Ethiopia is, with a GDP per capita of 772 € [249], the 15th poorest country in the world. There is however an annual growth of 11 percent since 2004, and a reduction of extreme poverty from 55 percent in 2000 to 34 percent in 2011. Nonetheless, there remains a high vulnerability to return to poverty, especially for the rural population, whose income depends mostly on rainfed agriculture.

Ethiopia is bestowed with an abundance of renewable energy resources, with potential for solar, wind, geothermal power, and especially hydropower. Currently, the hydropower capacity in operation is about 4,330 MW, with more than 6,600 MW under construction [238]. Dubbed the Water Tower of Africa, the massive hydropower potential is illustrated by the topological and rainfall maps of the country, as presented in Figure 5.1. With many elevation differences present and sufficient rainfall, many areas in Ethiopia have a lot of potential for hydropower or PHS.

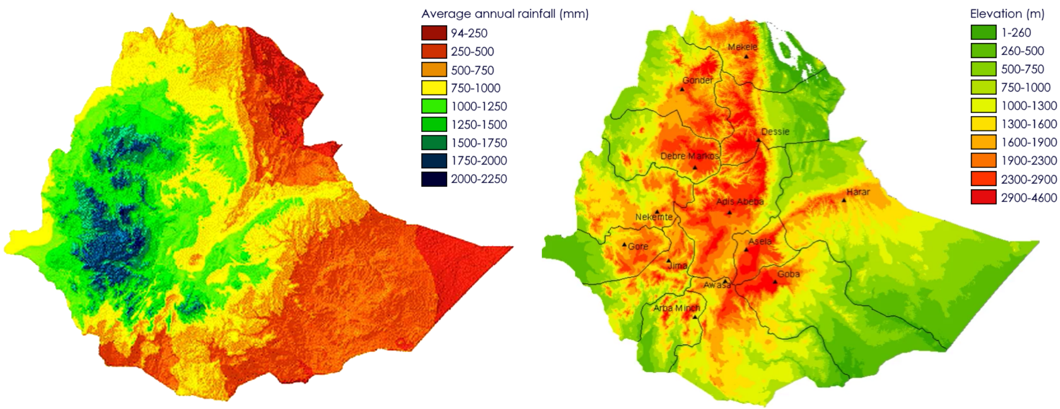


Figure 5.1: *Left:* the rainfall map of Ethiopia, in average annual precipitation in millimeter. *Right:* the elevation in Ethiopia in meters.

As for the situation regarding electricity access; about 45 percent of the population is electrified [247], and this percentage is about 30 percent for the rural population [248]. Of the rural population with electricity access, 11 percent is supplied with decentralised solutions. With the ambitious National Electrification Program, the Ethiopian government aims to reach a 100 percent electrification by 2025, with 35 percent off-grid and 65 percent grid connections [36]. A substantial expansion of the grid network in recent years, already led to the coverage by the electricity infrastructure of nearly 60 percent of towns and villages. However, the electricity sector does not provide effective service, and actual connections of household do not keep up with the expansion of infrastructure because of a lack of generation and financial resources. Taking into account an annual growth of national electricity demand of 11 percent, decentralised generation and mini-grids could prove to be very valuable.

The combination of low electricity access, reliance on off-grid solutions such as mini-grids to reach complete electrification, and high potential of hydropower makes Ethiopia a suitable location for mini-grids with Pumped Hydro Storage.

Local background In the province of Tigray in Ethiopia lies the village Adi Araha. From a field visit organised by DC Opportunities in April 2019, it was concluded access to electricity is very limited in the village. While a large portion of the inhabitants relies on solar energy to light their homes, only a few have multi-purpose solar technology available to them, which can in addition to lighting also be used for charging a phone or powering a radio. A majority of the population travel however 6 kilometer to the nearest city of Adigudem, in the west. Most of the energy use in Adi Araha comes from biomass, such as wood and cattle dung for cooking purposes.

A pilot project for the first step of electrification is planned by DC opportunities in 2020. An increase in demand will then eventually lead to the need to form an isolated mini-grid, where the terrain conditions allow PHS to be a suitable form of storage. The feasibility of using this form of storage will be assessed for different energy needs of the village, according to the percentage of each tier as presented in Figure 2.1. While, due to the relatively close proximity to the grid infrastructure, a grid connection to Adi Araha might prove more effective than establishing a mini-grid, it can be regarded as an effective case study since information is already known as a result of the field visit. Furthermore, the village is a realistic representation of an average rural community in Ethiopia. Conclusions of this case-study can thus also be extended to communities which are further away from the main grid.

5.1. Site analysis

The village of Adi Araha is situated in close proximity of the town of Adi Gudem, one of the larger towns in the Hintalo Wajirat Woreda; a Woreda is a district in Ethiopia. Adi Gudem has a population of 8,024 living in 2,061 housing units, of which 84% were electrified according to the 2007 census; while this was the most recent available information, the electrification rate is assumed to have gone up [16]. The most nearby city is Mek'ele, the regional capital of Tigray, with a popuplation of 315,000, at a distance of 45 kilometers. While the road from Mek'ele to Adigudem is asphalt, the 6 kilometer road from Adigudem to Adi Araha is unpaved. An overview of the village is given in Figure 5.2.

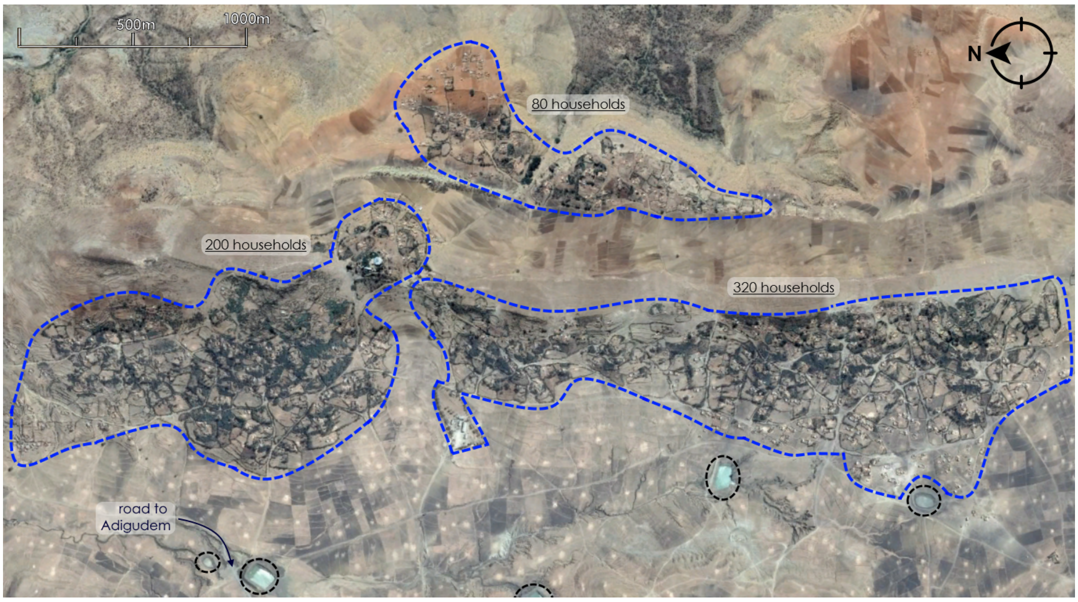


Figure 5.2: An overview of the village Adi Araha, Tigray, Ethiopia. Outlined in blue are the the households, and existing earth dam reservoirs are circled in black. Obtained from Google Earth.

A total of 600 households in the community have been counted, most of which rely on agriculture as a means of income. With a rural Ethiopian households consisting of, on average, 5 people [227], the village has a population of approximately 3,000.

It can also be observed from Figure 5.2 that earth dam reservoirs are a common occurrence, as a means of water retention. Table 5.1 clearly shows the existence of seasonal rainfall in the region, during July and August, making reservoir essential to a community relying on rain-fed agriculture. These reservoirs are thus commonly constructed to supply drinking water and small-scale irrigation [137].

Table 5.1: Weather data for Mek'ele region, as obtained from [242].

	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average temperature (°C)	21	19.5	20.5	21.5	22.5	23.5	23.5	20.5	20	21.5	20.5	19.5	18.5
Average precipitation (mm)	705 (total)	35	10	25	45	35	30	200	215	35	10	25	40

The proposed installation site is indicated on Figure 5.4. The reservoirs are built as earth dam reservoirs, which are a common occurrence in the area. The lower reservoir is installed at the bottom of the hill, where natural streams collect in order to fill it up in the rain season (July and August). The lower reservoir uses the natural slope of the hill as an embankment dam on the western side. The upper reservoir is built close to the village, and more importantly, within reach of arable farmland. It can thus also function as a water reservoir for irrigation, or for domestic water usage. It is built against a small hill, on the western side, which can again be used as an embankment dam on one side. A height profile, as shown in Figure 5.3, indicates the usable gross head, and the length requirement for the penstock.

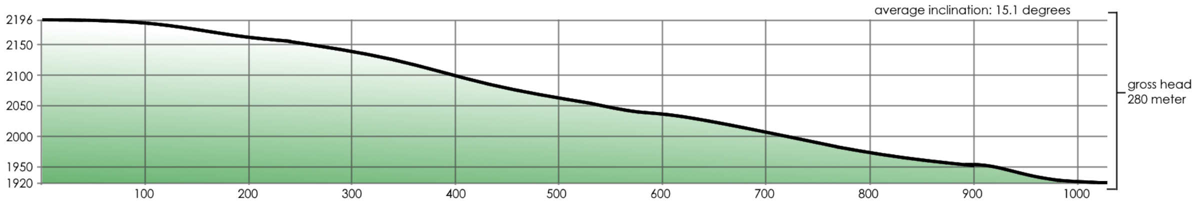


Figure 5.3: Height profile of the proposed installation site.

With an average inclination of 15.1 degrees, and a gross head of approximately 280 meter, the penstock length becomes 1,075 meter.

A disadvantage is the positioning of the village on top of the hill. Because of this, much longer cables are required from the powerhouse to the mini-grid. The powerhouse is installed at the bottom of the hill, which is accessible by road since a small quarry is located nearby, as can be seen in the proposed installation of the PHS plant in Figure 5.4.

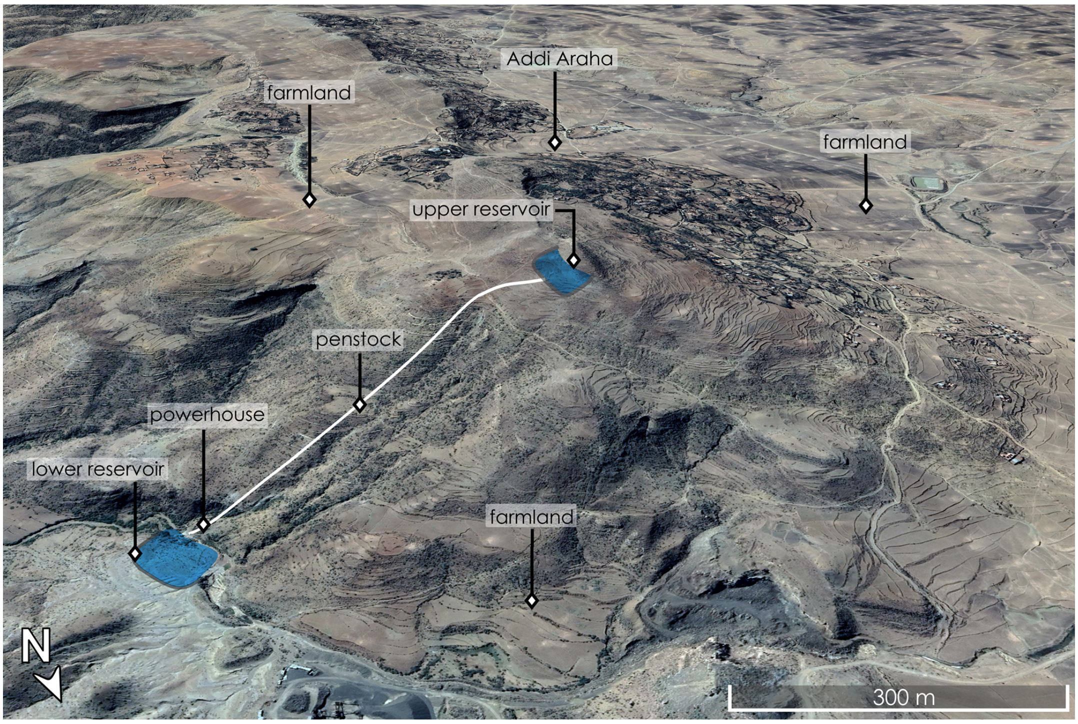


Figure 5.4: An overview of the suggested installation site for the PHS system. Obtained from Google Earth.

5.2. Boundary conditions

To properly assess the case study, boundary conditions are required. Whether the case study satisfies the technical design criteria is determined by the output of the model discussed in Section 5.3. However, the economic and socio-cultural boundary conditions are determined by context- and site-specific factors. It should thus first be assessed whether the design criteria as discussed in the program of requirements (2.4) are met for the case study.

Operating range To consider the system functionality properly, the system's functioning for different power requirements must be assessed. The reason for this is that the feasibility of PHS is likely to change depending on where in the power output and capacity range established in Section 2.1.1 we find ourselves; after all, conventional PHS has an economy of scale penalty. Therefore, two scenario's for the power requirements of a mini-grid installed in Adi Araha are established:

- Scenario 1: while all 600 households in the village are electrified, the power requirements are rather low. 10% of households are only using lighting and charging phones (tier 1), 20% have scaled up to include radio's, fans and television (tier 2), 40% of households also own a refrigerator. Moreover, 25% uses some of the more advanced appliances like laptops, kettles, rice cookers and even the occasional washing machine (tier 4). This is where demand increases to unattainable levels for Solar Homes Systems (SHS) and a mini-grid becomes essential. Finally, 5% falls within tier 5, where the energy demand of equipment such as power tools and water pumps is considered.

- Scenario 2: apart from all 600 households in the village, an additional 100 surrounding household are connected to the mini-grid. No households are stuck at tier 1, only 10% of households find themselves in tier 2, 30% in tier 3, 50% in tier 4 and 10% can be seen as small enterprises in tier 5.

Scenario 1 accounts for a situation where the mini-grid is established at an earlier stage in the electrification process, which could, with the improvement in economical development which accompanies electrification [103] [63] [89], be reached within 5 years after the initial electrification stage. Scenario 2 however, accounts for a longer term situation, where proper electrification has occurred. The scenario's thus present a range of power requirements to assess the feasibility, for the same case study. To assess a scalable system, it is assumed that the PHS plant is initially implemented for scenario 1, and then scaled up to scenario 2.

Quality of supply and power improvement The Energy Management Strategy (EMS) employed in in the model presented in Section 5.3 uses a Battery Energy Storage System for short-term transients and the Pumped Hydro Storage operation for long-term transients. Due to the short-term transients of solar generation, and the limited capacity of the BESS, excess energy is unavoidable, but this should have no impact on the reliability and quality of power in the mini-grid. Deficit power should however be constrained in the model.

Component availability As for the availability of components, manufacturers of pipes (General Industries LTD), turbines (Voith) and pumps and PATs (KSB) are present Nairobi, in the neighbouring country of Kenya. The additional transportation costs, including tariffs, are to be added in the financial assessment.

While Adi Araha is reachable by truck, this might not be the case for more remotely located villages. The weight of only the pipe segments for the penstock is already between 7,400 and 9,800 kilogram, which would be difficult to transport without truck accessibility.

Compatibility with connection to the main grid A geospatial analysis by the organization Power Africa [2] identified communities located at least 10 kilometers from the main grid as attractive sites for mini-grids. Adi Araha is only 6 kilometer removed from the main grid. Ethiopia has a national goal of reaching full electrification by 2025 [36]. While the Ethiopian national utility, the state-owned Ethiopian Electric Power, thus aims to extend the national grid to Adi Araha, this can easily take several more years. However, in case the grid extension program moves faster than expected, it is reasonable to expect and account for grid connection in the next few years. In this case, there is a proposal for a feed-in tariff scheme [8], throught the The Directive for Tariff Methodology Guidelines, which could allow the PHS to remain operational for energy arbitrage.

Alternatively, the nearby university, the Mekelle Institute of Technology, can implement itself into the project; this university already cooperates with the electrification project of DC Opportunities. The university can then, in collaboration with partner universities, be the responsible party for the implementation and management of a DC mini-grid with Pumped Hydro Storage. In this case, it can be seen as a practical research project, and remain financed and operational, with the goal of researching the viability of DC mini-grid, not only in Ethiopia but across the globe.

Increase mini-grid appeal The pumped-storage power plant can increase the appeal in the eye of donors in two ways: through addition of a multi-purpose water reservoir, and a reliability improvement of the mini-grid.

Firstly, the importance of a multi-purpose reservoir is demonstrated by the importance of rain-fed agriculture, comprises about 40 percent of total GDP in Ethiopia and 78 percent of the population is employed in agricultural activities [2]. This is no different in the Hintalo Wajirat Woreda (district), in which Adi Araha is situated. Crop cultivation and livestock provide the majority of the population with an income, but seasonal and unreliable rains lead to dry climatic conditions; the region is particularly prone to droughts and suffers from chronic food shortages [57]. Therefore, irrigation development in Tigray region is supported by organizations such as the Sustainable Agriculture and Environmental Rehabilitation in Tigray (SAERT), the Bureau of Water Resources Development and the Bureau of Agriculture and Rural Development [17]. In Figure 5.5, existing irrigation schemes in the Tigray region are shown, and it can be observed that the Hintalo Wajirat district, south of Mekelle, has many of these schemes installed. This shows that either a multi-purpose reservoir would receive support or that an existing reservoir might be found where the PHS plant might be installed as an addition to the irrigation scheme.

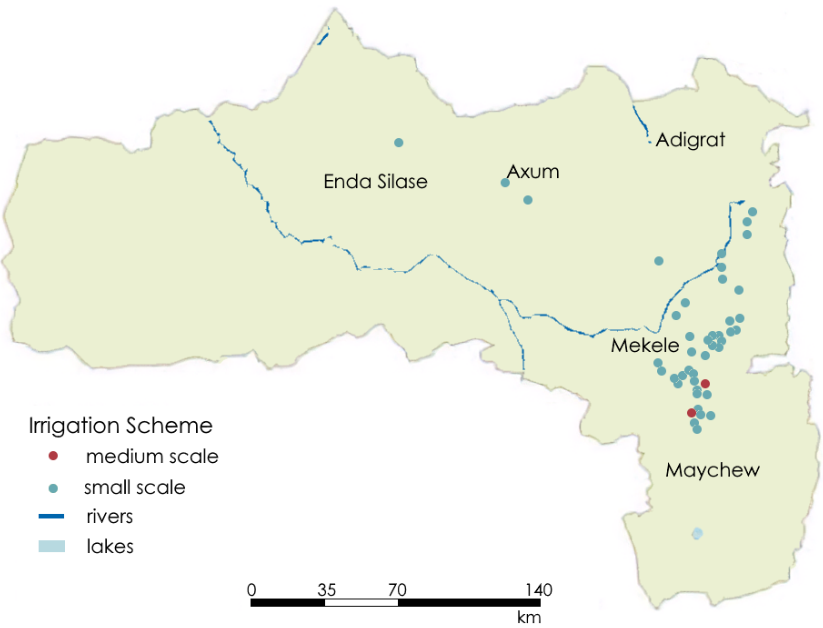


Figure 5.5: An overview of the irrigation schemes present in the Tigray region [17].

Secondly, the grid electricity in Ethiopia can also be unreliable. A majority of grid-connected customers experience between 4 and 14 power outages every week. A mini-grid with reliable power supply, even when no energy is generated by the PV panels, is thus an attractive alternative even to grid connection.

The Ethiopian Electric Utility (EEU) is responsible for the establishment of off-grid solutions for energy access. The EEU organises tenders for the establishment of mini-grids [113], and a close communication and collaboration should be maintained with this institution to ensure a successful electrification project. Funding could be obtained from this institution.

Low capital and operational cost Regarding both the capital and operational costs, there are several challenges. First of all, poverty in the district and Adi Araha specifically is extreme, and more than 45 percent of the district population lives below the poverty line [57]. This is a first hurdle to achieving a cost-recovering project, and it is further worsened by the lack of financial services and access to banking most rural Ethiopians face [2].

Secondly, as determined, several main components required for building the PHS plant, such as the pipes for the penstock and the electro-mechanical equipment, will have to be obtained from the neighboring country Kenya. Ethiopia has no clear exemptions for taxes on these components, and is performs very poorly when it comes to trading over borders (see Table 5.2). This will add significant extra costs in the form of transportation, tariffs and other associated costs. Finally, the electricity tariff is very low, even compared to other countries in the region [2]. While the tariff is rising, a mini-grid will find it difficult if not impossible to compete with these below-cost tariffs.

However, there are some positive prospects. For one, it has been observed that with sufficient capacity building, the community can participate in many tasks involving the implementation, operation and maintenance of earth dam reservoirs, which reduces costs significantly [252]. Moreover, the electrification process in sequential stages allows the development of the community to grow with the level of electrification. And even if the incomes of the local population is not reliable enough to sustain a mini-grid when the time arrives to build one, addition of a multi-purpose reservoir allows the agricultural community to develop faster: it has been found that the average income of non-irrigating households is around 50 percent less than that of irrigating households [85]. The addition of a PHS plant can thus further grow the local development, which helps to work towards a cost-recovering mini-grid. Finally, there are several support programs in Ethiopia to assist in establishing off-grid electrification. These are mostly funded by the international donor community. Major ones are Lighting Africa by the International Finance Corporation (IFC), and the Power Africa initiative established by the US government.

Community involvement It is important to determine whether it is possible to employ the organizational structure as discussed in Section 4.3.2. The social structure should be observed. In the district Hintalo Wajirat together with state authority, customary traditional leadership coexists, which consists of both male and female elders. These traditional authorities resolve both domestic and communal issues. The local elite can thus be seen as an integral part of the community.

Moreover, the organizational structure used in existing irrigation reservoirs can be assessed.The operation and maintenance rules of an earth dam reservoir in the Tigray region are based on local by-laws (known as ”serit laws”). These ”serit laws” are developed by the users in consultation with the Wereda Bureau of Agriculture and Natural Resources [99]. An irrigation leader (”Abo Mai”) is elected, who is in charge of water distribution.

This is the standard organizational structure employed for irrigation reservoirs, and fits in perfectly with the proposed organizational structure. The ”Abo Mai” is in this case not a single leader, but the board of elected community members. The ”serit laws” are similar to the decisions on energy and water management made by the community-based utility board. The strong hierarchical structure present in the region is thus taken advantage of.

Training of locals The nearby university of Me’kele, the Mekelle Institute of Technology, collaborates with DC Opportunities to establish the electrification project. They can thus play an integral role in local capacity building, by providing education and training required for the permanent technicians.

Moreover, the Tigray region contains many earthen dam schemes [99], leading to the conclusion that this construction method for this kind of reservoir is well known at the proposed case study site. Even around the village of Adi Araha itself, earthen dam reservoirs of dimensions not far off from the proposed reservoirs can be found (see Figure 5.2). Technical knowledge of the installation of electro-mechanical equipment can be provided by technicians of Me’kele Institute of Technology.

Theft and vandalism prevention Currently, several community members own solar panels. While there is no physical security protecting these, the closeness of the community ensures these panels are safe. Likewise, a strong feeling of primacy of the group is present, which would dissuade any ill will towards a common resource, such as a PHS plant. It seems it would not be very challenging to implement societal security.

Avoidance of political vertical networks Whether the regulatory environment of a country is conductive, is determined by the ease of doing business. Ethiopia ranks very low on the World Bank list of ’Ease of doing business’ [22]. As can be observed in Table 5.2, for some important elements of implementing a PHS plant, such as dealing with constructing permits, protection of minority investors, and trading across borders, as the electro-mechanical machinery and pipe segments need to be retrieved across the border. Almost all countries in Sub-Saharan Africa are generally ranked very low on the list of Ease of Doing Business rankings [21]. This makes the implementation of a large project more difficult, so a scalable design might be preferred; however, as shown in 5.4.3, this is more expensive.

Table 5.2: Ranking of Ethiopia on several elements determining the ease of doing business, on a ranking of 1-190. Obtained from [22].

