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Floating solar photovoltaics and hydropower: The potential for hybridization in a fixed price electricity market

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Master of science in Economics

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Abstract

With abundant solar resources, solar technology remains one of the cheapest, most readily available energy sources globally. However, its intermittent nature has hindered its utilization in the electricity sector, leading to many countries to rely upon more expensive thermal fuels for sustainable energy supply. Researchers have proposed the use of flexible conventional energy sources such as hydropower with reservoir to compliment solar photovoltaics(PV) grid integration. Therefore, this paper analyzes the economic performance of integrating and operating a combined floating solar photovoltaics and hydropower plant. Overall, I asses the per unit cost of energy for the individual energy systems and the hybrid system and quantify to what extent the cost of producing energy is reduced in Madagascar when the hybrid energy system is under operation. Lastly, I explore the degree to which the existing market conditions facilitate the operation of hydropower and floating solar photovoltaics as a hybrid energy system. The study reveals that the levelized cost of energy for the hydropower and floating solar is 0.108 $/kWh, 0.0889 $/kWh , respectively. The hybrid system stands out in terms of operation by allowing for more firm energy production, improved optimization during peak periods and increased substitution of thermal plants which leads to a reduction of approximately 18% in cost of energy in Madagascar. Lastly, it is concluded that the current power purchase agreement pricing mechanism and overall market conditions in Madagascar are not appropriately designed to stimulate investment in, or optimal operation of a hybrid plant-which would otherwise offer quantifiable benefits to the power sector of Madagascar.

Table of Contents

Acknowledgement I
Abstract II
Table of Figures IV
List of Tables IV
Abbreviations V
1 Introduction 1
1.1 Objectives of the study 3
1.2 Research questions 3
1.3 Outline of the thesis 3
2 Background 4
2.1 General overview of Madagascar 4
2.2 Electricity sector in Madagascar 4
2.3 Electricity sector institutional set-up 5
2.4 PPA 6
2.5 Solar PV and HP in Madagascar's electrification plan 6
3 Case study 8
3.1 HP project 8
3.1.1.HPP's PPA 8
3.2 FPV project 9
3.2.1 Why FPV? 9
3.2 Integration of HP and FPV energy technologies 11
4 Theoretical Framework 12
4.1 Cost minimization 12
5 Methods and data 13
5.1 Methodology 13
5.2 Reservoir modelling 16
5.3 Data 17
5.3.1 HPP with reservoir 18
5.3.2 FPV simulation 18
5.3.3 Madagascar's daily load profile 19
5.3.4 Average hourly energy cost 20
5.3 5 Hybrid system cost 20
6 Results and Discussion 22
6.1 LCOE 22
6.2 Contribution to Madagascar's energy supply 23
6.2.1.Hybrid operation on a rainy day 23
6.2.2 Hybrid operation on a dry day 24

6.2.3 Hybrid operation under constrained demand 25
6.3 PPA arrangement 25
6.4 Sensitivity analysis 26
6.4.1 Change in discount rate 27
6.4.2 Change in Investment cost 27
7 Conclusion 28

Table of Figures

Figure 1 Cumulative installed capacity of renewable energy sources 1
Figure 2 Available capacity versus generation in Madagascar source; Castalia 4
Figure 3 Madagascar power market Structure source: The World Bank(2020) 6
Figure 4 average monthly rainfall source. SN Power 8
Figure 5 Main components of a FPV system source: Oliveira-pinto & Stokkermans(2020) 9
Figure 6 Average monthly temperature source:Meteonorm 11
Figure 7 Average monthly solar irradiation Source: Meteonorm 11
Figure 8 HOMER Pro schematic 14
Figure 9 Average monthly stream flow 18
Figure 10 FPV simulation 19
Figure 11 Average daily demand 20
Figure 12 Hourly energy cost 20
Figure 13 LCOE 22
Figure 14 Hybrid operation on a rainy day 24
Figure 15 Hybrid operation on a dry day 24