Topics	**DB 2020 Rank**
Overall	159
Starting a Business	168
Dealing with Construction Permits	142
Getting Electricity	137
Registering Property	142
Getting Credit	176
Protecting Minority Investors	189
Paying Taxes	132
Trading across Borders	156
Enforcing Contracts	67
Resolving Insolvency	149

Apart from performing poorly in the ease of doing business ranking, the licensing process in Ethiopia for mini-grids is difficult and prohibitive, especially for organizations from outside of the country [2]. Local political connections are therefore almost a requirement.

Adherence to local regulations According to the constitution of Ethiopia, the state exclusively owns land, with people only having usufruct rights [57]. Furthermore, regional laws in the Tigray region prohibit the sale of land, but short-term land rental contracts can be made with the regional government.

The Ministry of Water Resources has the responsibility of the managing the water resources. The rules and regulations set by the Federal Ministry stipulate the Tigray Bureau of Agriculture and Natural Resources (BoANR) has a mandate to manage the regional water resources with regard to agricultural development. Water rights can be obtained under the Ethiopian Water Resources Management Proclamation.

Little environmental impact According to the governmental Proclamation 769/2012 the the investor has a responsibility to follow all Ethiopian environmental protection laws, and the Ethiopian Investment Board must to approve all environmental impact assessment studies.

While a local environmental impact assessment study is thus mandatory, using correctly placed earth dam reservoirs should have little impact or even a positive impact on the environment. Since the lower reservoir is located in a riverbed, care must be taken not to negatively influence the downstream water availability. However, by impounding water during the wet season, which can then be used in the dry season, the reservoir can play an important role in conservation.

5.3. PHS model

In order to get a clear picture of the functioning of a PHS system in an isolated mini-grid, it should be modelled. Only then a fair assessment can be made on the capacity requirements of the reservoir and the supporting Battery Energy Storage System (BESS), and the output obtained with different configurations. There are several methods to model an ESS, categorised as one of the following: dynamic, energy flow, physics-based or black box models. For a feasibility study an initial analysis of the system performance, and thus an understanding of the energy flows in the charging and discharging processes, is required. The most suitable model to use for this purpose is an energy flow model [42], which will be applied in this thesis. The model is programmed in *Python*.

In combination with the energy flow model, several steps are taken to size the HESS (technical assessment) so the economical and socio-cultural implications can subsequently be assessed. These steps are the following:

1. *Initial input:* input profiles are required. First a load profile is constructed, adjusted for demand response, using the method described in Section 2.1.1. Secondly, a generation profile is obtained and adjusted for the energy requirements. Subtracting the load profile from the generation profile leads to a power discrepancy profile (Section 5.3.1). It should further be noted that each of the profiles is created with 10 minute intervals. This is done for reasons of calculation speed, and

because the ramp rate of the PHS plant is not considered; this is lower than a minute [105] and can thus be neglected in a model where the interval is 10 minutes.

2. *Parameters and constraints:* parameters based on the required input and outputs required throughout the energy flow model. These parameters are subjected to constraints.

3. *Penstock dimensions:* the power discrepancy profile is used to estimate the power output requirement of the ESS. Based on this power output, the required pipe type is obtained by employing the model presented in Section 3.3.2 and 3.5.2.

4. *Energy flow model:* with the power discrepancy profile and the pipe type (and thus diameter and material) known, the model simulates the energy flow through the system, employing an energy management strategy. The output profile is obtained, and the deficit and excess energy is assessed. The output is adjusted to desired levels by tweaking several parameters such as the generation profile, the BESS capacity, the reservoir capacity, the pump power and the turbine power. This is done for several considered configurations.

5. *CAPEX assessment:* when an acceptable output is reached, the Hybrid Energy Storage System (HESS) is sized to feasible parameters. With the parameters known for each component, a cost analysis can be made. This is first done for an one-time installation, and subsequently a scalable design is assessed.

All steps are explained in greater detail below.

5.3.1. Input profiles

The input profile for the model is the power discrepancy profile. However, to obtain this, a demand profile and an initial generation profile are required. All input profiles are discussed below.

Demand profile For both scenarios discussed in the Boundary Conditions (2), a yearly demand profile has been established. They have been adjusted for demand response with the method described in Section 2.1.1. Since the yearly demand profiles present an unclear visualisation, only a single week is presented for both scenario's in Figure 5.6.

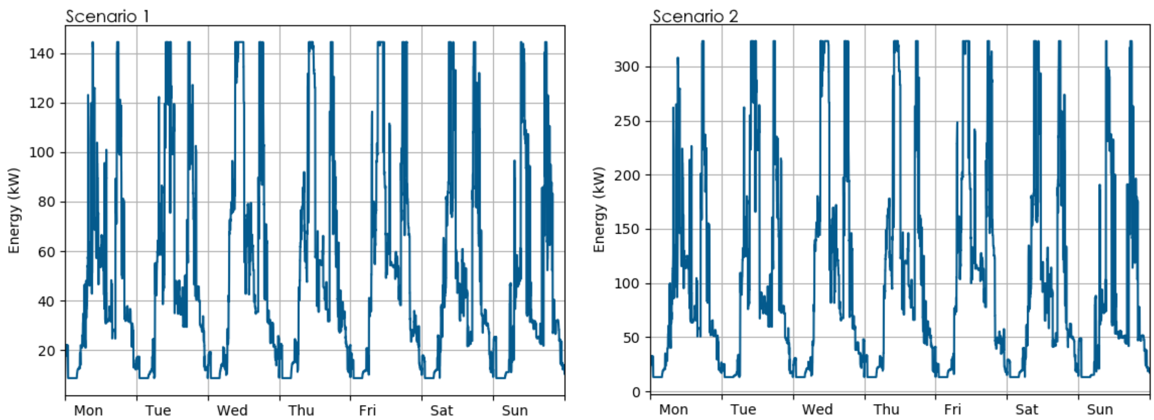


Figure 5.6: *Left:* weekly demand profile for Scenario 1, with 600 household electrified of which 10% tier 1, 20% tier 2, 40% tier 3, 25% tier 4 and 5% tier 5. *Right:* weekly demand profile of Scenario 2, with 700 household electrified of which 10% tier 2, 30% tier 3, 50% tier 4 and 10% tier 5.

From these demand profiles, scenario 1 has a peak demand of 142 kW and an annual energy requirement of 396,294 kWh. Scenario 2 has a peak demand of 324 kW and an annual energy requirement of 830,022 kWh.

Generation profile Generation and storage are linked, and storage can thus not be assessed without an estimation of the generation requirements. However, this is not the focus of the research and the depth of the generation sizing is thus minimal. Only solar generation is considered, as explained in Section 3.1.

At the basis of the generation sizing is the power output profile of 1 kWp installed solar power. This was obtained for the location of Adi Araha from the PVGIS tool, published by the European Commission Joint Research Centre [46]. The output over 10 years was gathered and averaged for an optimal azimuth and slope of a fixed module, to get the annual generation profile for one kWp installed solar power for a Typical Meteorological Year (TMY). In this generation profile, 14% system losses are assumed. The result is presented in Figure 5.7.

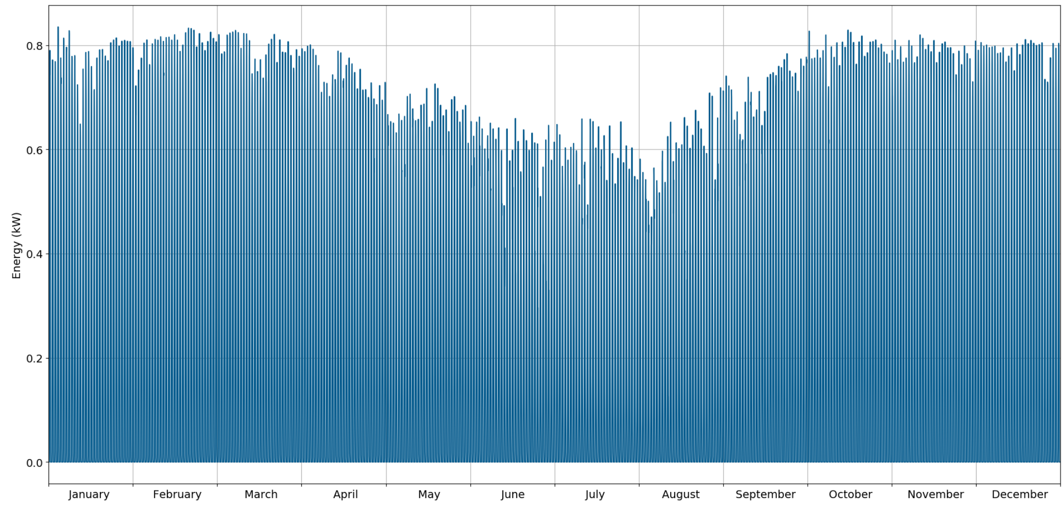


Figure 5.7: Generation profile of 1 kWp of installed solar power over a TMY in the location of Adi Araha, Ethiopia (Lat:13.284, Lon:39.520). The modules are assumed to have an optimal tilt and azimuth of 18°and 0°respectively.

The generation profile of 1 kWp installed solar can be adjusted by multiplying it with a generation factor (γ), in order to obtain the required amount of installed solar power. While γ is tweaked according to model outcomes, an initial generation profile should be established. This is done as follows, with the average round-trip efficiency of the ESS assumed at 60%:

$$\gamma_{initial} = \frac{E_{demand}}{E_{1kWp}} \cdot 1.4 \tag{5.1}$$

In this formula, E_{demand} is the total amount of energy demanded annually (kWh) and E_{1kWp} is the the total annual generation of 1 kWp installed solar power, which is calculated as 181 kWh.

Power discrepancy profile The power discrepancy profile is calculated by subtracting the demand from the generation. As explained, this will change if the generation factor is tweaked. However, the initial power discrepancy profiles for each scenario are presented in Figure . (scenario 1) and Figure . (scenario 2) below. These correspond to a γ of 322.85 and 641.35 for scenario 1 and 2, respectively. In the power discrepancy profiles, negative values represent power is required from the ESS (demand exceeds generation), and positive values represent excess power is generated and should be absorbed by the ESS (generation exceeds demand).

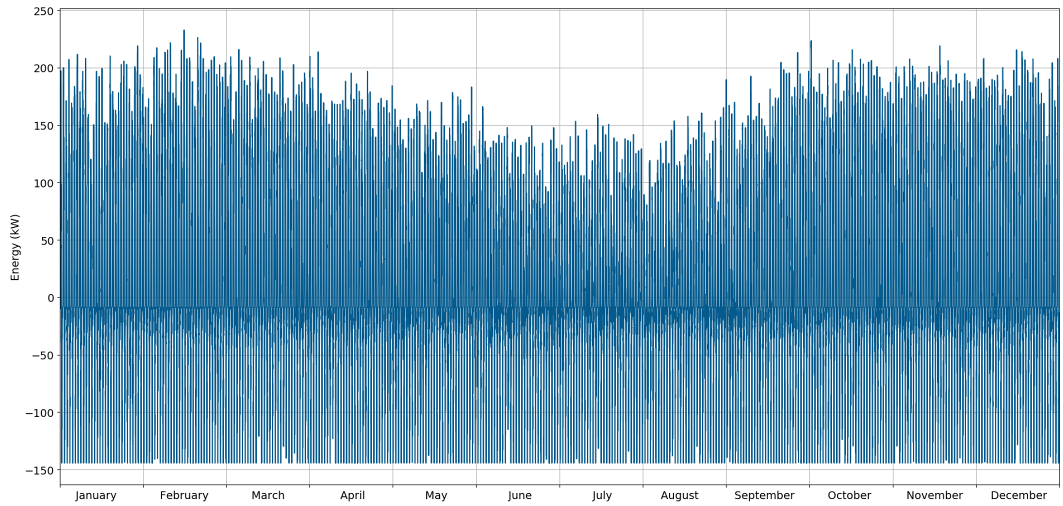


Figure 5.8: Power discrepancy profile for scenario 1.

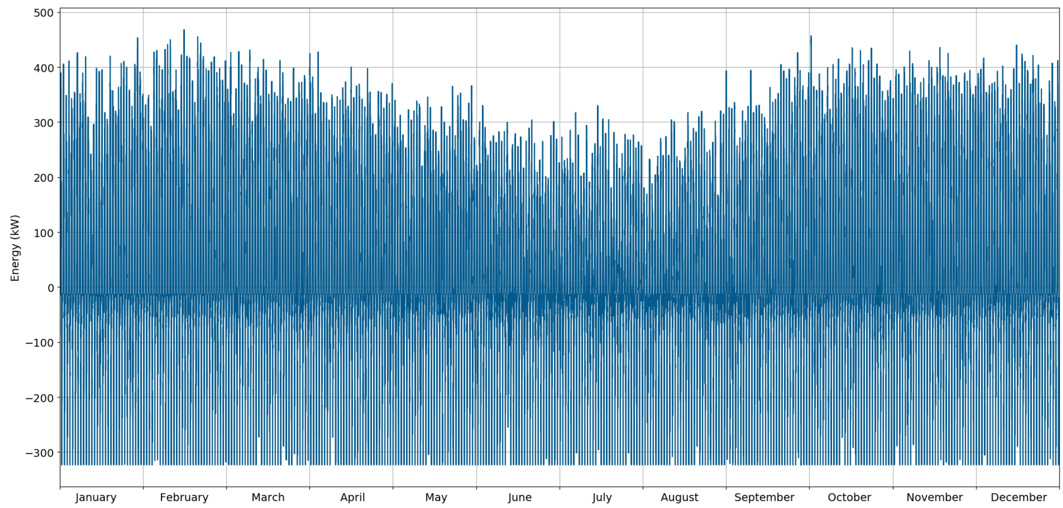


Figure 5.9: Power discrepancy profile for scenario 2.

The discrepancy profile is used to assess the functioning of the system, and subsequently size the system to achieve a desirable output. This is done through a model which simulates the energy flow of the HESS through an energy management strategy.

5.3.2. Parameters and constraints

To establish a energy management strategy to assess a realistic energy flow, several parameters, and subsequently their constraints, are explained initially.

Parameters Since a HESS is considered, the system can be divided into the BESS parameters and the PHS parameters.

First of all, the parameters of the battery are summarized in Table. The assumed battery used is a generic 1 kWh lithium-ion battery unit. The inner limits of the battery are determined based the fact that the lifetime of a lithium-ion battery is greatly improved if the State of Charge (SOC) is kept between 65 and 75% [250]. The outer limit is the absolute maximum and minimum SOC the battery can have.

Table 5.3: The parameters of the Battery Energy Storage System (BESS).

Parameter	Symbol	Value	Unit	Reference
Rated charge power	$P_{BC,max}$	0.5	kW	generic
Rated discharge power	$P_{BD,max}$	0.5	kW	generic
Charge efficiency	η_{charge}	95	%	[25]
Discharge efficiency	$\eta_{discharge}$	95	%	[25]
Maximum storage capacity	$E_{B,max}$	1	kWh	generic
State of charge (max outer)	$SOC_{B,max2}$	85	%	[250]
State of charge (min outer)	$SOC_{B,min2}$	25	%	[250]
State of charge (max inner)	$SOC_{B,max1}$	75	%	[250]
State of charge (min inner)	$SOC_{B,min1}$	65	%	[250]
State of charge (initial)	$SOC_{initial}$	60	%	

The generic battery is seen as a single unit, and the number of units is scaled according to the requirements.

Secondly, the parameters used for the pumping and turbine operation of the PHS system are considered, as shown in Table 5.4. The values of these parameters are determined specifically for scenario 1 and scenario 2, as explained in Section 5.3.3.

Table 5.4: The parameters of the Pumped Hydro Storage (PHS) system.

Parameter	Symbol	Unit	Parameter	Symbol	Unit
Rated turbine power	$P_{T,rated}$	kW	Upper reservoir content (max)	$C_{UR,max}$	m^3
Minimum turbine power	$P_{T,min}$	kW	Upper reservoir content (min)	$C_{UR,min}$	m^3
Turbine efficiency	η_T	%	Lower reservoir content (max)	$C_{LR,max}$	m^3
Rated pump power	$P_{P,rated}$	kW	Lower reservoir content (min)	$C_{LR,min}$	m^3
Minimum pump power	$P_{P,min}$	kW	Maximum flow rate	Q_{max}	m^3/s
Pump efficiency	η_P	%			

Finally, the parameters of the mini-grid used in the energy flow model are determined. P_{diff}, the power discrepancy at a moment t in time, is calculated as follows:

$$P_{diff} = P_{generation} - P_{demand} \tag{5.2}$$

Furthermore, the excess power and deficit power are calculated, according to equations 5.3 and 5.4, respectively.

$$P_{excess} = P_{diff} - P_P - P_{BC} \qquad if \quad P_{diff} > 0 \tag{5.3}$$

$$P_{deficit} = P_{diff} - P_T - P_{BD} \qquad if \quad P_{diff} < 0 \tag{5.4}$$

At any moment in time, P_{BC} and P_{BD} are the BESS charging and discharging power respectively. The pump power and turbine power are symbolised as P_P and P_T.

While the efficiency of the pumping and turbine operation are defined by the water flow (see Section 5.3.3), the efficiency of the BESS is implemented in the SOC calculation as follows:

$$\mathrm{SOC}_B(t+1) = \mathrm{SOC}_B(t) + \frac{\delta t}{E_B}\left(\eta_{BC} \cdot P_{BC}(t) - \frac{P_{BD}(t)}{\eta_{BD}}\right) \tag{5.5}$$

The time step δt considers 10 minute intervals, as explained before. Moreover, the SOC of the upper reservoir (where energy is stored in the form of potential energy of water) is calculated as follows:

$$\mathrm{SOC}_{UR}(t+1) = \frac{C_{UR}(t)}{C_{UR,max}} \cdot 100\% \tag{5.6}$$

Constraints The mentioned parameters are subject to constraints. Technical and functional limitations present the need to constrain the power flow of the BESS, the turbine operation and the pump operation.

$$P_{BC,min} < P_{BC} < P_{BC,max} \tag{5.7}$$

$$P_{BD,min} < P_{BD} < P_{BD,max} \tag{5.8}$$

$$P_{T,min} < P_{T} < P_{T,max} \tag{5.9}$$

$$P_{P,min} < P_{P} < P_{P,max} \tag{5.10}$$

Regarding the energy levels in the storage compartments, these also are constrained: the BESS by equation 5.11, where E_B is the energy level in the BESS at a moment in time. The reservoir levels are constrained by equation 5.12, with C_{UR} the water content in the upper reservoir and C_{LR} the water content in the lower reservoir.

$$\text{SOC}_B = \frac{E_B}{E_{B,max}} \cdot 100\%$$

$$\text{SOC}_{B,min} < \text{SOC}_B < \text{SOC}_{B,max} \tag{5.11}$$

$$C_{UR,min} < C_{UR} < C_{UR,max}$$

$$C_{LR,min} < C_{LR} < C_{LR,max} \tag{5.12}$$

5.3.3. PHS parameter determination

Rather than regarding the PHS as separate units like the batteries, the values for all PHS parameters are decided for both scenarios. There are two options considered for each scenario: a ternary unit with a Pelton turbine, and a binary unit with a Pump-As-Turbine.

Turbine rated power first a decision on the maximum power output of the turbine (which is the rated power of the turbine) must be made. This can be done by taking all negative power discrepancy values, and placing them in a histogram, as seen in Figure 5.10 and 5.11 for scenario 1 and 2 respectively.

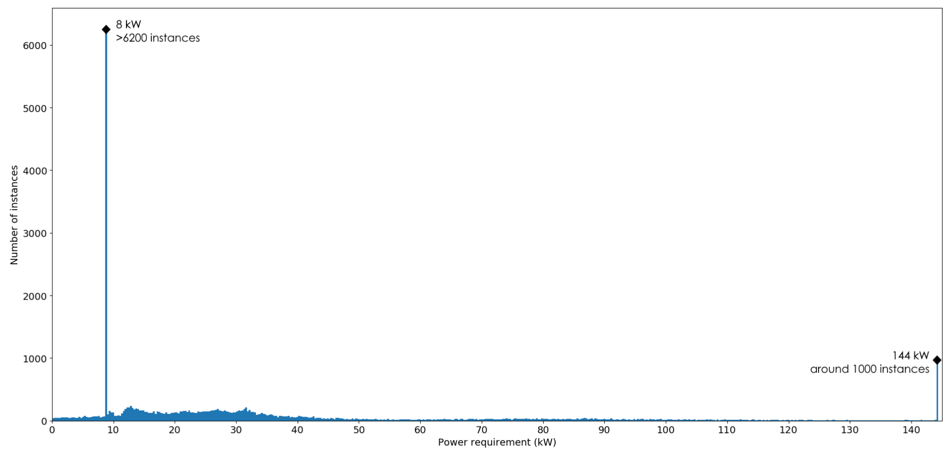


Figure 5.10: Histogram of the number of instances a certain power output is required (kW), based on the power discrepancy profile. This histogram is for scenario 1.

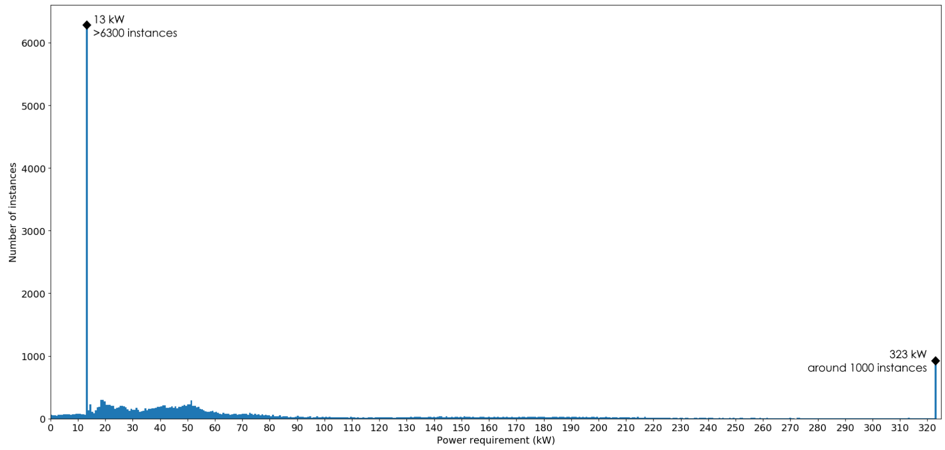


Figure 5.11: Histogram of the number of instances a certain power output is required (kW), based on the power discrepancy profile. This histogram is for scenario 2.

It can be seen from the histograms that for scenario 1, there are mostly instances where 8 kW is required, followed by 144 kW. Since the turbine has a limited operating range, it is most optimal to size it for the high power requirement, so 144 kW. the 8 kW will be supplied by the BESS.

For scenario 2, the turbine will be sized for 323 kW rated power, and the 11 KW power requirements will be supplied by the BESS.

As the head is 280 meter, both an binary unit with a PAT and a ternary unit with a Pelton turbine will be considered. While a specific Pelton turbine has not been identified, standard sizes were selected for 280 meter head: for scenario 1 a 150 kW Pelton turbine, and for scenario 2 a 300 kW Pelton turbine.

Additionally, a Pump-As-Turbine is considered for both scenarios. Since their efficiency curves are difficult to predict, and the assumption is the PAT is not custom-made and fit to the requirements, pump manufacturer KSB was approached to supply information on a suitable pump for both scenarios:

- Scenario 1: PAT Multitec 125/ 7-9.2 , at a head of 280 meter a rated flow of 204 m^3/h and a maximum power output of 122 kW at these conditions.
- Scenario 2: PAT Multitec 150 /2-11.2 , at a head of 280 meter a rated flow of 478 m^3/h and a maximum power output of 276 kW at these conditions.

While these PATs do not completely reach the required power output, they were determined the best fit for the situation from the available PATs.

Turbine efficiency The rated power of the turbine is defined as the maximum power it can supply and the rated flow is the associated flow rate. The efficiency of a turbine is dependent on power output and thus on the flow, which is indicated as a percentage of the rated flow of a turbine.

Pelton turbines follow characteristic efficiency curves. The model requires an equation for the efficiency curve of the turbine, in order the determine the efficiency connected to the power output at a moment in time. Based on the characteristic curves, as supplied by Kuanda et al. [124], a polynomial was established for Pelton (eq. 5.13) turbines, as seen below.

$$\eta_{pelton} = 1.73 \cdot 10^{-11} \frac{Q_t}{Q_r}^7 - 8.93 \cdot 10^{-9} \frac{Q_t}{Q_r}^6 + 1.91 \cdot 10^{-6} \frac{Q_t}{Q_r}^5 - 2.20 \cdot 10^{-4} \frac{Q_t}{Q_r}^4 + 1.46 \cdot 10^{-3} \frac{Q_t}{Q_r}^3 - 5.76 \cdot 10^{-1} \frac{Q_t}{Q_r}^2 + 12.92 \frac{Q_t}{Q_r} - 46.45 \quad (5.13)$$

This polynomial is visualised in Figure 5.12.

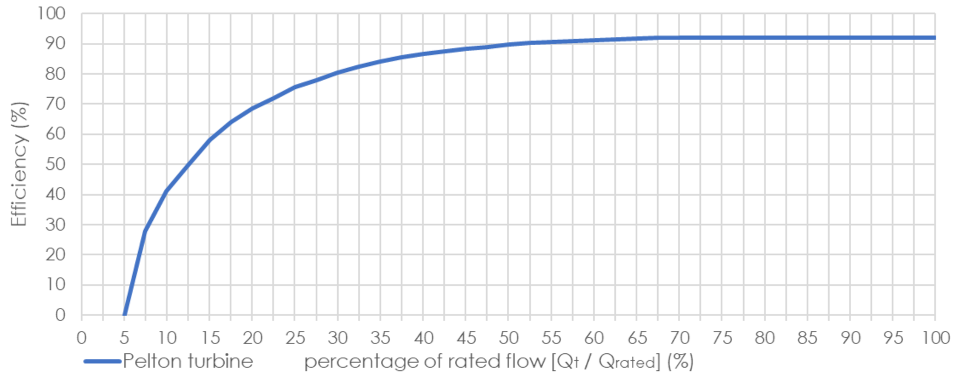


Figure 5.12: Visualization of characteristic efficiency curve of a Pelton turbine.

The efficiency curve of a pump used as turbine however is difficult to predict. For the two PATs recommended by KSB, efficiency curves for the turbine mode are known, and shown in Figures 5.13 and 5.14. For the purpose of the model, polynomials were also estimated for the PAT efficiency curves.

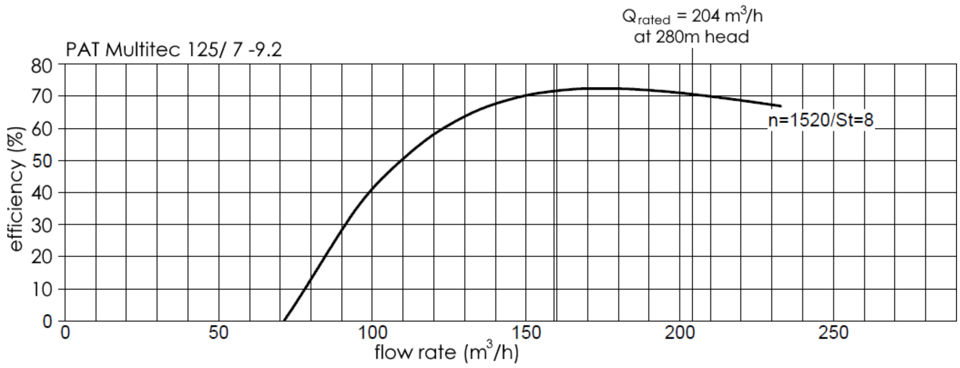


Figure 5.13: Efficiency curve for the turbine mode of the PAT used in scenario 1 (PAT Multitec 125/ 7-9.2).

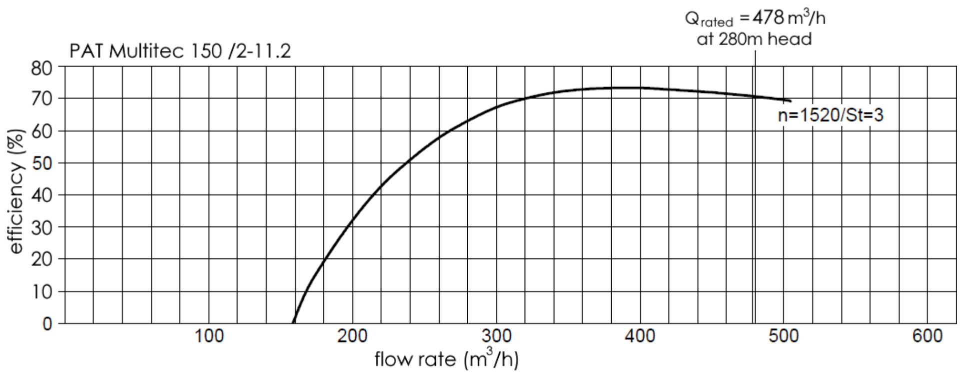


Figure 5.14: Efficiency curve for the turbine mode of the PAT used in scenario 1 (PAT Multitec 150 /2-11.2).

Penstock dimensions As explained earlier in Section 3.3.2, the power output is dependent on the flow rate in the penstock:

$$P = Q \cdot (H_{gross} - H_{losses}) \cdot \rho \cdot g \cdot \eta_g \tag{5.14}$$

In the same Section it was also explained that the head losses H_{losses} are likewise dependent on the flow rate, leading to the model of a vector function to find a corresponding head loss and pipe diameter. This vector function was subsequently used in Section 3.5.2 to find a suitable pipe type for the penstock if the gross head, power output requirements of the turbine and required length of the penstock are known. The pipe type should be determined to model the energy flow, because the pipe type determines the losses in the penstock and thus the efficiency of generation, together with the efficiency of the turbine. Similarly, it influences the efficiency of the pump operation.

The pipe type is determined based on the maximum generated power by the PHS, or the turbine rated power. The most cost effective pipe type is determined to be the one which can provide the flow required for the desired power output, with few losses, and for the lowest price per meter. The model determined the following pipe types the most cost-effective for each scenario and option:

- Scenario 1, Option 1 (Pelton, 150 kW) and 2 (PAT, 122 kW): GRP, pressure class PN32, 0.3m nominal diameter, approximately 21.32 €/m.
- Scenario 2, Option 1 (Pelton, 300 kW) and 2 (PAT, 276 kW): GRP, pressure class PN32, 0.35m nominal diameter, approximately 28.30 €/m.

The two options considered correspond to the possible configurations as discussed in 3.5.3.

Pump rated power While the pump power of the PATs is already determined, the ternary unit with Pelton turbine considers the pump as a separate unit. Therefore, the rated power used for the turbine should be assessed. This is done in a similar way as the determination for the turbine's rated power, but now with a histogram of the negative discrepancies. For each scenario, these are presented below.

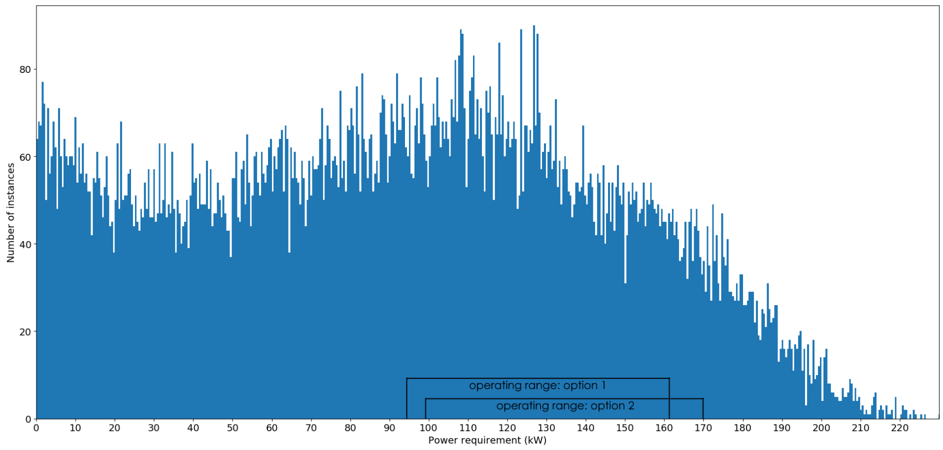


Figure 5.15: Histogram of the positive power discrepancies of scenario 1, and the power output operating ranges indicated for option 1 (ternary unit with Pelton) and option 2 (PAT).

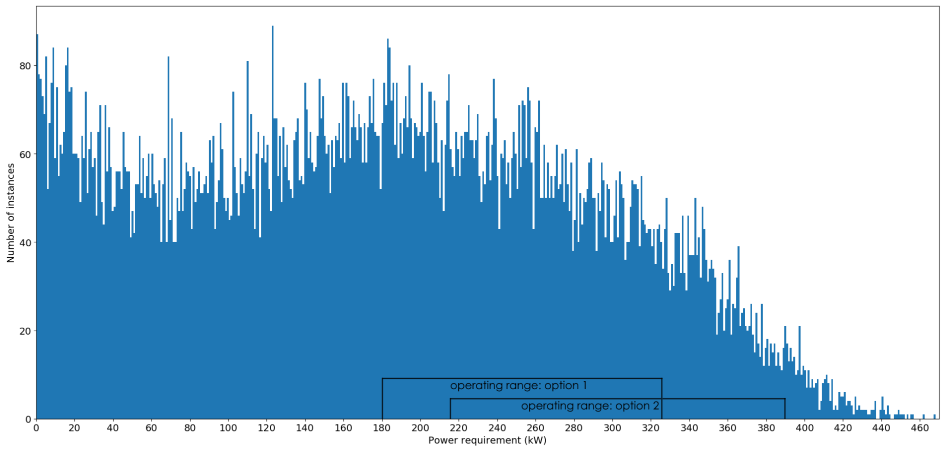


Figure 5.16: Histogram of the positive power discrepancies of scenario 2, and the power output operating ranges indicated for option 1 (ternary unit with Pelton) and option 2 (PAT).

The operating range of each pump is shown, as 60 to 125 percent of the rated power. The rated power of the binary unit with PAT is determined on the chosen PAT, but for the ternary unit the most optimal rated power for the turbine can be chosen.

Pump efficiency A converter is assumed to work as a variable speed drive for the pump, allowing it to work over a range of operating speeds. However, for each speed a specific efficiency curve is required. As explained in Section 3.4.2, the pumps is assumed to be able to run between 60 and 125 percent of the rated flow. While this range is increased with variable operating points, remaining within these levels ensures stable pump operation and thus less maintenance.

Due to the lack of access to pump efficiency curves for each operating point, and since with variable speed the efficiency does not vary significantly over the operating range, the pump efficiency is assumed to remain constant over the range of 60 to 125 percent of the rated flow.

Reservoir parameters The upper and lower reservoirs are assumed to have same capacity, so $C_{UR,max}$ = $C_{LR,max}$. Since the reservoirs can not be drained completely, there is assumed to be at minimum 20 percent of the total volume remaining in the reservoir, referred to as 'dead storage', so $C_{UR,min} = 0.1 \cdot C_{UR,max}$. The total water content in the system is calculated as $C_{UR,max} + C_{LR,min}$.

Conclusion Conclusively, there are two scenario's, both with different power requirements. For each of these scenario's, there is the option of using a binary unit with a PAT, and the option of using a ternary unit with a Pelton turbine. The chosen initial parameters are summarized in Table 5.5 below.

Table 5.5: Summary of the assessed options for each of the two scenarios.

		Configuration	Turbine power (kW)	Pump power (kW)	Penstock Diameter (m)	Initial installed kWp solar
Scenario 1	Option 1	Ternary unit (Pelton)	150	135	0.3	323
	Option 2	Binary unit (PAT)	122	138	0.3	323
Scenario 2	Option 1	Ternary unit (Pelton)	300	260	0.35	641
	Option 2	Binary unit (PAT)	276	310	0.35	641

5.3.4. Energy Management Strategy (EMS)

The energy flow is modelled through an Energy Management Strategy (EMS). In order to achieve a balance of power within the mini-grid, information on the generation and demand is transferred to a power discrepancy. This is done for each moment in time, using intervals of 10 minutes. The power discrepancy is either positive or negative. A positive value means there is excess power generated by the solar modules, which should be stored in the HESS. A negative value means there is a deficit in power, and the HESS should supply the demand.

After the determination whether the HESS should charge or discharge, a flow diagram determines the next course of action. The flow diagrams of the EMS are visualized in Appendix A, but a simplified version is shown in Figure 5.17 below.

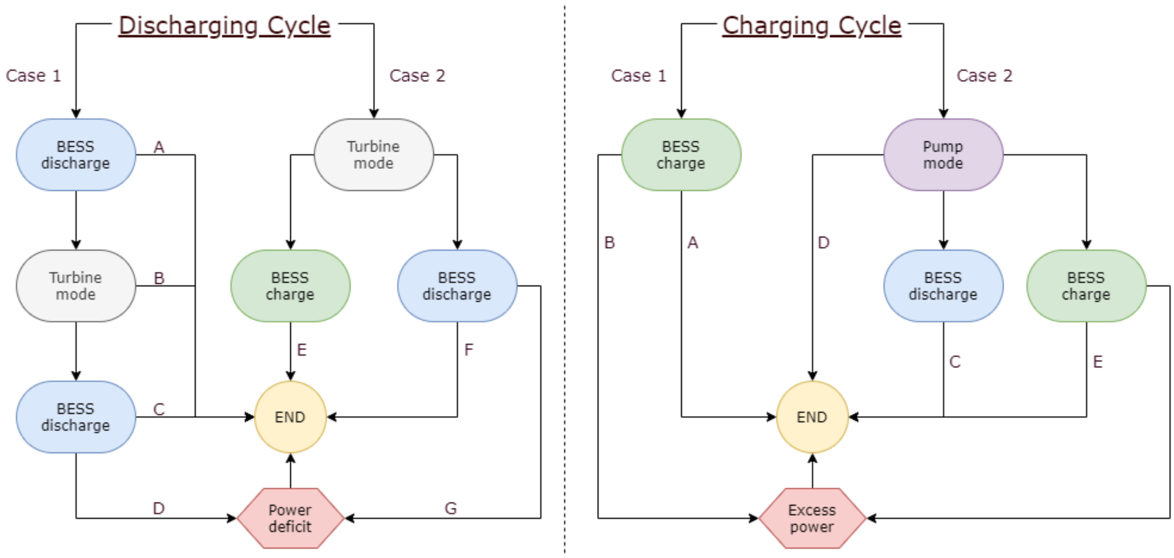


Figure 5.17: Simplified flow diagrams of the discharging (left) and charging (right) cycles of the HESS.

Discharging cycle The discharging cycle is divided into two cases, which both lead to several options. If the power discrepancy is negative, the EMS checks whether the BESS has an SOC within the inner limits, to extend the battery lifetime (Section 5.3.2). This is case 1; the batteries can either supply all required power (A), or only a part of the power, after which the turbine supplies the rest (B). If the turbine and battery combined can not supply all demand, the BESS is further discharged, up until the lower outer SOC limit (C). If this still does not supply all required power, the options have been exhausted, and the power not supplied by the BESS and PHS becomes a power deficit (D).

Case 2 starts in either of the following instances: either the SOC of the battery is not within the inner limits, or the minimum turbine power exceeds the deficit power and the unmet power after the BESS has ran. This second instance is to avoid the scenario where the BESS can only supply part of the required demand, and the unsupplied part is below the minimum turbine power and thus becomes unnecessary deficit power. If case 2 is activated, the turbine runs, and checks whether it can run well above the required demand, so it can also charge the battery (E) if its SOC is under the upper outer limit. If the turbine can not supply all required power, it will employ the BESS, if the SOC is within the outer limits (F). Again, if the power discrepancy in the mini-grid can still not be supplied, a deficit power occurs (G).

Charging cycle The charging cycle also knows two cases, and multiple options within these cases. Explanations of these options is simplified with Figure 5.18.

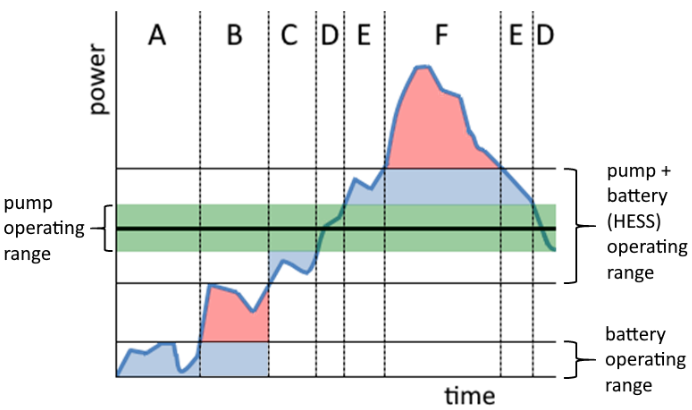


Figure 5.18: Visualisation of the alternatives occurring during the charging cycle.

In case 1, the discrepancy power is too low to fall within the operating range of the pump and BESS combined. The power discrepancy is either low enough that all of it can be used to charge the BESS (A), or part of the power becomes excess power, which is discarded (B). For case 2, the power discrepancy does fall within the operating range. The battery can be discharged, to add additional power to the power discrepancy so the total available power falls within the pump operating range (C). Or, the power discrepancy falls within the pump operating range without the need for additional power (D). If the power discrepancy exceeds the pump operating range, a portion of the power can be used to charge the BESS (E), or, when it is too high, part of the power becomes excess power (F).

Key Performance Indicators (KPI) As the objective is to model a well-functioning Hybrid Energy Storage System, the Key Performance Indicators (KPI) are solely based on technical functioning of the system, rather than on economical sizing. The financial assessment is thus based on a technically suitable system. The KPI are determined as Loss of Power Supply Probability (LPSP) and Excess Energy (EE).

The LPSP is defined as the probability that an insufficient power supply results when the generation is unable to satisfy the demand [254]. The deficit power is stored in an array for every simulation time step. The number of simulations where the deficit power has values other than zero is calculated and subsequently divided by the total number of time steps.

$$\text{LPSP} = \frac{\sum_{t=0}^{T} \text{Time}(P_{generation}(t) < P_{demand}(t))}{T} \tag{5.15}$$

Where T is the number of 10 minute intervals, which is for a year 52,560. Similarly, the EE can be calculated:

$$\text{EE} = \frac{\sum_{t=0}^{T} \text{Time}(P_{generation}(t) > P_{demand}(t))}{T} \tag{5.16}$$

The values for the LPSP and the EE will fall within the range of 0 to 1. A value of zero for the LPSP means the system can always supply the demand, and a value of 1 implies demand is never met. For the EE, a value of zero suggests all excess generated power is used to charge the ESS, and a value of 1 means power must be dumped at every time step.

For the LPSP, the value should not exceed 0.001 or 0.1% [64]. It is also desired to keep the EE low, however dumped power does not necessarily equate to an unreliable mini-grid. There is thus no maximum value for the EE.

5.3.5. Modelling results

The site specific conditions have been implemented in the energy flow model. Over the period of a year, the output has been simulated. Whether the output was deemed acceptable or not, is based on the KPI output, which are influenced by adjusting certain parameters. The output requirements and their associated parameters are explained, and thereafter the results of the model are presented.

Output requirements & parameters Acceptable results of the energy flow model are obtained by adjusting several parameters. The adjustment these parameters leads to a corresponding change in the output. The output need to adhere to certain requirements; when the requirements are not met, the parameters are thus further adjusted. The output and adjustable parameters are related as follows.

As explained, the LPSP must remain below 0.1%. If this requirement is not met, there is an issue in the discharging cycle, and several parameters can be adjusted. Firstly, a minimum efficiency of the turbine is set, which determines the minimum turbine power output, $P_{T,min}$. Lowering the acceptable minimum efficiency decreases $P_{T,min}$, and this leads to a larger operating range of the turbine, hence it can provide a larger range of power requirements. This step is especially useful when employing a PAT, since these have a smaller operating range to begin with. Alternatively, the BESS can be increased, allowing the batteries to supply a larger demand. Finally, there is also the possibility that the minimum upper reservoir content, $C_{UR,min}$, is reached. This can be solved by increasing the initial state of charge of the upper reservoir, $SOC_{UR,initial}$, or alternatively the capacity of the reservoir should be increased.

While the system is simulated for a period of a year, it is required to operate again the year after. Since energy is stored in the form of water in the upper reservoir, sufficient energy should be stored there at the end of the year, to be used the following year. Moreover, at the chosen location, there is little chance to refill the upper reservoir with natural inflow; the water is required to be pumped up from the lower reservoir (see Section 5.1). Therefore, the SOC of the upper reservoir at the end of the year ($SOC_{UR,end}$) should be at least equal to the SOC at the beginning of the year ($SOC_{UR,initial}$). If this is not the case initially, the amount of installed kWp solar should be increased; likewise, it can be decreased if the $SOC_{UR,end}$ is significantly higher than $SOC_{UR,initial}$, since that means costs can be saved on the generation installation. Increasing the capacity of the BESS can also assist in increasing the $SOC_{UR,end}$. This is because with more battery power, the operating range of the pump increases, so it can run more often.

Finally, each option for both scenario's has been assessed for several EE outputs. The parameters have been adjusted to obtain an EE below 10%, 5% and 2%; the HESS composition and parameters were assessed for all three EE requirements, and subsequently the most optimal one was chosen. The EE was lowered by increasing the BESS size and the reservoir capacity.

All output requirements, and the parameters used to reach these requirements are summarized in Table 5.6 below.

Table 5.6: The required outputs and the parameter associated with each output; adjusting the parameters leads to desired outputs.

Output requirement	**Associated parameter**
LPSP < 0.01%	· Reduce $P_{T,min}$ · Increase BESS size · Adjust $SOC_{UR,initial}$ or increase C_{UR}
$SOC_{UR,end}$ > $SOC_{UR,initial}$	· Adjust installed solar kWP · Increase BESS size
EE below 10% , 5% or 2%	· Adjust $SOC_{UR,initial}$ or increase C_{UR} · Increase BESS size

Results The 4 options, divided over 2 scenarios, have been simulated to obtain LPSP of less than 0.1% and $SOC_{UR,end}$ above $SOC_{UR,initial}$. The parameters obtained for each option are summarized in Table 5.7.

Table 5.7: Results of the parameters set to obtain an LPSP of less than 0.1% and at least an equal SOC of the upper reservoir at the end of the year as at the beginning of the year.

		Configuration	Turbine power (kW)	Pump power (kW)	Penstock diameter (m)	installed solar (kWp)	min. turbine efficiency (%)	max. turbine efficiency (%)
Scenario 1	Option 1	Ternary unit (Pelton)	150	135	0.3	318	40	85
	Option 2	Binary unit (PAT)	122	138	0.3	353	15	72
Scenario 2	Option 1	Ternary unit (Pelton)	300	260	0.35	627	40	85
	Option 2	Binary unit (PAT)	276	310	0.35	719	15	73

Subsequently, for each option, the set parameters for 3 situations are assessed: an EE of at most 10%, 5% or 2%. First, scenario 1 is analysed.

Scenario 1 The first scenario has a lower energy requirement, with a maximum peak of around 144 kW. The results of option 1, with a ternary unit utilizing a 150 kW Pelton turbine, are shown in Table 5.8. The output assessed are the LPSP, the excess energy which needs to be dumped in terms of kWh, the amount of battery units required in terms of capacity (kWh), the required reservoir capacity, which is the same for the lower reservoir as for the upper reservoir, the initially set SOC of the upper reservoir and the SOC after simulating the energy flow for a year, and finally the average efficiency at which the turbine runs. The chosen parameters are highlighted.

Table 5.8: Results of the simulations of the energy flow model for scenario 1, option 1.

EE:	LPSP (%)	Dumped energy (kWh)	Batteries (kWh)	Reservoir capacity (m^3)	$SOC_{UR,initial}$ (%)	$SOC_{UR,end}$ (%)	average turbine efficiency (%)
< 10%	0	16,178	58	44,000	55	57	84
< 5%	0	6,818	79	39,000	42	68	87.2
< 2%	0	2,308	115	39,000	45	73	89.7

For this scenario and option, the parameters for an EE lower than 5% are chosen. Compared to the option of EE lower than 10%, much less energy is dumped, the turbine runs on average at higher efficiency, more water is avalaible at the upper reservoir, and the required reservoir capacity is significantly smaller. While this comes at the cost of 21 kWh extra BESS installed, the advantages overcome this. If the EE is scaled down even further, many more batteries are required with little benefit. The output profile for the chosen parameters for the yearly simulation are visualised in Figure 5.19.

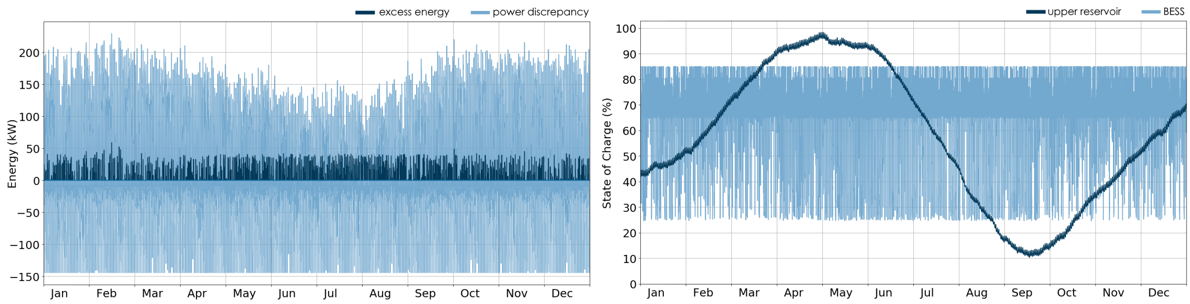


Figure 5.19: The associated graphs for the chosen parameters of option 1 for scenario 1. *Left:* the annual discrepancy profile, with the dumped power visualised. *Right:* The SOC of the batteries and the upper reservoir over a year.

The results of the second option for scenario 1, where a binary unit employs a PAT, is shown in Table 5.9.

Table 5.9: Results of the simulations of the energy flow model for scenario 1, option 2.

EE:	LPSP (%)	Dumped energy (kWh)	Batteries (kWh)	Reservoir capacity (m^3)	$SOC_{UR,initial}$ (%)	$SOC_{UR,end}$ (%)	average turbine efficiency (%)
< 10%	0.04	10,924	85	44,000	55	58	64.3
< 5%	0.02	9,883	97	43,000	50	62	66.2
< 2%	0.1	3,844	220	50,000	65	42	73

Here the parameters for an EE of less than 10% are deemed most suitable. Increasing the capacity of batteries to 97 kWh leads to a small decrease in the pumped power, but is not worth the additional investment. The LPSP is still well below 0.1%. Figure 5.20 shows the result of this chosen option.

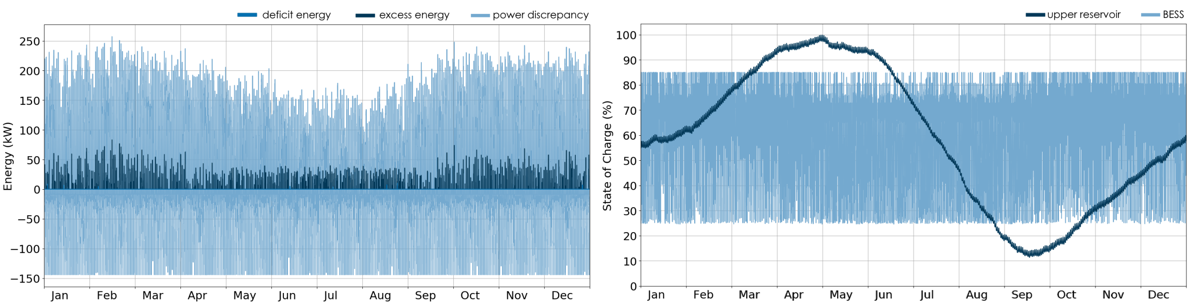


Figure 5.20: The associated graphs for the chosen parameters of option 2 for scenario 1. *Left:* the annual discrepancy profile, with the dumped power visualised. *Right:* The SOC of the batteries and the upper reservoir over a year.

Scenario 2 The same method is utilized for scenario 2, where the power requirements of the mini-grid are larger. The options of using a ternary unit with a 300 kW Pelton turbine are assessed first.

Table 5.10: Results of the simulations of the energy flow model for scenario 2, option 1.

EE:	LPSP (%)	Dumped energy (kWh)	Batteries (kWh)	Reservoir capacity (m^3)	$SOC_{UR,initial}$ (%)	$SOC_{UR,end}$ (%)	average turbine efficiency (%)
< 10%	0.08	26,261	110	86,000	53	58	84
< 5%	0	11,888	145	78,000	45	66.5	86.5
< 2%	0	4,861	240	84,000	54	57.5	90

The dumped energy becomes much lower if the EE must be below 5%. Moreover, the LPSP decreases to zero percent instead of 0.08, making the power supply more reliable. The reservoir can become smaller. If increasing the BESS size even more though, the advantages are small compared to how much the battery capacity must be increased.

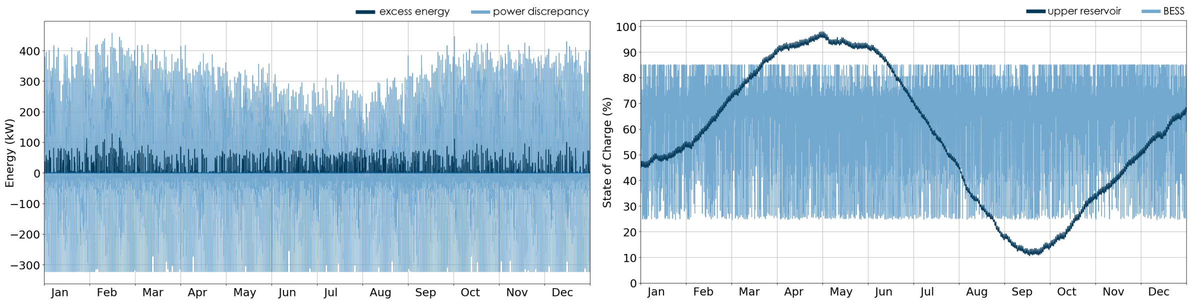


Figure 5.21: The associated graphs for the chosen parameters of option 1 for scenario 2. *Left:* the annual discrepancy profile, with the dumped power visualised. *Right:* The SOC of the batteries and the upper reservoir over a year.

Finally, the option of using a 276 kW PAT in a binary unit was simulated. The results are shown in table 5.11.

Table 5.11: Results of the simulations of the energy flow model for scenario 2, option 2.

EE:	LPSP (%)	Dumped energy (kWh)	Batteries (kWh)	Reservoir capacity (m^3)	$SOC_{UR,initial}$ (%)	$SOC_{UR,end}$ (%)	average turbine efficiency (%)
< 10%	0.1	11,964	185	95,000	54	57.5	63.7
< 5%	0.1	11,964	185	95,000	54	57.5	63.7
< 2%	0.06	6,034	280	90,000	50	60	69.3

The parameters could not be tweaked to keep EE between 5 and 10 percent, so these alternatives are the same. Again, reducing the EE more requires a significant addition to the BESS capacity. An interesting observation however is that the LPSP is at its maximum of 0.1%; this is due to the fact that the PAT has a limited range. The simulation for the chosen parameters is shown in Figure 5.22.

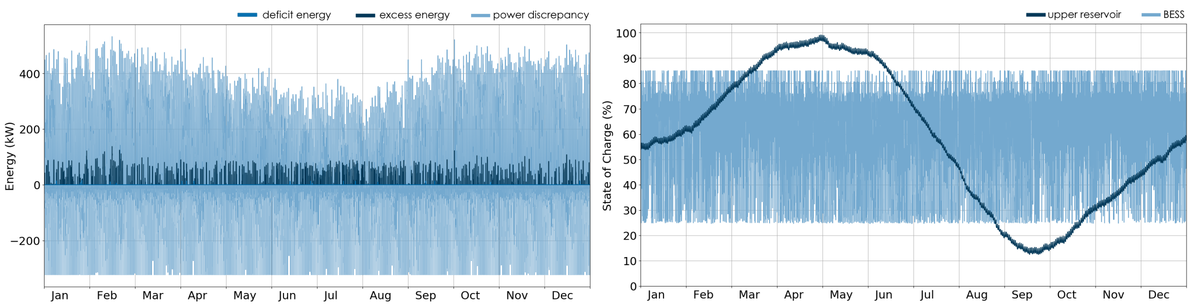


Figure 5.22: The associated graphs for the chosen parameters of option 2 for scenario 2. *Left:* the annual discrepancy profile, with the dumped power visualised. *Right:* The SOC of the batteries and the upper reservoir over a year.

Conclusion The most suitable parameters for each option for each scenario have been chosen; these determine the size of the HESS and thus also the costs. This is further explored in Section 5.4.1. Furthermore, several interesting observations can be made from the simulations.

Firstly, the energy storage requirements are much higher than initially estimated in Section 3.2.2. This is due to several factors. First of all, there is a lower efficiency present, due to the fact that the turbines often run at a lower efficiency than estimated in 3.2.2. Secondly, the storage capacity estimation in 3.2.2 assumes the capacity required consists of three days of power supply purely by the HESS; this is however not a correct assumption, since the cumulative power discrepancy requires a significantly larger capacity throughout the year.

Additionally, from all options of both scenarios, it can be observed that minimizing the dumped energy, and keeping the EE below 2%, leads to a significant increase in the BESS capacity requirements. From this it can be concluded that it is often better to dump excess generated power not within the HESS operating ranges rather than increasing these operating ranges further and further.

It can also be observed that the BESS still plays an important role within the HESS. This is mainly due to the limited operating range of the pump, and if a PAT is employed, the limited operating range of the turbine operation. This can be mitigated by adding another smaller pump for the ternary unit, or another smaller PAT for the ternary unit. This was however not added to the energy flow model, since that would require a complete overhaul of the EMS.

Finally, the options utilizing a PAT seem to require a larger generation, with more kWp solar power installed. The reason for this is the lower efficiency of the turbine; this translates into a higher required flow required for a PAT than for a Pelton turbine when the same power output is considered. Therefore, the upper reservoir empties at a quicker rate, and the pump needs to work harder to make up for this. A higher generation leads to more positive discrepancies, so the pump runs more frequent.

5.4. Financial assessment

The financial assessment first concentrates on a one-time installation, and its associated capital expenses and Levelized Cost of Storage (LCOS). Thereafter, a scalable design is assessed. It is important to note that in the financial assessment the costs for secondary water use are not accounted for, as this can be seen as separate from the storage system itself. Instead, this will be discussed at the end of the section in 5.4.4.

5.4.1. One-time installation

For both scenarios, the costs of the chosen options are assessed. The cost elements assessed are the following: water storage system (reservoir), water conveyance system (penstock, valves), powerhouse (hydro-mechanical and electro-mechanical equipment, control system), supporting BESS, and the transportation costs of all components. Each of these elements also include the installation costs. All capital expenses (CAPEX) for each of these elements have been discussed in Section 3.5. However, several additional costs have to be clarified:

- For the capital costs per kWh of the batteries, the decline in price predicted for the next years is taken into account, and set as 200 €/kWh [198]. This is done for the following reason: it is estimated the implementation of a hybrid system using PHS is likely to take several years. While many mini-grid projects have been announced, a report by Infinergia Consulting found out of 1,600 planned projects only 150 have been completed so far [112]; this signifies a completion rate of 9.3 %. The price of lithium ion batteries declines rapidly, and is likely to fall below 200 € per kWh before 2030 [50]. Additionally, a surplus of retired Electric Vehicle (EV) lithium ion batteries become available for re-purpose [14]. For these reasons, to make a fair comparison with a system employing only BESS in Section 5.4.2, a future price of lithium ion batteries is used.

- The transportation costs are estimated at 80 €/ttkm for the Eastern African Corridor [225]. All materials are assumed to be transported from Nairobi, Kenya; here offices of large pipe producers, and hydro-mechanical producers (such as Voith) are present. Nairobi is located at a distance of 2,300 km from Adi Araha. In the transportation costs are also included the importation costs from Kenya to Ethiopia, which are shown in Figure 2.4 and approximately 17.4% for electrical machinery and 21.7% for the pipes [184].

- Added to the capital costs of the water conveyance system are the costs of valves, which are for 300 and 350 mm pipes approximately 18,200 € for pressure relief valves, 6,800 € for butterfly valves (used for the ternary unit) and 21,600 € for flow control valves (used for the binary unit). These prices are obtained from the AVK group [92], which also have office locations in Sub-Saharan Africa.

- The costs of installation of 1 kWp of solar power in Sub-Saharan Africa is estimated as 1,750 €/kWp [222].

- The expenses involved in continual operation and maintenance are assumed to be similar to those of small scale hydropower: total operational expenses (OPEX) are expected to be around 6 percent of the total installation costs per year [115].

Scenario 1 For the first scenario, the costs for each element are presented in Table 5.12 below. A breakdown of the costs per element is shown in Figure 5.23. The powerhouse is the most expensive element; this is partly due to the substantial added cost of the converter. For the costs of the PAT, for option 2, an amount of 40,000 € as quoted by KSB was assumed.

It is observed that the second option, using a PAT, is significantly cheaper than the alternative. Not included in the cost breakdown however is the extra expense for additional PV installation required for option 2. Since 35 extra kWp installed solar power is required, this equates to an added cost $35 \cdot 1,750 =$ 61,250 €. Considering this, option 1 is cheaper.

Table 5.12: Summary of the costs for each element of the two options for scenario 1.

	Option 1 (€)	**Option 2** (€)
Water storage system	172,246	183,530
Water conveyance system	76,242	91,042
pipe cost	22,919	22,919
installation	485	485
valves	25,000	39,800
Powerhouse	207,486	113,800
Pump	25,322	40,000
Turbine	87,360	-
Converter	93,000	73,160
Governor	1,802	640
Supporting BESS	15,800	17,000
Transportation	43,356	27,055
Transportation costs	2,280	2,280
Tariffs	41,076	24,774
Total	487,294	404,589

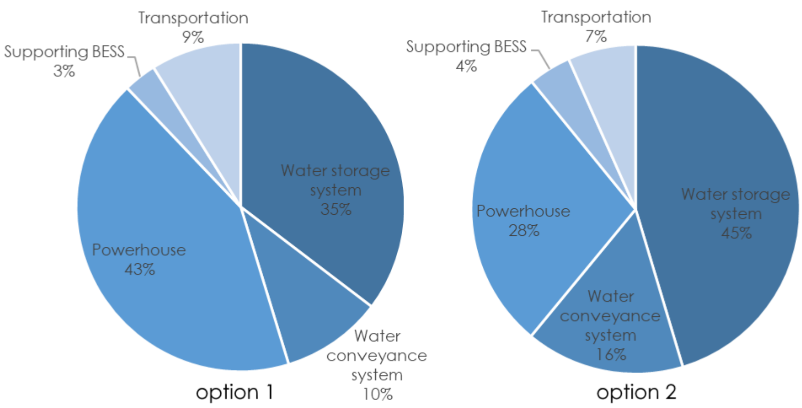


Figure 5.23: Cost breakdown for scenario 1, option 1 (left) and option 2 (right).

Scenario 2 The costs for each option of the second scenario are presented in Table 5.13, and a breakdown is shown in Figure 5.24. Again option 2 is the cheaper alternative at first glance; however, with and added 92 kWp solar requirement, an expense of 161,000 € is required.

Table 5.13: Summary of the costs for each element of the two options for scenario 2.

	Option 1 (€)	**Option 2 (€)**
Water storage system	248,023	275,127
Water conveyance system	92,968	107,768
pipe cost	30,444	30,444
installation	590	590.38
valves	25,000	39,800
Powerhouse	367,923	262,560
Pump	43,342	90,000
Turbine	135,715	-
Converter	186,000	171,120
Governor	2,864	1,440
Supporting BESS	29,000	37,000
Transportation	73,350	55,017
Transportation costs	2,725	2,725
Tariffs	70,624	52,291
Total	774,331	700,539

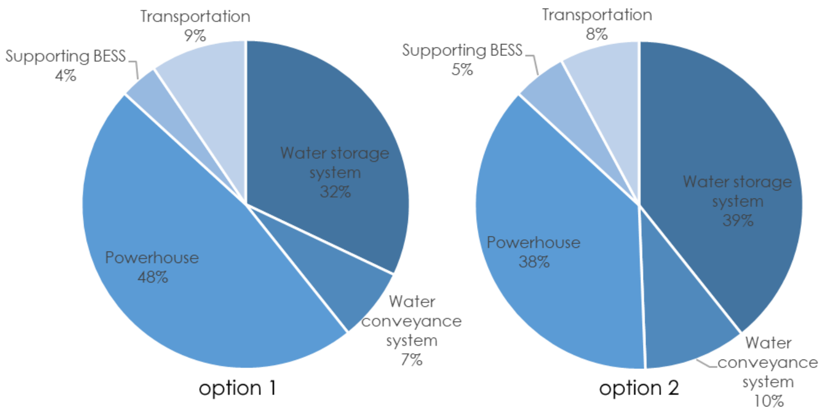


Figure 5.24: Cost breakdown for scenario 2, option 1 (left) and option 2 (right).

5.4.2. Comparison to Battery Energy Storage System (BESS)

To further assess the feasibility of a PHS in an isolated mini-grid in a low-resource region, a comparison with the alternative of an ESS employing purely batteries is required. As discussed, this is as of now the most commonly employed energy storage technology for the researched setting. Additionally, the feasibility of the system for the case study is further assessed.

To compare storage technologies, a commonly used method is finding the price per kWh. Expressing the investment cost in simple terms of €/kWh works for batteries, since the power (kW) and capacity (kWh) of batteries have a fixed ratio. However, for a PHS system these are detached; the capacity can be increased without scaling the power with it. Therefore, another method must be utilised, the Levelised Cost of Storage (LCoS). In its simplest form, the LCoS is calculated as follows [119]:

$$\text{LCoS} = \frac{C_{Capex} + \sum_{t=1}^{t=N} \frac{C_{Opex} + C_{Capex,Re}}{(1+r)^t}}{\sum_{t=1}^{t=N} \frac{W_{out}}{(1+r)^t}} \tag{5.17}$$

In this equation, the C_{Capex} are the capital expenses. C_{Opex} are the operational expenses and $C_{Capex,Re}$ the costs of replacing equipment, which are calculated for each year t over the total lifetime

N of the ESS, discounted with an interest rate r. W_out is the annual energy output of the system. The required information to calculate the LCoS for each option is summarized in Table 5.14. The lifespan of a grid-connected lithium ion battery is estimated at around 10 years with proper management [215] and the lifespan of a pump is assumed to be around 25 years [77], which means these components have to be replaced after their lifespan has ran out. The total lifespan of the PHS plant (N) is estimated at (a minimal of) 50 years, based on the lifespan of GRP pipes [10]. The interest rate is assumed to be 4% [209].

Table 5.14: The parameters required to calculate the LCoS, and the LCoS itself in $€/kWh$. The lifetime is assumed to be 50 years, except for the pump or PAT, which is replaced after 25 years.

	CapEx (€)	OpEx (€)/yr	$\mathbf{CapEx_{Re}}$ (€)	$\mathbf{W_{out}}$ (kWh/yr)	LCOS (€/kWh)
Scenario 1, option 1	487,294	29,237	37,199	179,873	0.298
Scenario 1, option 2	404,589	24,275	45,640	178,728	0.253
Scenario 2, option 1	774,331	46,459	66,744	347,800	0.246
Scenario 2, option 2	700,539	42,032	100,631	343,768	0.231

The LCoS of conventional pumped hydro storage is between 0.15-0.40 €/kWh, and of lithium ion batteries between 0.20 to 0.55 €/kWh in 2020, as obtained from [209]. The LCoS of PHS however is assumed to remain rather constant, while the LCoS of lithium ion energy storage is expected to decrease dramatically. Small-scale PHS, with a calculated cost of 0.231 to 0.298 €/kWh is in 2020 thus cheaper compared to utilizing batteries, for the researched setting. However, the cost of small-scale PHS is assumed to increase rather than decrease; this is due to the maturity of the technology involved, and an assumption that the cost of labour will increase with rising wages in Sub-Saharan Africa. Already in 2025, a BESS will close in on the LCoS range of small-scale PHS. This is visualized in Figure 5.25.

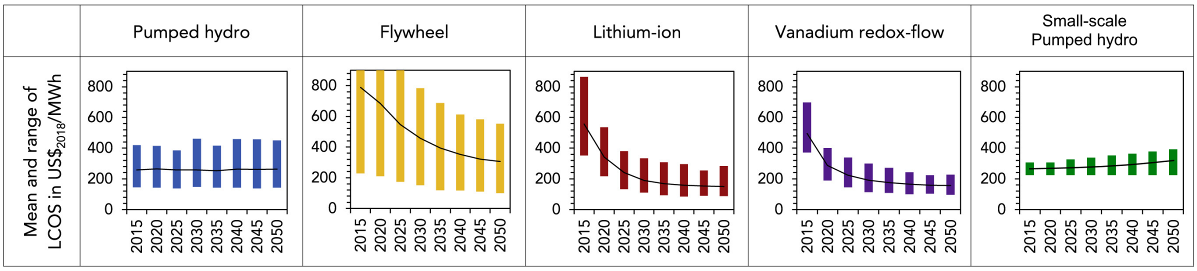


Figure 5.25: Projections of LCoS for several energy storage technologies. Adjusted from [209].

Another option is to compare the costs of the project for each scenario when the ESS is based solely on batteries, by simulating the system with only a BESS through HOMER. This simulation and optimization program defines the optimal microgrid configuration, which is the configuration with the minimum total net present cost. To consider also the operation and maintenance expenses, as well as replacement necessities and the energy output over a lifetime, the Levelised Cost of Electricity (LCoE) can be used, which is calculated as follows:

$$\text{LCoE} = \frac{C_{Capex} + \sum_{t=1}^{t=N} \frac{C_{Opex} + C_{Capex,Re}}{(1+r)^t}}{\sum_{t=1}^{t=N} \frac{W_{out}}{(1+r)^t}} \tag{5.18}$$

Which is similar to the LCoS, but now the solar panel expenses are also considered. The simulation in HOMER led to the results presented in Table 5.15. when considering only batteries for both scenario 1 and 2. The same value for solar installation costs and battery price per kWh, which assume the price in the future, are used.

Table 5.15: The results of simulating with the Homer Pro software.

	Solar power installed (kWp)	Batteries (kWh)	Dumped energy (kWh/yr)	LCoE (€/kWh)
Scenario 1	841	1,212	965,459	0.401
Scenario 2	1,517	2,843	1,652,784	0.393

It can be observed that significantly more solar panels are installed in both scenarios. When calculating the LCoE for small-scale PHS, the same parameters for the solar installation as in HOMER are used: 1,750 € per kWp installation costs, with an O&M of 10 € per kW per year, and a lifespan of 25 years. With these values, and the solar requirements as presented in Table 5.7, the LCoE of the several options are calculated an presented in Table 5.16.

Table 5.16: Levelised Cost of Energy (LCoE) for each option.

	Solar power installed (kWp)	LCoE (€/kWh)
Scenario 1, option 1	318	0.514
Scenario 1, option 2	353	0.494
Scenario 2, option 1	627	0.456
Scenario 2, option 2	719	0.509

The LCoE is thus lower when only batteries are used. This considers the significant price reduction in lithium ion batteries; if the comparison would be made for a system installed today, the LCoE of the system using only a BESS would exceed 0.55 €/kWh. However, as argued in Section 5.4.1, keeping in mind the declining trend in lithium ion battery prices leads to a better comparison. Interesting to note is also the smaller difference between the LCoE of both options in scenario 1, and for scenario 2 the second option even has a higher LCoE. This is due to the need for additional photovoltaic generation, caused by the smaller operating range of the PAT.

The economic feasibility has been assessed with two different calculations: an Levelized Cost of Storage (LCoS) and a Levelized Cost of Electricity (LCoE) comparison. The LCoS comparison gives a more accurate estimation, since the same method of calculation is used. The HOMER simulation adds additional factors to the LCoE calculation, and the addition of the PV generation in the LCoE calculation adds a lot of uncertainties; the generation is sized in different ways for the considered HESS and the HOMER simulation.

5.4.3. Scalable design

It has been discussed in Section 4.2 that a scalable design, which can be implemented in phases over time, has many advantages. These advantages include an earlier implementation, building trust over time, circumvention of political vertical networks, and the chance for a trial period. However, the effect on the financial viability of implementing a PHS plant over time should be researched. In order to do this, it is assessed what the effect on the capital cost and LCOS would be if a PHS plant is installed initially for scenario 1, and subsequently scaled up to scenario 2. This is done for two design configurations:

1. The initial configuration is a ternary unit with a Pelton turbine (150kW), which is then extended with a binary unit with a PAT (Multitec 125/ 7-9.2; 122kW). The initial storage capacity (both reservoirs sizes and battery capacity) is estimated as equal to that of scenario 1, option 1. The eventual storage capacity is estimated as the same of that in scenario 2, option 1. This is due to the fact that, due to the modulation of the first binary unit, the operating range of both the ternary and the binary units together will be the same as a single Pelton turbine.
2. The initial configuration is a binary unit with a PAT (Multitec 125/ 7-9.2; 122kW), which is then extended with another binary unit with the same PAT. The initial storage capacity is estimated as equal to that of scenario 1, option 2. The eventual storage capacity is estimated as the same of that in scenario 2, option 2, because the operating range of both the PATs together will be the same as a single PAT.

Table 5.19: Summary of the four different configuration options to reach scenario 2, and their capital expenses and Levelized Cost of Storage.

	One-time installation		Scalable	
Configuration	Ternary unit (Pelton)	Binary unit (PAT)	initial: ternary unit (Pelton) extension: binary unit (PAT)	initial: binary unit (PAT) extension: binary unit (PAT)
CAPEX (€)	774,331	700,539	initial: 487,294 extension: 387,064	initial: 404,589 extension: 421,131
LCOS (€/kWh)	0.246	0.231	0.278	0.269

The total capital costs of these two options are summarized in Table 5.17. It can be observed, that to get to scenario 2 in 2 phases, it would be 6.6 or 40.2 percent more expensive than an one-time installation of respectively a ternary unit with a Pelton turbine or a binary unit with a PAT.

Table 5.17: Total capital costs for a scalable design, from scenario 1 to scenario 2.

	Option 1 (€)	**Option 2 (€)**
Water storage system	344,494	381,881
Water conveyance system	111,608	126,408
Powerhouse	318,844	226,320
Supporting BESS	29,000	37,000
Transportation	70,412	54,111
Total	**874,358**	**825,720**

To further assess the financial impact of a scalable design instead of an one-time installation, the LCOS is calculated, as summarized in Table 5.18.

Table 5.18: The Levelized Cost of Storage of a scalable design, with either a ternary unit and binary unit (option 1) or two binary units (option 2).

	CapEx (€)	**OpEx (€)**	$\mathbf{CapEx_{Re}}$ **(€)**	$\mathbf{W_{out}}$ **(kWh/yr)**	**LCOS (€/kWh)**
Option 1	874,358	52,461	76,575	347,800	0.278
Option 2	825,720	49,543	96,228	343,768	0.269

Finally, all options to reach scenario 2, their capital costs and LCOS, are presented in Table . This thus constitutes an overview of all configuration options as presented in Section 3.5.3 and Figure 3.20.

5.4.4. Secondary water use

To assess how much larger a multi-purpose water reservoir would be, an example of earth dam reservoirs in the Tigray region is observed. Two existing reservoirs in Gumsalasa an Korir, used for irrigation have been researched by Hagos [99]. The characteristics of these earth dam reservoirs are presented in Table 5.20.

Table 5.20: Two existing earth dam reservoirs in the Tigray region. Information obtained from [99].

	Gumsalasa	**Korir**
capacity (m^3)	1,900,000	1,600,000
area (ha)	40	32
potential households served	615	410

It can be observed that both these reservoirs have a significantly larger capacity than what is required for energy storage purposes. Even if the water for secondary water use is divided over both the upper and the lower reservoir, each reservoir would still impound approximately 950,000 m^3 of water to provide around 600 households (which is number of households in the case study) with water for irrigation. This means the water needed for energy storage is only around 10 percent of the total water capacity. Especially considering research has shown that an increase in electrification leads to higher irrigation requirements [78], the water used for pumped hydro storage operation is a small percentage.

From this it can be concluded that a PHS plant can be easily integrated with a multi-purpose reservoir, even with an existing one. Otherwise, since the capital costs for larger reservoirs exhibit a logarithmic growth (see Figure 5.26), it is worthwhile to expand the reservoir significantly and reap the benefits of a multi-purpose reservoir.

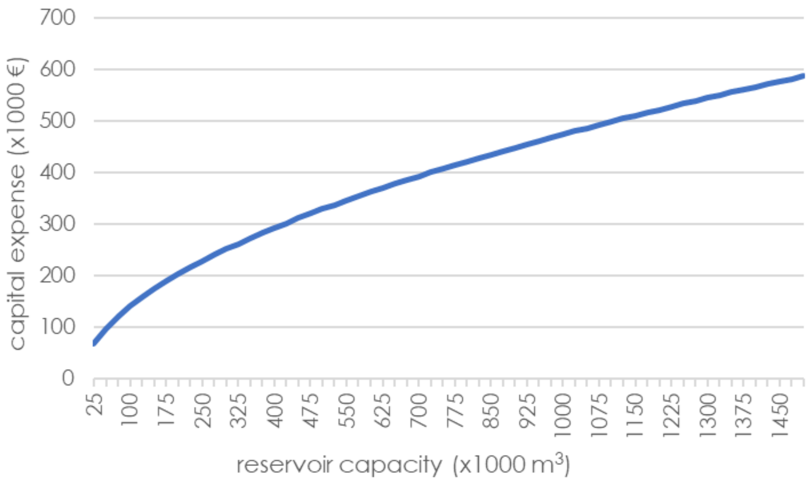


Figure 5.26: Logarithmic growth of reservoir capital expense with increasing capacity.

5.4.5. Conclusion on the case study

It can be deducted from the LCoS comparisons (5.4) that in the near future a HESS employing PHS technology will rapidly become less financially viable than an energy storage system consisting entirely of batteries. This is due to the rapid decline of the price of Lithium-ion batteries, and this combined with the influx of many retired EV batteries will make a BESS economically superior.

However, especially in the next few years, a small-scale PHS plant remains financially competitive. Combined with several advantages over battery storage, small-scale PHS remains an attractive option to research further. These advantages are, among others:

- Batteries have the negative externality of chemical waste, and can not easily be recycled in low-resource regions.
- Pumped Hydro Storage can be integrated with multi-purpose reservoirs, potentially even existing earth dam reservoirs.
- A PHS system has a longer lifetime than a BESS.
- a PHS plant allows for more community involvement and participation than a BESS, embedding it into the community.
- The components for a PHS plant are available at reasonable distance, while a BESS balancing generation and demand for a mini-grid requires a large amount of batteries, which are likely not available regionally.

To compare the proposed mini-grid with grid connection, the LCoE must be used. For the main grid in Ethiopia, this is among the lowest in the world, with an average of only 0.10 €/kWh [95]. This is thus more than 4 times lower than the LCoE calculated for the proposed mini-grid. While Adi Araha will ikely be connected to the main grid in the coming years, many villages in Ethiopia will not be electrified through national grid extension. Considering many of these villages will rely on off-grid solutions, this research proves a mini-grid utilizing PHS is a viable solution for this.

Furthermore, it could even be beneficial to approach it from the reverse direction; if an earth dam irrigation reservoir is present, it can be assessed if the conditions at the site permit the installation of a PHS plant.

5.5. General feasibility

While the case study in Adi Araha has yielded positive results, the site-specific conditions make it difficult to draw a conclusion on the general feasibility. The dependence of the socio-cultural factors on the location becomes clear from the case-study: the advantage of the case study location's proximity to a technical institute, and the experience with earth dam reservoir construction and operation are clearly favorable conditions which not every location might have. However, the case study does adhere to most of the design criteria without having situational conditions completely out of the ordinary for Sub-Saharan African villages; these earth dam reservoirs are common throughout Sub-Saharan Africa [218], and while the proximity of a technical institution can assist in meeting the design criteria, it is by itself not a requirement. The required local knowledge can be transferred through different means, and technical knowledge on the installation does not have to be available at the installation site itself. There is no unusual availability of components and materials for the case study either; as a matter of fact, the components might be less difficult to obtain at many other locations. The strong social hierarchical structure, which can be used in the organizational structure, is likewise present throughout the SSA region [55].

Conclusively, the local factors enabling the socio-cultural feasibility of the case study are helpful, but not uncommon and do not constrict the socio-cultural feasibility to the Tigray region specifically, but can be found or created at many other locations throughout the Sub-Saharan African region. In short, the complete design described in this thesis, including the technical design and the strategy on the planning, implementation and operation of the PHS plant, satisfies local conditions present in rural and remote sub-Saharan African communities, as has ben demonstrated in the case study.

Regarding the general conclusion on the technical and economic feasibility, the gross head difference and required penstock length have been determined as important site-specific geographical conditions to consider. The geographical and hydrological conditions as found in the case study can be found all over the continent. The developed penstock selection tool, combined with the energy flow model and the cost calculations, provides a solid basis for a conclusion of the general technical and economic feasibility. To consider the general feasibility, several situations have been assessed with the model. Three different power output requirements of the PHS system, found within the determined range from Section 2.1.1, have been assessed. For a maximum power output of 75kW, 300 and 550kW for different gross head differences of 100 to 600 meter a well functioning system was designed through the energy flow model. Since the goal is now to find a general picture on the technical and economic feasibility, a generic situation has to be used. This means the penstock length is not known, so a ratio of 1:5 of gross head and penstock length is assumed. Moreover, transportation distance and import taxes are assumed to be the same as for the case study. Further assumptions state the hydrological and geographical conditions are suitable for earth dam reservoir construction. Finally, it is assumed a ternary unit is used; as discussed in Section 5.4.2, there is only a slight difference in the LCoS of ternary units and binary units with a PAT, and that does not take into account the additional PV generation required. Besides, a PAT can only be modeled if the efficiency curve of the turbine operation is known. Moreover, the incoming flow is harder to control, due to the unidirectional nature of most control valves. Since the penstock cannot be split when using a binary unit, the PAT uses the same pipe for incoming and outgoing flow. This makes it difficult to use for both generating and pumping operating over a range of power requirements. It is therefore better to use a ternary unit.

Three annual demand profiles have been established to conform to the maximum PHS power output of 75, 150, 300 and 550 kW. For different heads, a system has been designed with the method and model described in this chapter. The reservoir capacity requirements and an estimation of the LCoS have been calculated, as visualized in Figures 5.27 and 5.28 respectively.

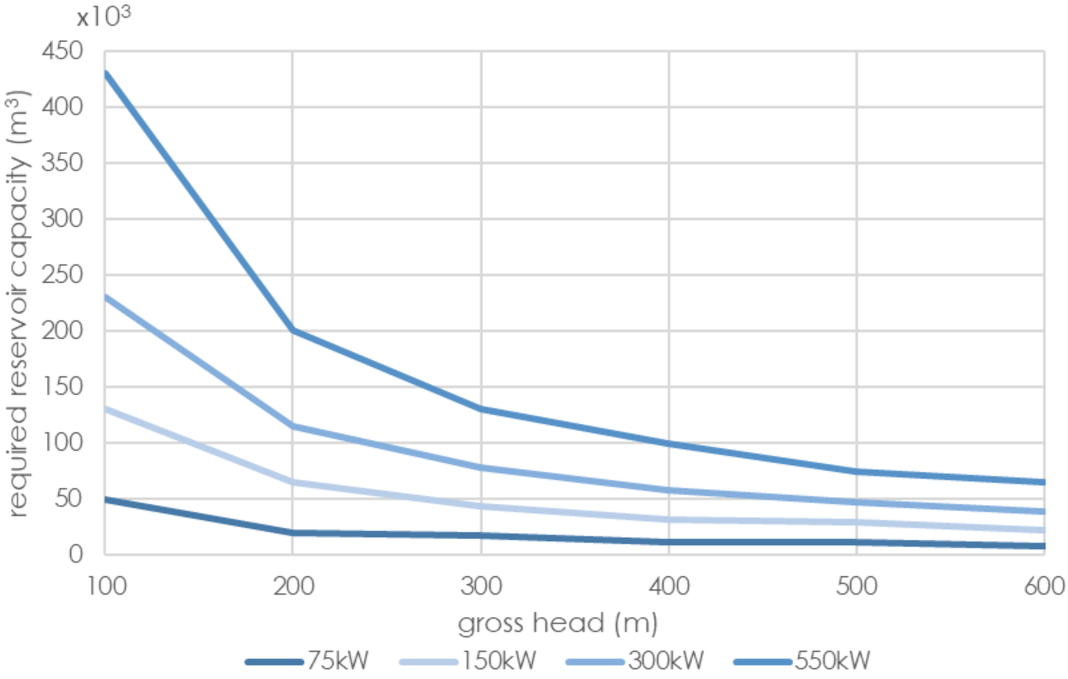


Figure 5.27: The required reservoir storage capacity (for each reservoir) for a required power output of 75kW, 150kW, 300kW and 550kW. This has been calculated for gross head differences of 100, 200, 300, 400, 500 and 600 meter.

From Figure 5.27 it becomes clear that the relationship between the gross head difference and the corresponding reservoir capacity requirements is not linear as the graph in Figure 3.2 suggests, while the energy demand does not differ with the head. The exponential decaying function of the reservoir capacity requirements can be explained because in reality different pipe types are required and the system functions differently when the head changes. This once again illustrates the need to model the system output for certain site conditions instead of relying on standard relations between these site conditions.

The ability to use earth dam reservoirs can be considered as an essential part of the economic feasibility, since the reservoir costs constitute a significant portion of the total costs. However, a larger capacity of the earth dam reservoirs leads to more complex projects, and hydrological conditions must be very advantageous to initially fill the reservoir and balance the water level. Therefore, larger heads are preferred; from 300 meter gross head onward however, the reservoir capacity requirements decrease much less than from 100 to 300 meter.

In Figure 5.28, the LCoS for a system designed for the different demand profiles has been calculated. Several observations can be made from the outcome of the LCoS calculations. First of all, the demand profile with an output of 75kW has a significantly higher LCoS, while the 300kW and 550kW are much closer. This can be explained by the economy of scale penalty associated with PHS. Gross heads of at least 300 meters provide the best LCoS results, and for some demand profiles the LCoS even increases for heads exceeding 300 meter. This can be explained by the necessity of a Mild Steel penstock instead of a GRP penstock, due to the added hydrostatic pressure. Mild Steel is more expensive and heavier in weight, which adds transportation and installation costs and difficulties.

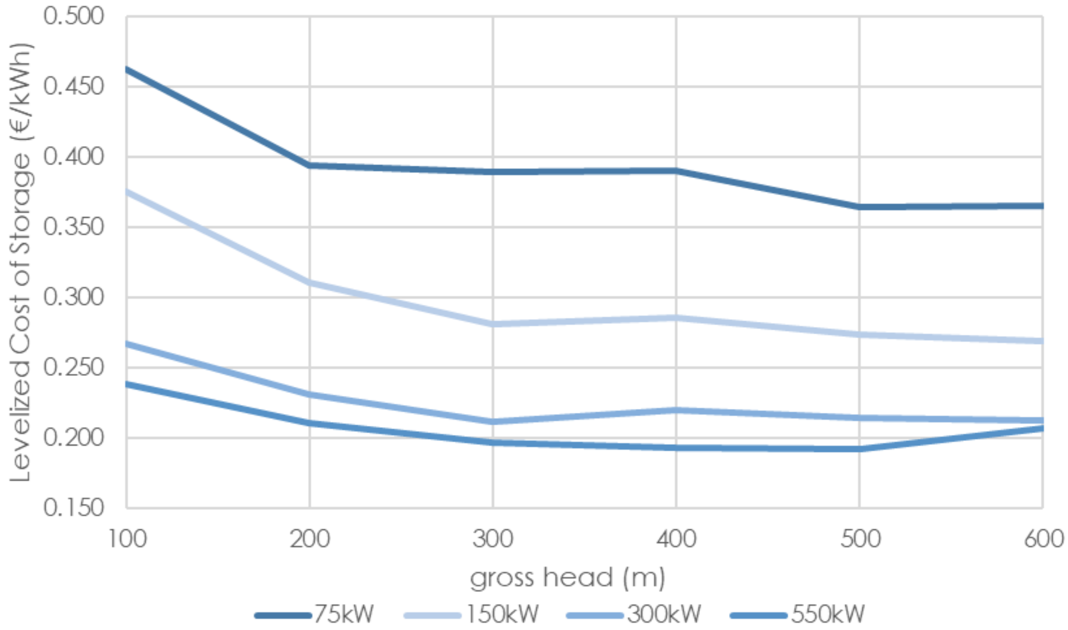


Figure 5.28: The calculated LCoS for a HESS employing PHS with a required power output of 75kW, 150kW, 300kW and 550kW. This has been calculated for gross head differences of 100, 200, 300, 400, 500 and 600 meter.

From the results of this research, it can be concluded that PHS in remote mini-grids in low-resource regions can very well be feasible. This is provided that the geographical and hydrological conditions are sufficient; a gross head of at least 200-300 meter and sufficient rainfall are required. Furthermore, even with a gross head of at least 300 meter, very low mini-grid energy requirements lead to a excessive LCoS which can not compete with battery energy storage. From a energy storage system with a power output of at least 150kW the LCoS becomes feasible. The range of site conditions determined to be ideal is thus a gross head exceeding 250 meter, preferably around 300 meter, and a maximum power output requirement of at least 150kW.

6
Conclusions

Throughout this research, the research sub-question have been answered in an effort to ultimately answer the main research question. In this conclusion, the answers to the research questions are presented. Subsequently, recommendations for future work are presented.

6.1. Research findings

The main research question of this thesis is how the technical, economical and socio-cultural feasibility of Pumped Hydro Storage,as a means of energy storage in a remote and isolated mini-grid in low-resource regions, be assessed. This is answered with the aid of three research sub-questions.

Which design criteria need to be considered when employing a Pumped Hydro Storage(PHS) system in an isolated mini-grid in a low-resource setting? Since an isolated mini-grid in a low resource setting, specifically rural sub-Saharan Africa, is considered, it is important to establish which challenges are present. These challenges have led to a program of requirements, a list of design criteria the complete design of a PHS plant in this setting has to satisfy in order to be successful.

Firstly, the technical challenges and associated design criteria determine the required operating range of the PHS plant. Additionally, the quality of power and supply in the mini-grid must be ensured by the PHS plant, as this builds trust, allows for added revenue for the mini-grid and attracts anchor customers. The availability of components of the PHS plant in Sub-Saharan African regions was also assessed, to found out whether these components are available and what the radius of availability is. Here it was concluded that while component availability does not bound the radius by itself, the high transportation costs on the continent enforce a design criterion on the system to utilize components and materials available locally. As a final technical challenge, the PHS plant should either be prepared for the arrival of the main grid, or the mini-grid should be sufficiently remotely located that this will not be an issue.

Secondly, the economic challenges indicated that electrification projects are often dependent on funding through donors or subsidies. Moreover, due to the high poverty rates for the proposed setting of remote, rural villages, costs should be reduced as much as possible. The low incomes of the designated customers combined with below-cost electricity prices in Sub-Saharan Africa makes financial viability of any electrification project difficult.

Finally, the socio-cultural challenges found that trust and acceptance from the targeted community should be gained through community involvement and participation, in all phases of the PHS plant (design, planning, implementation and operation). Furthermore, multiple recent hydropower projects were assessed. With a large part of the main contractors of these projects coming from outside the project's region, and limited education of the local population, it was concluded sufficient technical skills can not be assumed to be present locally. Therefore, the PHS system is bounded to reduce complexity where possible. There is also the challenge of theft and vandalism, caused by government inequality, crime to survive or sabotage. Apart from physical security, local ownership can prove useful as societal security to counteract this challenge. Political vertical networks and the associated corruption is another hurdle, which can be mitigated with a step-by-step implementation, requiring a scalable design. Furthermore, local practices and regulations need to be considered. Considering local practices, secondary water use is not just seen as unavoidable, but actually as an positive side-effect which can help to embed the PHS plant into the community. Finally, due to the agricultural societies present in rural SSA, any environmental and ecological impact should be avoided.

What are the implications on the holistic design of a PHS plant when taking these design criteria into consideration? The word holistic is used purposefully, since the design constitutes not only a technical design, but also a strategy on the planning, implementation and operation of a Pumped Hydro Storage plant in a remote and rural mini-grid in sub-Saharan Africa. This is divided in a technical design synthesis, which resulted in four suitable provisional designs based on the program of requirements set by the design criteria. After that, the organizational design synthesis discusses the planning, implementation and operation phases of the PHS plant.

The design synthesis listed and subsequently discarded design options for a PHS plant, based on the design criteria. For the water storage system the most suitable design options is to use earth dam reservoirs. In the case of the water conveyance system, economical constraints and the range of power output requirements determined suitable options for penstock material are GRP for low-medium head and Mild Steel for high head applications. Whether the penstock is buried or remains exposed is dependent on site-specific conditions. Finally, the powerhouse can either employ a ternary unit with a Pelton turbine or a binary unit with a Pump-As-Turbine. The configuration for the provisional technical design can be one of four alternatives, of which two are one-time installations and the other two are scalable designs.

The provisional technical design is, along with the design criteria, the basis for the synthesis of the organizational design. During the design phase, it has been established that local ownership, trust and acceptance is at the core of a successful electrification project, which results in community involvement and participation becoming the premise of the strategy for planning, implementation and operation. In the planning phase, the choice must be made whether to start with a smaller PHS plant which is later scaled up, or to wait until a more advanced electrification level and immediately implement a larger PHS system. Furthermore, the community is involved in energy need estimation and site selection, and their expectations should be managed. The implementation and operation phase ensure local ownership through community participation in the construction, installation and operation of the plant. Additionally, a organizational structure is presented which aims to take advantage of the existing hierarchical structure present in rural SSA, and shifts responsibility from the implementing organization to the community.

How does a PHS plant, with a design suited to the design criteria, function in a practical application? With suitable design options and their associated design parameters and costs established, the functional application of a PHS storage system in an isolated mini-grid could be assessed through a developed energy flow model. Due to the site-specific parameters influencing the functioning of such a system, a case study in the village of Adi Araha in Ethiopia was used for assessment. Two scenarios were established to give a greater range of power requirements leading to a broader understanding of the feasibility of the system. After setting up parameter and constraints for an energy flow model, an Energy Management Strategy was used to obtain the outputs of 2 options for each scenario. Subsequently, an analysis of the technical and economic feasibility of the system for the case study was performed. The economic analysis led to the conclusion that GRP pipes have a significant benefit regarding the costs, due to lower weight, which reduces transportation and installation costs compared to Mild Steel pipes. Furthermore, the technical and economic analysis combined showed that PATs some economical advantage over conventional turbines for a PHS system, despite their shorter lifetime and limited operating range. Finally, the financial impact of using a scalable design is assessed. To further assess the feasibility of the system in the case study, it is discussed to which degree the design challenges are addressed. This led to the conclusion that Pumped Hydro Storage is indeed technically, economically and socially feasible for isolated mini-grids in low-resource settings, albeit the costs of a battery energy storage system will rapidly become cheaper in the coming years.

Employing the model to reach a general feasibility conclusion has led to the outcome of certain site specific condition requirements to make further inquiry worthwhile for a designated site. These are gross head requirements of at least 250 meter, and a preference of around 300 meter. Furthermore, a demand profile requiring a maximum power output from the PHS of less than 150kW is economically unfeasible.

The answers to the above research sub-question ultimately lead to a result regarding the main research question.

How can the technical, economical and socio-cultural feasibility of Pumped Hydro Storage, as a means of energy storage in a remote and isolated mini-grid in low-resource regions, be assessed? The technical, economical and socio-cultural feasibility of using PHS to store energy, specifically for the setting of isolated mini-grids in regions where many people still lack access to electricity due to a scarcity of resources, knowledge and development, can be assessed through the framework developed throughout this thesis.

The framework presents insights on which local factors should be accounted for and how to tackle local challenges. These insights can be used to assess a potential site for PHS plant implementation. The framework goes through each phase; firstly, for the design phase, the design criteria associated with the challenges determine whether the local circumstances allow for the implementation of a PHS plant. Subsequently, for the planning, implementation and operation phase, insights gathered in this thesis on increasing the chance of successful PHS plant implementation are presented.

Starting at the design phase, the necessity for the presence of several local circumstances leads to an initial delimitation at a proposed site, whether the proposal to use a PHS plant for energy storage should be further assessed or should be abandoned. With challenges established, the technical design synthesis, the organizational design synthesis, the case study and the subsequent discussion, where the developed model was employed for insight into the general feasibility, have determined several local circumstances are required. These local circumstances assess the technical, the economical and the socio-cultural feasibility. Without the presence of the following circumstances, successful operation of a PHS plant in the intended setting is unlikely and a further pursuit of installing a PHS plant is not recommended:

- Geographic conditions: a minimum gross head of 200 meter is required, to obtain an acceptable LCoS. However, a gross head of 250 to 300 meter is recommended, allowing for the use of a GRP penstocks. Moreover, an angle of 11 degrees or more is needed for the slope on which the penstock is installed (which corresponds to a head-length ratio of 1:5). Furthermore, the soil of the designated reservoir sites should be suitable for the construction of earth dam reservoirs, which significantly reduce the costs of the total system. There should also be sufficient rainfall to fill up either on of the reservoirs, and to maintain the water level. Lastly, the proposed village for mini-grid installation should be thus far removed from the main grid that grid extension is either economically unfeasible or can not be realised at all.
- Demand: the maximum power the isolated mini-grid requires from the storage system should be at least 150 kilowatt, corresponding to a annual energy requirement of 200 Megawatt-hour. Mini-grids which require smaller energy storage system than this are likely to benefit more from a Battery Energy Storage System than from a small PHS plant.
- Local technical skills: while the installation does not require local engineers, there should be local inhabitants available who are willing to assist in the construction and take responsibility for the day-to-day operation of the plant. While these should be paid employees, the successful operation and longevity of the plant is determined by these trained technicians, so when no motivated villagers can be found to take on this role the project is likely to fail. Moreover, annual inspections and advanced maintenance by professional engineers should be carried out throughout the lifetime of the plant. This means such a energy storage system can not simply be installed and

subsequently left unattended; a continued effort by the mini-grid operator is required in order to have a well-functioning storage system.

- Component availability: it must be possible to transport the required components, mostly the electro-mechanical equipment and pipes for the penstock, to the target site.

- Community: considering the construction of a PHS plant, even on a small scale, alters the terrain and requires land, the community for which it is intended should approve of the installation, and willing to be involved in each phase of the project. Even more so, their participation in the installation and maintenance of the PHS plant plays an important role in the success of the project, since it creates a sense of local ownership. The community should therefore be aware of the implications as well as the limitations of the PHS system, and preferably embrace it as a communal responsibility; if the entire community is on the same page, conflicts can be avoided. A cooperating, willing and cohesive community is thus an essential local factor.

If these circumstances are present at a site, further investigation into the feasibility should be pursued. This analysis is simplified by using the provisional techincal design for a PHS plant suggested in this research, which aims to satisfy the design criteria posed by the local challenges. This layout for a small-scale PHS power plant is visualized in Figure 6.1. Here, either one or both reservoirs can be used for secondary water usage. For the powerhouse configuration, a ternary unit with a Pelton turbine or a binary unit with a PAT is recommended. Whether the design is implemented through a one-time installation or made scalable, depends on the site-specific conditions but also on the preference of the implementing organization. Both options have their benefits, which have been discussed in this research. This discussion assists in making a choice for the implementation.

To further assess the feasibility of a PHS plant, data on the required demand profile can be used in the developed energy flow model to size the Hybrid Energy Storage System. Finally, local data on the component and labour prices and availability, together with transportation distances and costs, can be obtained and combined with the capital cost equations presented in this research, to make an initial assessment of the financial viability.

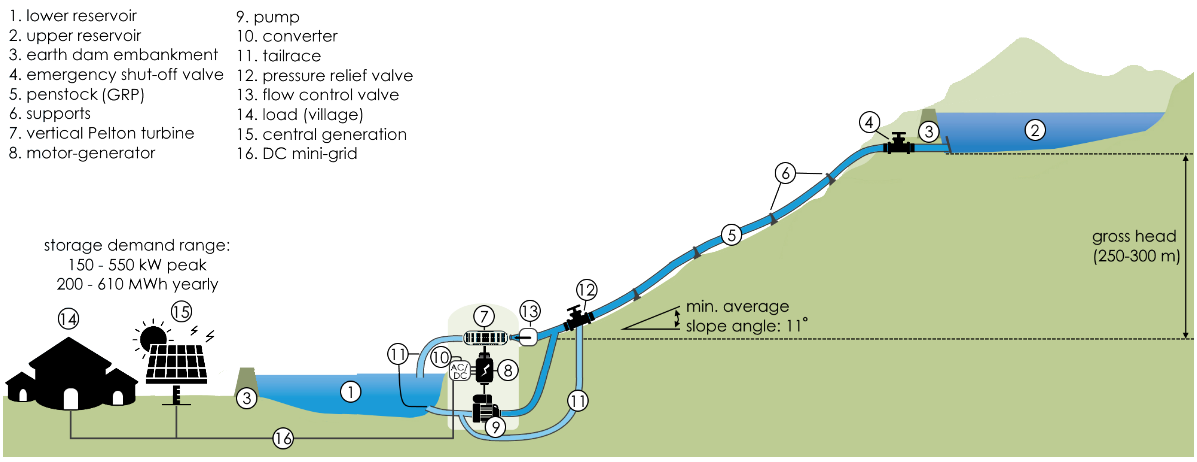


Figure 6.1: Visualisation for the final design conditions for a feasible Pumped Hydro Storage plant for an isolated DC mini-grid.

The planning phase should already start at the beginning of the electrification project. To properly embed into the community, DC Opportunities has to work to understand the social structure present, acquire their trust and acceptance, and start capacity building in preparation for the mini-grid including the PHS plant. Moreover, the planning phase contains expectation management, to prepare the community for the abilities and limitations of the system, and the importance of their role in the installation, operation and maintenance of the PHS plant.

The next phase is the implementation phase, where DC Opportunities should strive to involve the local population as much as possible in the installation of the PHS plant, and establish a organizational structure for the PHS plant using the existing power structure of the community, with built in check and balances. This organizational structure is integrated with the local community-based utility managing the mini-grid, the board of which is elected. Since the community is more aware of the needs of its own members, the community-based utility becomes the responsible party for the energy and water management; the division of water to be used for secondary water use must be ratified through a public meeting of the entire community, as a means of avoiding corruption or local elite favoritism.

Together with the community-based utility and guidance and training supplied by DC Opportunities, an operational structure is established. Through this, the community becomes responsible for operation, maintenance and repairs, giving them control and a sense of ownership of the complete system.

6.2. Future work and recommendations

This thesis aims to conduct a general feasibility study, which is just the first step in the actual implementation of a technology. A preliminary analysis is conducted with this research, making the next logical step market research. The energy flow model developed in this research can assist with the market research, but several improvements can be made to get more accurate results.

Local research This research conducted a case study analysis, based on remotely obtained information and limited information acquired from a field visit not directly related to the implementation of a small-scale PHS plant. Moreover, the challenges presented in this thesis are general for the sub-Saharan African region, but locally additional challenges might present themselves. Therefore, in order to get a more reliable overview of the situation, an additional field visit would be required to acquire more accurate information on the following:

- Local demand, and development and electrification rate.
- Technical and engineering skills present.
- willingness of the community to participate in the proper functioning of the PHS plant.
- local prices and costs.
- the current planning of grid extension by the governments.
- geographical and hydrological conditions.
- Social structure within the community, to adjust the organizational structure to local conditions. Moreover, a community can extend beyond the borders of a village, so this needs to be assessed. Finally, the role of women within the social structure, to develop a method for inclusion.
- Inter-communal relations, to determine the relation of the targeted community with neighbouring communities.
- The political situation and the view of the government regarding off-grid electrification and hydropower. Local support from the government and institutions can greatly benefit an electrification project.

Since mini-grids are the third step in the electrification process, much of this information can be obtained throughout the time of implementation of the first two electrification steps. This gradual process will make a more thorough analysis of the feasibility of a PHS based storage system more reliable. A more situational study can also expand the impact of choosing either a scalable or an one-time installation design.

Model improvements As for the energy flow model, as with any model several assumptions have been made. However, one assumption which could affect the output to a significant degree, is the constant of pump efficiency over its operating range. However, the addition of the turbine efficiency adapting to the flow rate is already a huge improvement over the simulation in HOMER Pro. Additionally, the whole Energy Management Strategy is more advanced.

Furthermore, considering the model improvements, the energy flow model could be combined with a generation sizing model to get more accurate results on the entire mini-grid architecture. This could even be extended to include an optimization of the entire mini-grid. Moreover, the EMS could be adjusted to allow for a smaller pump or PAT to be added for the smaller power requirements. This could improve the efficiency of the entire system, leading to smaller capacity requirements for the reservoirs. Finally, a more in depth approach to simulating a scalable system should be established.

Design It would be interesting to explore a standardized design for a scalable PHS plant, which uses modular components which can be combined for any situation. If implementation is standardized, this will greatly reduce costs for installing a PHS system at different locations.

Bibliography

[1] US ACE. General design and construction considerations for earth and rock-fill dams. *Engineer Manual*, 130, 2004.

[2] Power Africa. Off-grid solar market assessment: Ethiopia. Technical report, USAID, 2019.

[3] Tarang Agarwal. Review of pump as turbine (pat) for micro-hydropower. *International Journal of Emerging Technology and Advanced Engineering*, 2(11):163–169, 2012.

[4] Japan International Cooperation Agency. *Guideline and manual for hydropower development*. Electric Power Development Co., Ltd., 2011.

[5] Helene Ahlborg and Martin Sjöstedt. Small-scale hydropower in africa: Socio-technical designs for renewable energy in tanzanian villages. *Energy Research & Social Science*, 5:20–33, 2015.

[6] Junaid Ahmad, Stephen Commins, Shantayanan Devarajan, Deon Filmer, Jeffrey Hammer, Lant Pritchett, Ritva Reinikka, Shekhar Shah, and Agnès Soucat. World development report 2004: Making services work for poor people. Technical report, The World Bank, 2003.

[7] Abdul Hai Alami. *Pumped Hydro Storage*, pages 51–65. Springer International Publishing, Cham, 2020. ISBN 978-3-030-33788-9. doi: 10.1007/978-3-030-33788-9_6. URL https://doi.org/10.1007/978-3-030-33788-9_6.

[8] Richter Alexander. Proposed feed-in-tariff to help spur private development by ipp in ethiopia, Aug 2011. URL https://www.thinkgeoenergy.com/proposed-feed-in-tariff-to-help-spur-private-development-by-ipp-in-ethiopia/.

[9] Latifa Alimi, Kamel Chaoui, Abdelaziz Amirat, and Salaheddine Azzouz. Study of reliability index for high-density polyethylene based on pipe standard dimension ratio and fracture toughness limits. *The International Journal of Advanced Manufacturing Technology*, 96(1-4):123–136, 2018.

[10] Ancas Ana Diana, M. Profire, I. Cirstolovean, M. Hornet, and G. Cojocaru. Lifetime glass reinforced plastic pipes by measuring the stiffness. *Journal of Applied Engineering Sciences*, 8: 7–12, 05 2018. doi: 10.2478/jaes-2018-0001.

[11] JS Anagnostopoulos and DE Papantonis. Simulation and size optimization of a pumped–storage power plant for the recovery of wind-farms rejected energy. *Renewable Energy*, 33(7):1685–1694, 2008.

[12] A. Anderson, P. Loomba, I. Orajaka, J. Numfor, S. Saha, S. Janko, N. Johnson, R. Podmore, and R. Larsen. Empowering smart communities: Electrification, education, and sustainable entrepreneurship in ieee smart village initiatives. *IEEE Electrification Magazine*, 5(2):6–16, 2017.

[13] Michael A Anderson. Influence of pumped-storage hydroelectric plant operation on a shallow polymictic lake: Predictions from 3-d hydrodynamic modeling. *Lake and Reservoir Management*, 26(1):1–13, 2010.

[14] André Assunção, Pedro S. Moura, and Aníbal T. de Almeida. Technical and economic assessment of the secondary use of repurposed electric vehicle batteries in the residential sector to support solar energy. *Applied Energy*, 181:120 – 131, 2016. ISSN 0306-2619. doi: https://doi.org/10.1016/j.apenergy.2016.08.056.

[15] David Atkin and Dave Donaldson. Who's getting globalized? the size and implications of intranational trade costs. Technical report, National Bureau of Economic Research, 2015.

[16] Central Statistical Authority. 2007 population and housing census of ethiopia. Technical report, CSA, Addis Abeba, Ethiopia, 2012.

[17] Seleshi Bekele Awulachew, Aster Denekew Yilma, Makonnen Loulseged, Willibald Loiskandl, Mekonnen Ayana, and Tena Alamirew. *Water resources and irrigation development in Ethiopia*, volume 123. Iwmi, 2007.

[18] Scott N Backhaus, Gregory William Swift, Spyridon Chatzivasileiadis, William Tschudi, Steven Glover, Michael Starke, Jianhui Wang, Meng Yue, and Donald Hammerstrom. Dc microgrids scoping study. estimate of technical and economic benefits. Technical report, Los Alamos National Lab.(LANL), Los Alamos, NM (United States), 2015.

[19] Marie-Caroline Badjeck, Allison Perry, Silvia Renn, David Brown, and Florence Poulain. The vulnerability of fishing-dependent economies to disasters. *FAO Fisheries and Aquaculture Circular*, (C1081):I, 2015.

[20] Hassan M Badr and Wael H Ahmed. *Pumping machinery theory and practice*. John Wiley & Sons, 2015.

[21] World Bank. Ease of doing business rankings, May 2019. URL https://www.doingbusiness.org/en/rankings?region=sub-saharan-africa.

[22] World Bank. Doing business: Measuring business regulations, 2020. URL https://www.doingbusiness.org/en/data/exploreeconomies/ethiopia/.

[23] Edward Barbour, IA Grant Wilson, Jonathan Radcliffe, Yulong Ding, and Yongliang Li. A review of pumped hydro energy storage development in significant international electricity markets. *Renewable and Sustainable Energy Reviews*, 61:421–432, 2016.

[24] Şağdan Başkaya, E Başkaya, and A Sari. The principal negative environmental impacts of small hydropower plants in turkey. *African Journal of Agricultural Research*, 6(14):3284–3290, 2011.

[25] Marc Beaudin, Hamidreza Zareipour, Anthony Schellenberg, and William Rosehart. Chapter 1 - energy storage for mitigating the variability of renewable electricity sources. In Pengwei Du and Ning Lu, editors, *Energy Storage for Smart Grids*, pages 1 – 33. Academic Press, Boston, 2015. ISBN 978-0-12-410491-4. doi: https://doi.org/10.1016/B978-0-12-410491-4.00001-4.

[26] SA Berezinskii, AV Egorov, VS Lashmanova, and IA Polinkovskii. Design of penstocks of pumped-storage stations. *Hydrotechnical Construction*, 19(4):180–187, 1985.

[27] Gebremedhin Berhane, Tesfamichael Gebreyohannes, Kristine Martens, and Kristine Walraevens. Overview of micro-dam reservoirs (mdr) in tigray (northern ethiopia): Challenges and benefits. *Journal of African Earth Sciences*, 123:210–222, 2016.

[28] Tanguy Bernard. Impact analysis of rural electrification projects in sub-saharan africa. *The World Bank Research Observer*, 27(1):33–51, 2012. ISSN 02573032, 15646971.

[29] M. Bhatia, N. Angelou, E. Portale, R. Soni, M. Wilcox, and D. Corbyn. Defining and measuring access to energy for socio-economic development, 2013.

[30] Subhes C Bhattacharyya. Electrification experiences from sub-saharan africa. In *Rural electrification through decentralised off-grid systems in developing countries*, pages 131–156. Springer, 2013.

[31] Subhes C. Bhattacharyya and Debajit Palit. *Mini-grids for rural electrification of developing countries: analysis and case studies from South Asia*. Springer, 2014.

[32] Haroon Bhorat, Ravi Kanbur, and Benjamin Stanwix. Minimum wages in sub-saharan africa: a primer. *The World Bank Research Observer*, 32(1):21–74, 2017.

[33] Mark Blackden, Sudharshan Canagarajah, Stephan Klasen, and David Lawson. Gender and growth in sub-saharan africa: issues and evidence. In *Advancing Development*, pages 349–370. Springer, 2007.

[34] Eline Boelee, Philippe Cecchi, and André Koné. *Health impacts of small reservoirs in Burkina Faso*, volume 136. Iwmi, 2010.

[35] Lucius Botes and Dingie Van Rensburg. Community participation in development: nine plagues and twelve commandments. *Community development journal*, 35(1):41–58, 2000.

[36] Stéphanie Bouckaert, Tae-Yoon Kim, and Kieran McNamara. Africa energy outlook 2019. Technical report, International Energy Agency, 2019.

[37] Emmanuel Branche. The multipurpose water uses of hydropower reservoir: the share concept. *Comptes Rendus Physique*, 18(7-8):469–478, 2017.

[38] Alan Colin Brent and David E. Rogers. Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the african context. *Renewable Energy*, 35(1): 257–265, 2010. doi: 10.1016/j.renene.2009.03.028.

[39] Mitja Brilly, Simon Rusjan, Matjaž Mikoš, Anja Horvat, Andrej Kryžanowski, Simon Schnabl, Andrej Vidmar, Maja Koprivšek, Thom Bogaard, Giuliano Di Baldassarre, et al. *Critical review of structural measures for water-related risks*. KULTURisk, 2011.

[40] Glenn Brown. The history of the darcy-weisbach equation for pipe flow resistance. *Proc. Environmental and Water Resources History*, 38, 10 2002. doi: 10.1061/40650(2003)4.

[41] C Bueno and Jose A Carta. Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the canary islands. *Renewable and sustainable energy reviews*, 10(4):312–340, 2006.

[42] Raymond H Byrne, Tu A Nguyen, David A Copp, Babu R Chalamala, and Imre Gyuk. Energy management and optimization methods for grid energy storage systems. *IEEE Access*, 6:13231–13260, 2017.

[43] G Caralis and A Zervos. Analysis of the combined use of wind and pumped storage systems in autonomous greek islands. *IET Renewable Power Generation*, 1(1):49–60, 2007.

[44] G Caralis, K Rados, and A Zervos. On the market of wind with hydro-pumped storage systems in autonomous greek islands. *Renewable and Sustainable Energy Reviews*, 14(8):2221–2226, 2010.

[45] Gero Carletto, Katia Covarrubias, Benjamin Davis, Marika Krausova, Kostas G Stamoulis, Paul C Winters, and Alberto Zezza. Rural income generating activities in developing countries: Reassessing the evidence. *eJADE: electronic Journal of Agricultural and Development Economics*, 4(853-2016-56112):146–193, 2007.

[46] European Commission Joint Research Centre, Jan 2016. URL https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html.

[47] Haisheng Chen, Thang Ngoc Cong, Wei Yang, Chunqing Tan, Yongliang Li, and Yulong Ding. Progress in electrical energy storage system: A critical review. *Progress in Natural Science*, 19 (3):291 – 312, 2009. doi: https://doi.org/10.1016/j.pnsc.2008.07.014.

[48] Jack T. Chow. Small earth dam technical assessment report. Technical report, Karamoja Productive Asset Program (KPAP), 2010.

[49] Luc J. Christiaensen and Lionel Demery. *Households in Rural Africa Still Rely on Agriculture*. World Bank, 2017.

[50] Wesley J Cole and Allister Frazier. Cost projections for utility-scale battery storage. Technical report, National Renewable Energy Lab (NREL), 2019.

[51] Hydropower Committee. *Civil engineering guidelines for planning and designing hydroelectric developments*. American Society of Civil Engineers, 1989.

[52] Devlink Resources Consultants. Environmental impact assessment study report for the proposed daystar dam project. Technical report, Daystar University Kenya, 2016.

[53] Bill Cooke and Uma Kothari. *Participation: The new tyranny?* Zed books, 2001.

[54] Gerard M. Crawley. *Energy storage*. World Scientific Publishing Co, 2017.

[55] William K. Darley and Charles Blankson. African culture and business markets: implications for marketing practices. *Journal of Business & Industrial Marketing*, 23(6):374–383, 2008. doi: 10.1108/08858620810894427.

[56] Peter Darvas, Shang Gao, Yijun Shen, and Bilal Bawany. *Sharing Higher Education's Promise beyond the Few in Sub-Saharan Africa*. The World Bank, 2017.

[57] Benjamin Davis, Pamela Pozarny, et al. Qualitative research and analyses of the economic impacts of cash transfer programmes in sub-saharan africa. Technical report, Food and Agriculture Organization of the United Nations, 2012.

[58] Benjamin Davis, Stefania Di Giuseppe, and Alberto Zezza. Are african households (not) leaving agriculture? patterns of households' income sources in rural sub-saharan africa. *Food policy*, 67:153–174, 2017.

[59] Gertjan De Graaf and Luca Garibaldi. The value of african fisheries. *FAO Fisheries and Aquaculture Circular*, (1093), 2014.

[60] Uwe Deichmann, Craig Meisner, Siobhan Murray, and David Wheeler. The economics of renewable energy expansion in rural sub-saharan africa. *Energy Policy*, 39(1):215 – 227, 2011. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2010.09.034.

[61] Stefan Dercon. Rural poverty: Old challenges in new contexts. *The World Bank Research Observer*, 24(1):1–28, 2009.

[62] Ranjit Deshmukh, Juan Pablo Carvallo, and Ashwin Gambhir. Sustainable development of renewable energy mini-grids for energy access: A framework for policy design. Technical report, Lawrence Berkeley National Laboratory, 04 2013. URL https://isswprod.lbl.gov/library/view-docs/private/output/rpt82612.PDF.

[63] Dinkelman, T. The effects of rural electrification on employment: New evidence from south africa, August 2008.

[64] Weiqiang Dong, Yanjun Li, and Ji Xiang. Optimal sizing of a stand-alone hybrid power system based on battery/hydrogen with an improved ant colony optimization. *Energies*, 9(10):785, 2016.

[65] Tomislav Dragicevic, Pat Wheeler, and Frede Blaabjerg. *DC distribution systems and microgrids*. The Institution of Engineering and Technology, 2018.

[66] Guilherme de Oliveira e Silva and Patrick Hendrick. Pumped hydro energy storage in buildings. *Applied energy*, 179:1242–1250, 2016.

[67] Anton Eberhard, Vivien Foster, Cecilia Briceño-Garmendia, Fatimata Ouedraogo, Daniel Camos, and Maria Shkaratan. Underpowered: the state of the power sector in sub-saharan africa. Technical report, World Bank, Washington, DC, 2008.

[68] Jonas M Eder, Christopher F Mutsaerts, and Pranpreya Sriwannawit. Mini-grids and renewable energy in rural africa: How diffusion theory explains adoption of electricity in uganda. *Energy Research & Social Science*, 5:45–54, 2015.

[69] Mohammad Faisal, Mahammad A Hannan, Pin Jern Ker, Aini Hussain, Muhamad Bin Mansor, and Frede Blaabjerg. Review of energy storage system technologies in microgrid applications: Issues and challenges. *Ieee Access*, 6:35143–35164, 2018.

[70] Joshua W Faulkner, Tammo Steenhuis, Nick van de Giesen, Marc Andreini, and Jens R Liebe. Water use and productivity of two small reservoir irrigation schemes in ghana's upper east region. *Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage*, 57(2):151–163, 2008.

[71] Gao Fei, Kang Ren, Cao Jun, and Yang Tao. Primary and secondary control in dc microgrids: a review. *Journal of Modern Power Systems and Clean Energy*, 7(2):227–242, 2019.

[72] Stephen E Fick and Robert J Hijmans. Worldclim 2: new 1-km spatial resolution climate surfaces for global land areas. *International journal of climatology*, 37(12):4302–4315, 2017.

[73] Karin Flury and Rolf Frischknecht. Life cycle inventories of hydroelectric power generation. *ESU-Services, Fair Consulting in Sustainability, commissioned by Oko-Institute eV*, pages 1–51, 2012.

[74] Jimeno A Fonseca and Arno Schlueter. Novel approach for decentralized energy supply and energy storage of tall buildings in latin america based on renewable energy sources: Case study–informal vertical community torre david, caracas–venezuela. *Energy*, 53:93–105, 2013.

[75] Franklin and Andrews. *Spon's African construction costs handbook*. Taylor and Francis, 2005.

[76] Michael Franz, Nico Peterschmidt, Michael Rohrer, and Bozhil Kondev. Mini-grid policy toolkit. Technical report, European Union Energy Initiative Partnership Dialogue Facility (EUEI PDF), 2014.

[77] Lars Frenning. *Pump life cycle costs: A guide to LCC analysis for pumping systems*. Hydraulic Institute, 2001.

[78] Stephie Fried and David Lagakos. Rural electrification, migration and structural transformation: Evidence from ethiopia. Technical report, International Growth Centre, 1 2017. E-32301-ETH-1.

[79] Emma Frosina, Dario Buono, and Adolfo Senatore. A performance prediction method for pumps as turbines (pat) using a computational fluid dynamics (cfd) modeling approach. *Energies*, 10 (1):103, 2017.

[80] Marian Gaiceanu, Iulian Nicusor Arama, and Iulian Ghenea. *DC Microgrid Control*, pages 357–380. Springer International Publishing, 2020. ISBN 978-3-030-23723-3. doi: 10.1007/978-3-030-23723-3_14.

[81] Benno Galjart. Participatory development projects; some conclusions from research. *Sociologia Ruralis*, 21(1):142–159, 1981.

[82] David Wenzhong Gao. *Energy storage for sustainable microgrid*. Elsevier, 2015.

[83] Mirco Gaul, Fritz Kölling, and Miriam Schröder. Policy and regulatory framework conditions for shp in sub-saharan africa. Technical report, Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, 07 2010.

[84] Madhur Gautam. Managing drought in sub-saharan africa: Policy perspectives. Technical report, International Association of Agricultural Economists, 2006.

[85] Gebrehaweria Gebregziabher, Regassa E Namara, and Stein Holden. Poverty reduction with irrigation investment: An empirical case study from tigray, ethiopia. *Agricultural water management*, 96(12):1837–1843, 2009.

[86] Ahmad Ghasemi and Mehdi Enayatzare. Optimal energy management of a renewable-based isolated microgrid with pumped-storage unit and demand response. *Renewable energy*, 123: 460–474, 2018.

[87] R Gommes and F Petrassi. Rainfall variability and drought in sub-saharan africa. *Food and Agriculture Organization of the United Nations*, 1996.

[88] J.L. Gordon and D.G. Murray. Material selection for penstocks. *Hydro Review*, 1985.

[89] Grogan, L. and Sadanand, A. Electrification and the household, 2008.

[90] Andritz Group. Pumps: energy efficient in forward and reverse mode, 2019.

[91] Andritz Group. Small and mini hydropower solutions, 2019. URL https://www.andritz.com/products-en/group/markets/small-mini-hydropower-plants.

[92] AVK Group. Avk product offering and gross price list 2020, 2020.

[93] Independent Evaluation Group. World bank group support to electricity access, fy2000-2014, 2014.

[94] World Bank. Independent Evaluation Group. *World Bank Assistance to Agriculture in Sub-Saharan Africa: An IEG Review*. World Bank Publications, 2007.

[95] Dawit Diriba Guta and Jan Borner. Energy security, uncertainty, and energy resource use option in ethiopia: A sector modelling approach. *International Journal of Energy Sector Management*, 11:91–117, Apr 2017. doi: 10.2139/ssrn.2637865.

[96] Timothy G Gutowski, Sahil Sahni, Julian M Allwood, Michael F Ashby, and Ernst Worrell. The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 371(1986):20120003, 2013.

[97] Skjalg E Haaland. Simple and explicit formulas for the friction factor in turbulent pipe flow. *Journal of Fluids Engineering*, 105(1):89–90, 1983.

[98] Ioannis Hadjipaschalis, Andreas Poullikkas, and Venizelos Efthimiou. Overview of current and future energy storage technologies for electric power applications. *Renewable and Sustainable Energy Reviews*, 13(6):1513 – 1522, 2009. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2008.09.028.

[99] Eyasu Yazew Hagos. *Development and management of irrigated lands in Tigray, Ethiopia*. Taylor & Francis Group plc, London, UK, 2005.

[100] John Harriss. *Depoliticizing Development: The World Bank and Social Capital*. Anthem Press, 01 2002.

[101] Hans Hartung, Emmanuel Michael Biririza, Wycliff Jagwe, and Florian Lenz. Advanced scoping for technical capacity building on small hydropower in east africa. Technical report, Africa-EU Renewable Energy Cooperation Programme (RECP), 2015.

[102] Stephen Hodgson. *Modern water rights: theory and practice*. Number 92. Food & Agriculture Organization of the Unied Nations (FAO), 2006.

[103] R. Holland, L. Perera, T. Sanchez, and R. Wilkinson. Decentralised rural electrification: the critical success factors. *Refocus*, 2(6):28–31, 2001.

[104] Guy Howard, Jamie Bartram, Sanitation Water, World Health Organization, et al. Domestic water quantity, service level and health. Technical report, World Health Organization, 2003.

[105] Zechun Hu. *Energy Storage for Power System Planning and Operation*. John Wiley & Sons, 2020.

[106] IEA. Energy access outlook. Technical report, IEA Publications, France, 2017.

[107] IEA. World energy outlook. Technical report, IEA Publications, France, 2018.

[108] International Energy Agency (IEA). Africa energy outlook: A focus on energy prospects in sub-saharan africa. *World Energy Outlook Special Report, Paris*, 2014.

[109] Patrick Edobor Igbinovia. *Oil thefts and pipeline vandalization in Nigeria*. Safari Books Ltd., 2014.

[110] Eugene CX Ikejemba and Peter C Schuur. Analyzing the impact of theft and vandalism in relation to the sustainability of renewable energy development projects in sub-saharan africa. *Sustainability*, 10(3):814, 2018.

[111] Eugene C.x. Ikejemba, Peter B. Mpuan, Peter C. Schuur, and Jos Van Hillegersberg. The empirical reality & sustainable management failures of renewable energy projects in sub-saharan africa (part 1 of 2). *Renewable Energy*, 102:234–240, 2017. doi: 10.1016/j.renene.2016.10.037.

[112] Infinergia. Mini-grids for village electrification: Industry and african & asian markets analysis—2020 edition. Technical report, Infinergia Consulting, 2019.

[113] Rocky Mountain Institute. It takes a village: Ethiopia builds on global minigrid experience, Jan 2020. URL https://rmi.org/it-takes-a-village-ethiopia-builds-on-global-minigrid-experience/.

[114] International Renewable Energy Agency (IRENA). *Biomass Potential in Africa*. IRENA, 2013.

[115] IREA Irena. Renewable energy technologies: Cost analysis series. *Concentrating solar power*, 2012.

[116] Rakib Islam, Iqbal Husain, Abbas Fardoun, and Kevin McLaughlin. Permanent magnet synchronous motor magnet designs with skewing for torque ripple and cogging torque reduction. In *2007 IEEE Industry Applications Annual Meeting*, pages 1552–1559. IEEE, 2007.

[117] Sanjay V Jain and Rajesh N Patel. Investigations on pump running in turbine mode: A review of the state-of-the-art. *Renewable and sustainable energy reviews*, 30:841–868, 2014.

[118] F.S. Javadi, B. Rismanchi, M. Sarraf, O. Afshar, R. Saidur, H.W. Ping, and N.A. Rahim. Global policy of rural electrification. *Renewable and Sustainable Energy Reviews*, 19:402 – 416, 2013. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2012.11.053. URL http://www.sciencedirect.com/science/article/pii/S1364032112006673.

[119] Verena Jülch. Comparison of electricity storage options using levelized cost of storage (lcos) method. *Applied Energy*, 183:1594 – 1606, 2016. ISSN 0306-2619. doi: https://doi.org/10.1016/j.apenergy.2016.08.165.

[120] JK Kaldellis, M Kapsali, and KA Kavadias. Energy balance analysis of wind-based pumped hydro storage systems in remote island electrical networks. *Applied energy*, 87(8):2427–2437, 2010.

[121] M Kapsali, JS Anagnostopoulos, and JK Kaldellis. Wind powered pumped-hydro storage systems for remote islands: a complete sensitivity analysis based on economic perspectives. *Applied energy*, 99:430–444, 2012.

[122] Stephen Karekezi and Waeni Kithyoma. Renewable energy strategies for rural africa: is a pv-led renewable energy strategy the right approach for providing modern energy to the rural poor of sub-saharan africa? *Energy policy*, 30(11-12):1071–1086, 2002.

[123] Dimitris Al Katsaprakakis, Dimitris G Christakis, Kosmas Pavlopoylos, Sofia Stamataki, Irene Dimitrelou, Ioannis Stefanakis, and Petros Spanos. Introduction of a wind powered pumped storage system in the isolated insular power system of karpathos–kasos. *Applied Energy*, 97: 38–48, 2012.

[124] Chiyembekezo S Kaunda, Cuthbert Z Kimambo, and Torbjorn K Nielsen. Potential of small-scale hydropower for electricity generation in sub-saharan africa. *ISRN Renewable Energy*, 2012, 2012.

[125] Charles Kirubi, Arne Jacobson, Daniel M Kammen, and Andrew Mills. Community-based electric micro-grids can contribute to rural development: evidence from kenya. *World development*, 37 (7):1208–1221, 2009.

[126] CP Kittredge. Centrifugal pumps used as hydraulic turbines. *Journal of Engineering for Power*, 83(1):74–78, 1961.

[127] Robert M Koerner and Y Grace Hsuan. Lifetime prediction of polymeric geomembranes used in new dam construction and dam rehabilitation. In *Proceedings of State Dam Safety, Officials Conference, Lake Harmony, Pa*, pages 4–6, 2003.

[128] Amit Kohli and Karen Frenken. Evaporation from artificial lakes and reservoirs. *FAO-AQUASTAT, Rome*, page 10, 2015.

[129] V Koritarov, L Guzowski, J Feltes, Y Kazachkov, B Gong, B Trouille, P Donalek, and V Gevorgian. Modeling ternary pumped storage units. *Argonne National Laboratory*, 2013.

[130] Ioannis Kougias and Sándor Szabó. Pumped hydroelectric storage utilization assessment: Forerunner of renewable energy integration or trojan horse? *Energy*, 140:318–329, 2017.

[131] T. Kousksou, P. Bruel, A. Jamil, T. El Rhafiki, and Y. Zeraouli. Energy storage: Applications and challenges. *Solar Energy Materials and Solar Cells*, 120:59 – 80, 2014. ISSN 0927-0248. doi: https://doi.org/10.1016/j.solmat.2013.08.015.

[132] Otto Kroesen, Rudi Darson, and David Ndegwah. *Cross-cultural Entrepreneurship and Social Transformation: Capacity in the Global South*. Lambert Academic Publishing, 01 2020. ISBN 978-620-0-24843.

[133] Arun Kumar. *Civil Works– Hydraulic and Structural Design*. Alternate Hydro Energy Centre, 2013.

[134] Ravi kumar and S.K. Singal. Operation and maintenance problems in hydro turbine material in small hydro power plant. *Materials Today: Proceedings*, 2(4):2323 – 2331, 2015. ISSN 2214-7853. doi: https://doi.org/10.1016/j.matpr.2015.07.284.

[135] Ravi Kumar and SK Singal. Penstock material selection in small hydropower plants using madm methods. *Renewable and Sustainable Energy Reviews*, 52:240–255, 2015.

[136] Rajnikant Jayachand Kumbhani. *Prestressed concrete penstock design for water hammer*. PhD thesis, Massachusetts Institute of Technology, 1953.

[137] Ralph Lasage, Jeroen CJH Aerts, Peter H Verburg, and Alemu Seifu Sileshi. The role of small scale sand dams in securing water supply under climate change in ethiopia. *Mitigation and Adaptation Strategies for Global Change*, 20(2):317–339, 2015.

[138] Edward T Linacre. A simple formula for estimating evaporation rates in various climates, using temperature data alone. *Agricultural meteorology*, 18(6):409–424, 1977.

[139] Paras Loomba, Sonal Asgotraa, and Robin Podmore. Dc solar microgrids—a successful technology for rural sustainable development. In *2016 IEEE PES PowerAfrica*, pages 204–208. IEEE, 2016.

[140] Ione Loots, Marco Van Dijk, SJ Van Vuuren, JN Bhagwan, and Adriaan Kurtz. Conduit-hydropower potential in the city of tshwane water distribution system: A discussion of potential applications, financial and other benefits. *Journal of the South African Institution of Civil Engineering*, 56(3):02–13, 2014.

[141] Dahiana López-García, Adriana Arango-Manrique, and Sandra X Carvajal-Quintero. The impact of residential demand response in the active power balance of an isolated microgrid: A case of study. In *Workshop on Engineering Applications*, pages 535–547. Springer, 2018.

[142] Henry Louie. *Off-grid electrical systems in developing countries*. Springer, 2018.

[143] Paul L Lucas, Anteneh G Dagnachew, and Andries F Hof. Towards universal electricity access in sub-saharan africa. *PBL Netherlands Environmental Assessment Agency*, 2017.

[144] Tao Ma, Hongxing Yang, and Lin Lu. Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island. *Energy Conversion and Management*, 79:387–397, 2014.

[145] Tao Ma, Hongxing Yang, Lin Lu, and Jinqing Peng. Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in hong kong. *Renewable energy*, 69:7–15, 2014.

[146] Reinhard Madlener and Jan Specht. An exploratory economic analysis of underground pumped-storage hydro power plants in abandoned coal mines. 2013.

[147] D Manolakos, G Papadakis, D Papantonis, and S Kyritsis. A stand-alone photovoltaic power system for remote villages using pumped water energy storage. *Energy*, 29(1):57–69, 2004.

[148] Ghazala Mansuri and Vijayendra Rao. Community-based and -driven development: A critical review. *The World Bank Research Observer*, 19(1):1–39, 2004. ISSN 02573032, 15646971. URL http://www.jstor.org/stable/3986491.

[149] Michael Manwaring, Debbie Mursch, and Kelly Tilford. Challenges and opportunities for new pumped storage development. *A White Paper Developed by NHA's Pumped Storage Development Council. NHA—Pumped Storage Development Council, USA*, 2012.

[150] Maxwell Mapako and Abel Mbewe. *Renewables and Energy for Rural Development in Sub-Saharan Africa*. Zed Books, 2013.

[151] Lubna Mariam, Malabika Basu, and Michael F Conlon. A review of existing microgrid architectures. *Journal of Engineering*, 2013, 2013.

[152] Bancy Mbura Mati. *Overview of water and soil nutrient management under smallholder rain-fed agriculture in East Africa*, volume 105. IWMI, 2006.

[153] Scott Mayeux and Jana Miller. Designing storage tanks: Software based on the latest international codes enables straightforward design of storage tanks in a range of load conditions. Technical report, Intergraph, 2016.

[154] B McStraw. Inspection of steel penstocks and pressure conduits. *Facilities instructions, standards, and techniques*, pages 2–8, 2000.

[155] M. Moner-Girona, M. Solano-Peralta, M. Lazopoulou, E.K. Ackom, X. Vallve, and S. Szabó. Electrification of sub-saharan africa through pv/hybrid mini-grids: Reducing the gap between current business models and on-site experience. *Renewable and Sustainable Energy Reviews*, 91:1148 – 1161, 2018. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2018.04.018.

[156] A Morabito, J Steimes, and P Hendrick. Pumped hydroelectric energy storage: A comparison of turbomachinery configurations. *Sustainable Hydraulics in the Era of Global Change*, pages 261–268, 2016.

[157] Alessandro Morabito and Patrick Hendrick. Pump as turbine applied to micro energy storage and smart water grids: A case study. *Applied energy*, 241:567–579, 2019.

[158] Alessandro Morabito, Gilton Furtado, Andre Mesquita, and P. Hendrick. Variable speed regulation for pump as turbine in micro pumped hydro energy storage. 10 2019. doi: 10.3850/38WC092019-1200.

[159] Jose Roberto Moreira and Alan Douglas Poole. *Hydropower and its constraints*. Island Press, Washington, DC (United States), 1993.

[160] David Mosse. People's knowledge, participation and patronage: Operations and representations in rural development. *Participation: The new tyranny?*, pages 16–36, 01 2001.

[161] KH Motwani, SV Jain, and RN Patel. Cost analysis of pump as turbine for pico hydropower plants–a case study. *Procedia Engineering*, 51:721–726, 2013.

[162] Geoffrey C Mrema, Lawrence O Gumbe, Hakgamalang J Chepete, and Januarius O Agullo. *Rural structures in the tropics: design and development*. Food and Agriculture Organization of the United Nations, 2012.

[163] M Mulholland. General guidelines for the design of small homogeneous earthfill dams. *Environment Waikato*, 1987.

[164] PK Nag. *Power plant engineering*. Tata McGraw-Hill Education, 2002.

[165] Oona Nanka-Bruce. The socioeconomic drivers of rural electrification in sub-saharan africa. *The Journal of Energy and Development*, 33(2):215–247, 2008. ISSN 03614476.

[166] N.S. Narayan, P. Bauer, M. Zeman, and Z. Qin. *Solar home systems for improving electricity access*. PhD thesis, Technical University of Delft, 2019.

[167] Himanshu Nautiyal, Anoop Kumar, et al. Reverse running pumps analytical, experimental and computational study: A review. *Renewable and Sustainable Energy Reviews*, 14(7):2059–2067, 2010.

[168] Pragya Nema and Sayan Dutta. Feasibility study of 1 mw standalone hybrid energy system: For technical institutes. *Low Carbon Economy*, 03, 01 2012. doi: 10.4236/lce.2012.33009.

[169] Pragya Nema, Rajesh Nema, and Saroj Rangnekar. Pv-solar/wind hybrid energy system for gsm/cdma type mobile telephony base station. *International Journal of Energy and Environment*, 1(2), 01 2010.

[170] Franz Nestmann, Peter Oberle, Muhammad Ikhwan, Daniel Stoffel, Hans Joachim Blaß, Dietrich Töws, and Steffen Schmidt. Transfer of adapted water supply technologies through a demonstration and teaching facility. *Applied Water Science*, 6(3):215–228, 2016.

[171] Patrick W O'Connor, Qin Fen Zhang, Scott T DeNeale, Dol Raj Chalise, and Emma E Centurion. Hydropower baseline cost modeling. Technical report, Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 2015.

[172] Ayodele Odusola. Agriculture, rural poverty and income inequality in sub-saharan africa. *Income Inequality Trends in Sub-Saharan Africa: Divergence, Determinants and Consequences*, 2017.

[173] Ayodele F. Odusola, Giovanni Andrea Cornia, Haroon Bhorat, and Conceição Pedro. *Income inequality trends in sub-Saharan Africa: divergence, determinants and consequences*. United Nations Development Programme, Regional Bureau for Africa, 2017.

[174] Tanzania Ministry of Energy and Minerals. Energy access situation report. Technical report, Tanzania National Bureau of Statistics, Dodoma, Tanzania, 2017.

[175] North Carolina Department of Environment & Natural Resources. *Dam operation, maintenance and inspection manual*. North Carolina Department of Environment and Natural Resources, 2007.

[176] United States. Bureau of Reclamation. *Design of small dams*. US Department of the Interior, Bureau of Reclamation, 1987.

[177] Kenya Ministry of Water and irrigation. Practice manual for small dams, pans and other water conservation structures in kenya, 2015. URL http://smalldamsguidelines.water.go.ke/structures/.

[178] Samuel Ofordile Ani. *Low cost small wind turbine generators for developing countries*. PhD thesis, Technical University of Delft, 2013.

[179] B Ogayar and PG Vidal. Cost determination of the electro-mechanical equipment of a small hydro-power plant. *Renewable Energy*, 34(1):6–13, 2009.

[180] Olayinka S. Ohunakin, Sunday J. Ojolo, and Oluseyi O. Ajayi. Small hydropower (shp) development in nigeria: An assessment. *Renewable and Sustainable Energy Reviews*, 15(4):2006 – 2013, 2011. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2011.01.003. URL http://www.sciencedirect.com/science/article/pii/S1364032111000049.

[181] O Chima Okereke. Causes of failure and abandonment of projects and project deliverables in africa. *PM World J*, 6(1):1–16, 2017.

[182] Gülce Onbaşılı, Arthur Williams, and Sandeep Dhundhara. Storage for community electricity: A comparison between batteries and mini pumped hydro. In *Renewable Energy and Sustainable Buildings*, pages 281–292. Springer, 2020.

[183] Bryan Orchard and Sander Klos. Pumps as turbines for water industry. *World Pumps*, 2009(8): 22–23, 2009.

[184] World Trade Organization. Trade statistics - tariff profiles, 2020. URL `https://www.wto.org/english/res_e/statis_e/tariff_profiles_list_e.htm`.

[185] Oliver Paish. Micro-hydropower: status and prospects. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 216(1):31–40, 2002.

[186] Oliver Paish. Small hydro power: technology and current status. *Renewable and sustainable energy reviews*, 6(6):537–556, 2002.

[187] Debajit Palit and Akanksha Chaurey. Off-grid rural electrification experiences from south asia: Status and best practices. *Energy for Sustainable Development*, 15(3):266–276, 2011.

[188] Georgios Papaefthymiou, Katharina Grave, and Ken Dragoon. Flexibility options in electricity systems. *Project number: POWDE14426, Ecofys*, 2014.

[189] Stefanos V Papaefthymiou and Stavros A Papathanassiou. Optimum sizing of wind-pumped-storage hybrid power stations in island systems. *Renewable Energy*, 64:187–196, 2014.

[190] Thomas Parks. The rise and fall of donor funding for advocacy ngos: Understanding the impact. *Development in Practice*, 18(2):213–222, 2008. ISSN 09614524.

[191] Samuel Paul. *Community participation in development projects*. World Bank Washington, DC, 1987.

[192] Estefanía Planas, Jon Andreu, José Ignacio Gárate, Iñigo Martínez de Alegría, and Edorta Ibarra. Ac and dc technology in microgrids: A review. *Renewable and Sustainable Energy Reviews*, 43: 726–749, 2015.

[193] Andreas Poullikkas. A comparative overview of large-scale battery systems for electricity storage. *Renewable and Sustainable energy reviews*, 27:778–788, 2013.

[194] Estanislao Pujades, Philippe Orban, Anna Jurado, Carlos Ayora, Serge Brouyère, and Alain Dassargues. Water chemical evolution in underground pumped storage hydropower plants and induced consequences. *Energy Procedia*, 125:504–510, 2017.

[195] Gaël Raballand and Patricia Macchi. Transport prices and costs: the need to revisit donors' policies in transport in africa. *Bureau for Research & Economic Analysis of Development Working Paper*, 190, 2008.

[196] Md Mizanur Rahman, Jukka V Paatero, and Risto Lahdelma. Evaluation of choices for sustainable rural electrification in developing countries: A multicriteria approach. *Energy Policy*, 59: 589–599, 2013.

[197] Md Touhid Nur Rahman, Md Momin Turzo, Ahammed Masum Billah, Md Masum Akanda, and Md Rahat Rahman. Repairing and commissioning of an ac motor speed controller for a centrifugal pump. *Journal of Physics and Its Applications*, 1(2):47–52, 2019.

[198] P Ralon, M Taylor, A Ilas, H Diaz-Bone, and K Kairies. Electricity storage and renewables: costs and markets to 2030. *International Renewable Energy Agency: Abu Dhabi, UAE*, 2017.

[199] H Ramos and A Borga. Pumps as turbines: an unconventional solution to energy production. *Urban Water*, 1(3):261–263, 1999.

[200] Md Juel Rana and Mohammad Ali Abido. Energy management in dc microgrid with energy storage and model predictive controlled ac–dc converter. *IET Generation, Transmission & Distribution*, 11(15):3694–3702, 2017.

[201] Vijayendra Rao and Ana Maria Ibanez. The social impact of social funds in jamaica: A 'participatory econometric'analysis of targeting, collective action, and participation in community-driven development. *Journal of Development Studies*, 41(5):788–838, 2005.

[202] Shafiqur Rehman, Luai M Al-Hadhrami, and Md Mahbub Alam. Pumped hydro energy storage system: A technological review. *Renewable and Sustainable Energy Reviews*, 44:586–598, 2015.

[203] Jesse C. Ribot. From exclusion to participation: Turning senegal's forestry policy around? *World Development*, 23(9):1587 – 1599, 1995. ISSN 0305-750X. doi: https://doi.org/10.1016/0305-750X(95)00060-P. URL http://www.sciencedirect.com/science/article/pii/0305750X9500060P.

[204] Hannah Ritchie and Max Roser. Access to energy, Sep 2019. URL https://ourworldindata.org/energy-access.

[205] Antoine Rogeau, Robin Girard, and Georges Kariniotakis. A generic gis-based method for small pumped hydro energy storage (phes) potential evaluation at large scale. *Applied energy*, 197: 241–253, 2017.

[206] Simon Rolland and Guido Glania. Hybrid mini-grids for rural electrification: lessons learned. *Alliance for Rural Electrification*, 2011.

[207] Norbert F. M. Roozenburg and J. Eekels. *Product design: fundamentals and methods*. Wiley, 1995.

[208] P Savage, R.R. Nordhaus, and S.P. Jamieson. Dc microgrids: Benefits and barriers. Technical report, Yale School of Forestry and Environmental Studies, 2018.

[209] Oliver Schmidt, Sylvain Melchior, Adam Hawkes, and Iain Staffell. Projecting the future levelized cost of electricity storage technologies. *Joule*, 3(1):81 – 100, 2019. ISSN 2542-4351. doi: https://doi.org/10.1016/j.joule.2018.12.008.

[210] Philip A Schweitzer et al. *Metallic materials: physical, mechanical, and corrosion properties*, volume 19. CRC press, 2003.

[211] Mamdouh Shahin. *Hydrology and water resources of Africa*, volume 41. Springer Science & Business Media, 2006.

[212] Bekele Shiferaw, Kindie Tesfaye, Menale Kassie, Tsedeke Abate, BM Prasanna, and Abebe Menkir. Managing vulnerability to drought and enhancing livelihood resilience in sub-saharan africa: Technological, institutional and policy options. *Weather and Climate Extremes*, 3:67–79, 2014.

[213] Lyn Simpson, Leanne Wood, and Leonie Daws. Community capacity building: Starting with people not projects. *Community Development Journal*, 38(4):277–286, 2003.

[214] MK Singhal and Arun Kumar. Optimum design of penstock for hydro projects. *International Journal of Energy and Power Engineering*, 4(4):216, 2015.

[215] Kandler Smith, Aron Saxon, Matthew Keyser, Blake Lundstrom, Ziwei Cao, and Albert Roc. Life prediction model for grid-connected li-ion battery energy storage system. In *2017 American Control Conference (ACC)*, pages 4062–4068. IEEE, 2017.

[216] M Stefanizzi, M Torresi, B Fortunato, and SM Camporeale. Experimental investigation and performance prediction modeling of a single stage centrifugal pump operating as turbine. *Energy Procedia*, 126:589–596, 2017.

[217] Tim Stephens. *Handbook on small earth dams and weirs. a guide to siting, design and construction*. Bedford (UK) Cranfield Press, 1991.

[218] Tim Stephens. *Manual on small earth dams: a guide to siting, design and construction.* Food and Agriculture Organization of the United Nations (FAO), 2010.

[219] David Stiedl, Ulf Brudefors, and Mike Shone. *Productivity norms for labour-based construction*. International Labour Organisation, Advisory Support, Information Services and Training, 1998.

[220] Sandor Szabo, K Bódis, T Huld, and M Moner-Girona. Energy solutions in rural africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. *Environmental Research Letters*, 6(3):034002, 2011.

[221] Xingguo Tan, Qingmin Li, and Hui Wang. Advances and trends of energy storage technology in microgrid. *International Journal of Electrical Power & Energy Systems*, 44(1):179–191, 2013.

[222] Michael Taylor and Eun Young So. Solar pv in africa: Costs and markets. Technical report, IRENA (Bonn, Germany), 2016.

[223] Bernard Tenenbaum, Chris Greacen, Tilak Siyambalapitiya, and James Knuckles. *From the bottom up: how small power producers and mini-grids can deliver electrification and renewable energy in Africa*. The World Bank, 2014. doi: 10.1596/978-1-4648-0093-1.

[224] Andrei Ter-Gazarian. *Energy storage for power systems*. Institution of Engineering and Technology, 2011.

[225] Supee Teravaninthorn and Gaël Raballand. *Transport prices and costs in Africa: a review of the main international corridors*. World Bank Publications, 2009.

[226] Julia Terrapon-Pfaff, Carmen Dienst, Julian König, and Willington Ortiz. A cross-sectional review: Impacts and sustainability of small-scale renewable energy projects in developing countries. *Renewable and Sustainable Energy Reviews*, 40:1–10, 2014.

[227] Central Statistical Agency & the World Bank. Ethiopia rural socioeconomic survey. Technical report, CSA, Addis Abeba, Ethiopia, 2013.

[228] Mark Thornbloom, Debo Ngbangadia, and Mambo Assama. Using micro-hydropower in the zairian village. *Solar energy*, 59(1-3):75–81, 1997.

[229] Wellington Didibhuku Thwala. Community participation is a necessity for project success: A case study of rural water supply project in jeppes reefs, south africa. *African Journal of Agricultural Research*, 5(10):970–979, 2010.

[230] Engineering ToolBox. Young's modulus - tensile and yield strength for common materials, 2003. URL https://www.engineeringtoolbox.com/young-modulus-d_417.html.

[231] Liliana Topliceanu, Puiu Gabriel, and Iulian Furdu. Functional problems and maintenance operations of hydraulic turbines. *TEM Journal*, 5(1):32, 2016.

[232] Wendy R Townsend. Participatory investigation as a means to promote community based management: Examples from the bolivian lowlands. *Washington DC, The World Bank/WBI's CBNRM Initiative*, 1998.

[233] Philipp A. Trotter. Rural electrification, electrification inequality and democratic institutions in sub-saharan africa. *Energy for Sustainable Development*, 34:111 – 129, 2016. ISSN 0973-0826. doi: https://doi.org/10.1016/j.esd.2016.07.008.

[234] Nasim Uddin et al. Preliminary design of an underground reservoir for pumped storage. *Geotechnical & Geological Engineering*, 21(4):331–355, 2003.

[235] UNHCR. Water manual for refugee situations. 1992.

[236] Division for Sustainable Development Goals United Nations. Analysis of the voluntary national reviews relating to sustainable development goal 7, 2018.

[237] Tania Urmee and Anisuzzaman Md. Social, cultural and political dimensions of off-grid renewable energy programs in developing countries. *Renewable Energy*, 93:159 – 167, 2016. ISSN 0960-1481. doi: https://doi.org/10.1016/j.renene.2016.02.040.

[238] Bob van der Zwaan, Agnese Boccalon, and Francesco Dalla Longa. Prospects for hydropower in ethiopia: An energy-water nexus analysis. *Energy Strategy Reviews*, 19:19–30, 2018.

[239] VA Varaksin and AM Palvanov. Experience in operating hes wooden penstocks. *Hydrotechnical Construction*, 1(9):820–822, 1967.

[240] René Véron, Glyn Williams, Stuart Corbridge, and Manoj Srivastava. Decentralized corruption or corrupt decentralization? community monitoring of poverty-alleviation schemes in eastern india. *World Development*, 34(11):1922–1941, 2006.

[241] Robert Wade. The management of common property resources: Finding a cooperative solution. *The World Bank Research Observer*, 2(2):219–234, 1987.

[242] Weatherbase. Mekele, ethiopia travel weather averages (weatherbase), 2019. URL `http://www.weatherbase.com/weather/weather.php3?s=592516&units=metric&cityname=Mekele,+Tigray,+Ethiopia`.

[243] Wayne W. Weaver, Rush D. Robinett, Gordon G. Parker, and David G. Wilson. Energy storage requirements of dc microgrids with high penetration renewables under droop control. *International Journal of Electrical Power & Energy Systems*, 68:203–209, 2015. doi: 10.1016/j.ijepes.2014.12.070.

[244] WELL. and Great Britain. Dept. for International Development. *Guidance manual on water supply and sanitation programmes*. WEDC, Loughborough University, 1998.

[245] Sarah C White. Depoliticising development: the uses and abuses of participation. *Development in practice*, 6(1):6–15, 1996.

[246] Nathaniel J. Williams, Paulina Jaramillo, Jay Taneja, and Taha Selim Ustun. Enabling private sector investment in microgrid-based rural electrification in developing countries: A review. *Renewable and Sustainable Energy Reviews*, 52:1268 – 1281, 2015. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2015.07.153. URL `http://www.sciencedirect.com/science/article/pii/S136403211500800X`.

[247] Worldbank. Access to electricity (% of population), 2017. URL `https://data.worldbank.org/indicator/eg.elc.accs.zs`.

[248] Worldbank. Access to electricity, rural (% of rural population), 2017. URL `https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS`.

[249] Worldbank. Gdp per capita (current us$) - ethiopia, 2018. URL `https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=ET`.

[250] Bolun Xu, Alexandre Oudalov, Andreas Ulbig, Göran Andersson, and Daniel S Kirschen. Modeling of lithium-ion battery degradation for cell life assessment. *IEEE Transactions on Smart Grid*, 9(2):1131–1140, 2016.

[251] Annabel Yadoo and Heather Cruickshank. The value of cooperatives in rural electrification. *Energy policy*, 38(6):2941–2947, 2010.

[252] Mastewal Yami. Sustaining participation in irrigation systems of ethiopia: what have we learned about water user associations? *Water Policy*, 15(6):961–984, 2013.

[253] Chi-Jen Yang and Robert B Jackson. Opportunities and barriers to pumped-hydro energy storage in the united states. *Renewable and Sustainable Energy Reviews*, 15(1):839–844, 2011.

[254] Hongxing Yang, Wei Zhou, Lin Lua, and Zhaohong Fang. Optimal sizing method for stand-alone hybrid solar–wind system with lpsp technology by using genetic algorithm. *Solar Energy*, 82(4): 354 – 367, 2008. ISSN 0038-092X. doi: https://doi.org/10.1016/j.solener.2007.08.005.

[255] Sun-Sheng Yang, Shahram Derakhshan, and Fan-Yu Kong. Theoretical, numerical and experimental prediction of pump as turbine performance. *Renewable Energy*, 48:507–513, 2012.

[256] S Akbar Zaidi. Ngo failure and the need to bring back the state. *Journal of International Development: The Journal of the Development Studies Association*, 11(2):259–271, 1999.

[257] Behnam Zakeri and Sanna Syri. Electrical energy storage systems: A comparative life cycle cost analysis. *Renewable and Sustainable Energy Reviews*, 42:569 – 596, 2015. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2014.10.011.

A
Power flow diagrams

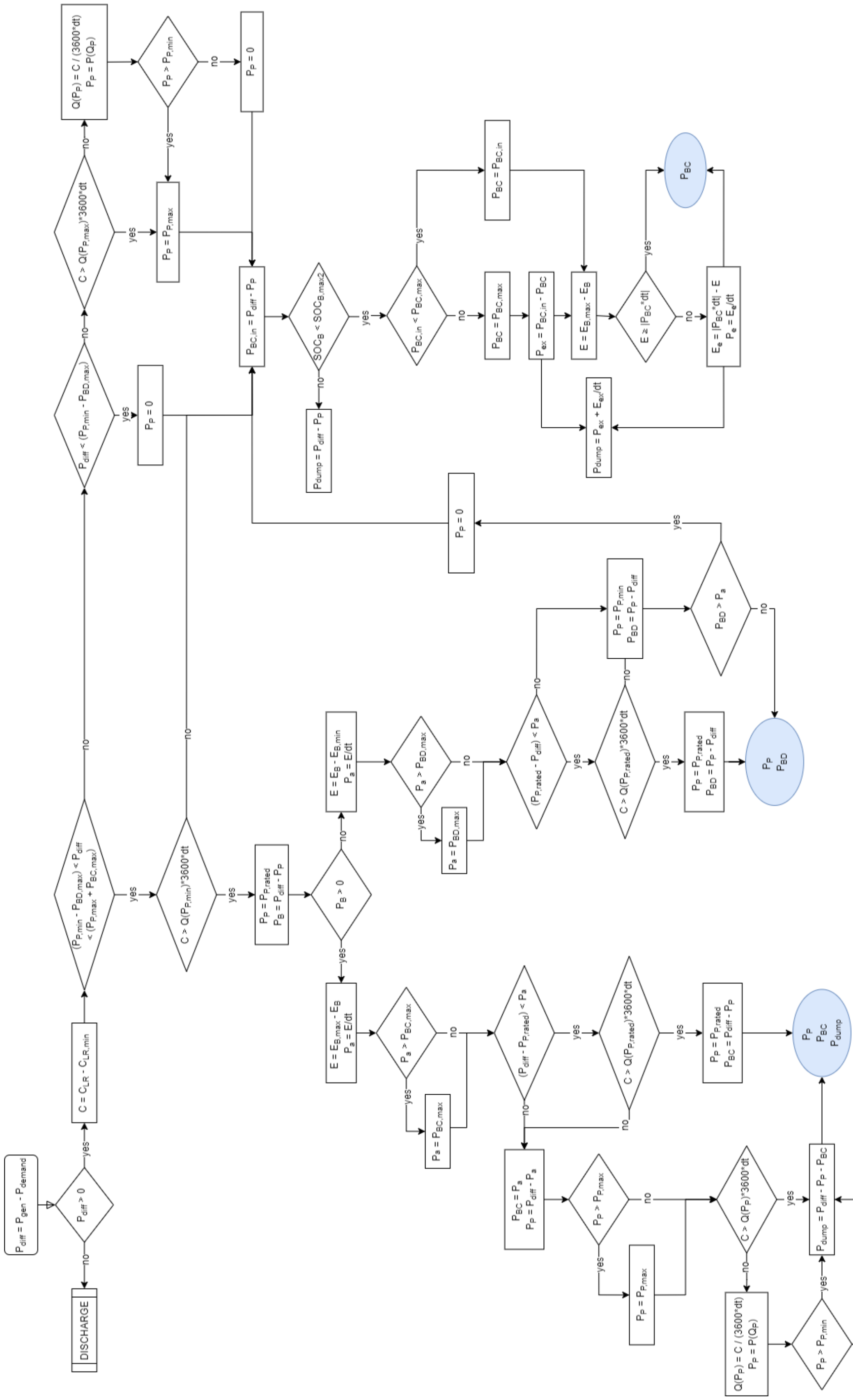


Figure A.1: The power flow diagram of the energy management strategy for the charging cycle.

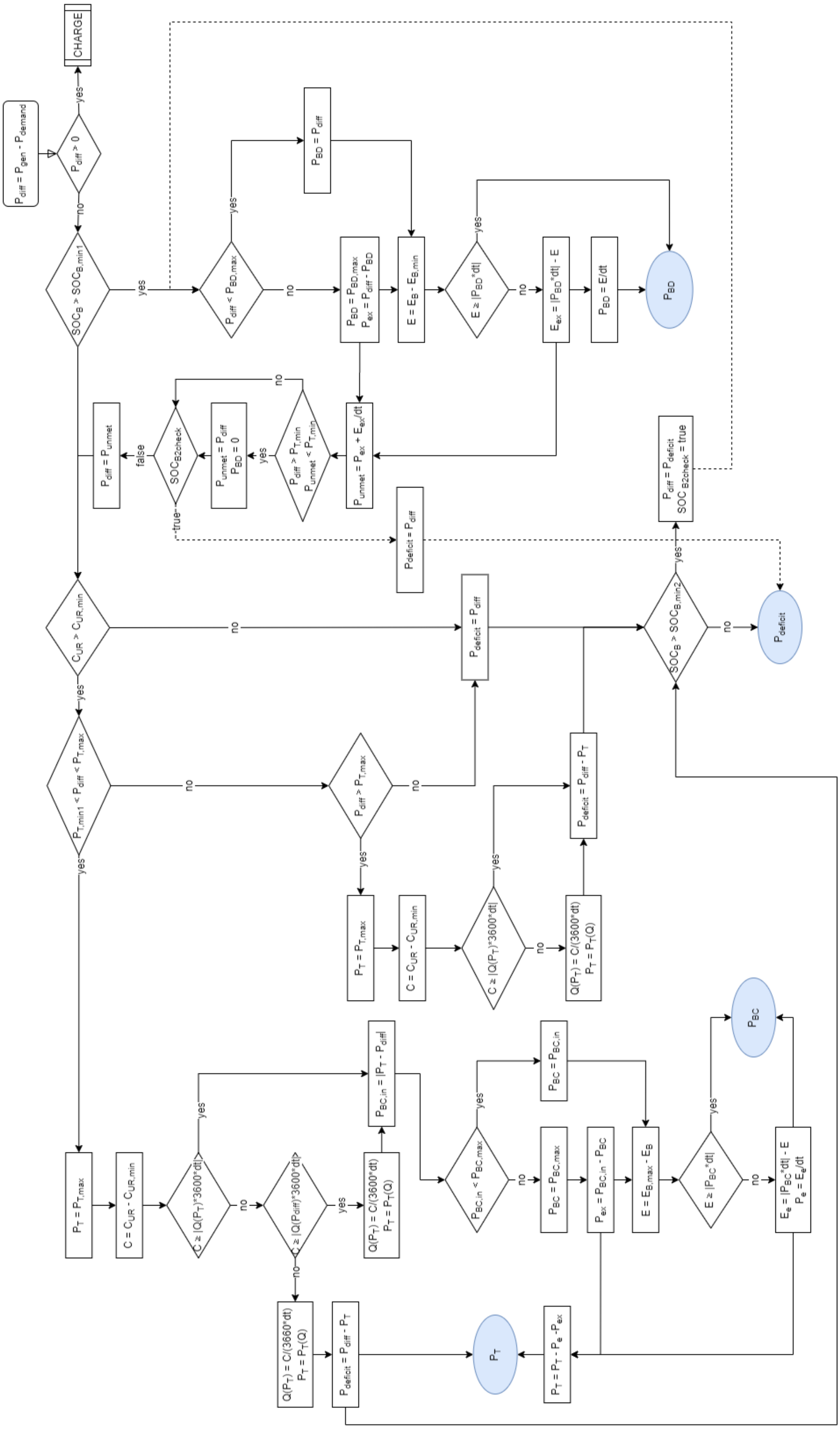


Figure A.2: The power flow diagram of the energy management strategy for the discharging cycle.

B

Steel tank costs

As steel tanks are commonly used in industrial and agricultural context, it is a mature and well developed technology. Modular plate segments allow for easy transportation and on site construction. Another advantage is the possibility to cover the tank, reducing evaporation significantly. The design of steel storage tanks is discussed, and subsequently the capital costs involved. The information on steel tanks as discussed in this section, was mostly gathered through contact with suppliers, namely Buwatec, Outokumpu, and Mienis Water.

Building materials Steel tanks are constructed from stainless steel, with the most common types, their yield strength (MPa) [210], density (kg/m^3) and price (euro/ton) summarized in Table B.1 below:

Table B.1: Stainless steel materials used for the construction of steel water tanks.

Stainless steel	Yield strength (MPa)	Density (kg/m^3)	Price (euro/ton)
1.4301/7 (304/L)	160	7,900	3400
1.4404 (316L)	173	8000	4400
1.4162 (LDX 2101)	260	7800	3700
1.4462 (DX 2205)	260	7800	4700

Tank dimensions The aforementioned steel tank suppliers have indicated the maximum dimensions of their steel storage tanks are roughly 30 meters in diameter and up to 5 meters in height; this corresponds roughly to a capacity of 3500 m^3.

The plate thickness of the steel tank is dependent on the dimensions, and can be calculated using standardized equations. There are two standards commonly used for storage tank design, the European Norm NEN-EN 14015 and the the American Petroleum Institute Standard API 650. In this thesis, the European Norm will be used, which is described as follows: *”Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperature and above.”*

The equation for the minimal required shell thickness of a storage tank, according to the European standard *NEN-EN 14015* [153]:

$$e_c = \frac{D}{20S}[98W(H_c - 0.3) + P] + c \qquad \text{(B.1)} \qquad e_t = \frac{D}{20S_t}[98W_t(H_c - 0.3) + P_t] + c \qquad \text{(B.2)}$$

In this equation, the required thickness is e_c (for design conditions) and e_t (for test conditions) ,*c* is the corrosion allowance (mm), *D* is the tank diameter (m), H_c is the distance from the bottom of the shell course (m), *P* is the design pressure and P_t the test pressure (mbar), *S* is the allowable stress for the appropriate condition (N/mm^2) and *W* is the density of the liquid under storage conditions, in this case water (kg/l). *P* and P_t can be neglected for tanks with a pressure less or equal to 10 mbar, which the storage tanks in this design will be.

The required shell thickness can thus be related to the height and diameter of the tank, as illustrated in Figure B.1 In the Figure, the reservoir capacity linked to a certain tank height and diameter is shown on the left, and next to it its associated shell thickness. A standard corrosion allowance of 2 mm is assumed here, and a yield strength of 160 MPa.

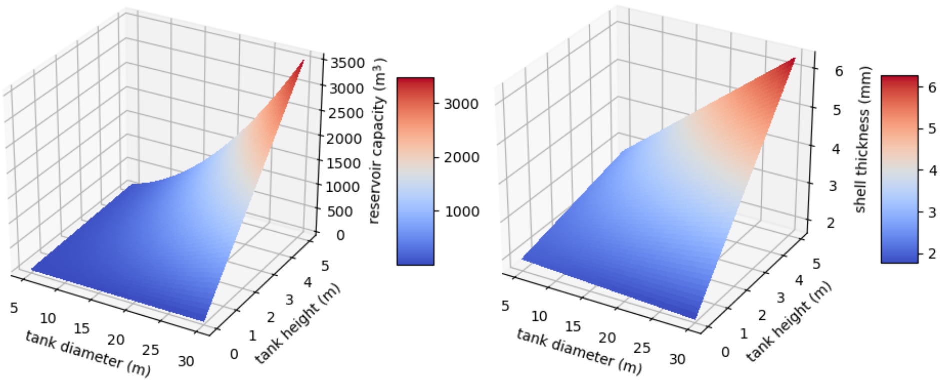


Figure B.1: *Left:* Relation between the capacity, diameter and height of a storage tank. *Right:* Relation between the shell thickness, diameter and height of a storage tank.

It can be observed that for a set capacity, increasing the diameter while decreasing the height leads to a lower required wall thickness. Since this leads to less material and thus less costs, the ratio of diameter to height should be high.

The costs and required expertise for the installation of a steel tank reservoir can be divided as follows:

- Site evaluation: this stage requires much less effort than for an earth dam reservoir, since the terrain and soil do not influence the possibility for a steel tank significantly and thus do not need to be tested thoroughly. The terrain should be flat and the site hydrological characteristics should permit the reservoir to be filled up initially. This is estimated as a base cost of 2,500 €, the wage of a civil engineer for one month.
- Site clearing: as with an earth dam reservoir, this is estimated to cost 0.038 € per m^2.
- Tank foundation: to prevent the steel tank from sagging or tipping over, a concrete slab of at least 20 cm should be built as foundation. This can be done by local labourers. The cost of cement is on average approximately 110.00 €/m^3 in Sub-Saharan Africa [75].
- Material: the amount of material needed for the tank depends on the stainless steel type used and the thickness, which in turn depends on the dimensions of the tank. The costs for each steel type are given in Table B.1.
- Tank construction: due to the modular nature of the steel tank, the stainless steel plates can be easily transported and bolted together on site. This can be done by local labourers and requires approximately 20 worker days per 1000 m^3, including manual transportation from the road to the construction site. Included in this is also the labour cost for laying the cement foundation.
- Liner: to waterproof the steel tank, a liner is required for the bottom and walls, along with a base. As quoted by the mentioned suppliers, the base and the liner together will cost approximately 9.60 €/m^2.

Adding these costs together, leads to the following equation for the total cost for the tank, up to a maximum V_{tank} of 3,500 m_3:

$$C_{tank} = C_{evaluation} + C_{clearing} + C_{cement} + C_{steel} + C_{construction} + C_{liner} \quad \text{(B.3)}$$

$$C_t = 2,500 + 0.038 \cdot \frac{\pi D^2}{4} + 5.5 \cdot \pi D^2 + C_{steel}(\pi DHt) + 84\left(\frac{V_{tank}}{1000}\right) + 9.60\left(\pi DH + \frac{\pi D^2}{4}\right) \quad \text{(B.4)}$$

As with the earth dam reservoirs, no clear dimensional relations between the diameter and height have been established. Several reasonable tank dimensions have been established, along with their associated costs. Every time the desired total capacity exceeds a multiple of 3,500 m_3, the capacity is split equally between tanks of maximum 3,500 m_3 capacity. The steel type which results in the lowest cost for the desired configuration is selected, which in all cases turned out to be LDX2101.

Table B.2: Realistic tank dimensions and their associated wall thickness and cost. If more than 3,500 m^3 is required, the desired capacity is divided over multiple tanks.

Capacity (m^3)	tanks	D (m)	thickness (mm)	H_{tank} (m)	C (euro)	euro/m^3
1000	1	20	3.18	3.09	14385.85	14.39
2000	1	25	4.07	3.78	21048.25	10.52
3000	1	30	4.24	4.23	28944.45	9.65
4000	2	25	4.07	3.78	42432.51	10.61
5000	2	30	3.54	3.83	57500.37	11.50
6000	2	30	4.24	4.23	58392.89	9.73
7000	2	30	4.95	4.63	59285.52	8.47
8000	3	30	3.77	3.96	87369.52	10.92
9000	3	30	4.24	4.23	88345.34	9.82
10000	3	30	4.72	4.50	89321.23	8.93
11000	4	30	3.89	4.03	117741.24	10.70
12000	4	30	4.24	4.23	118801.79	9.90
13000	4	30	4.60	4.43	119862.39	9.22
14000	4	30	4.95	4.63	120923.04	8.64
15000	5	30	4.24	4.23	149762.23	9.98

The cost for tank reservoirs does not decline if a higher capacity is used, but increases linearly:

$$C_t = 9.9 \cdot V_t \quad \text{(B.5)}$$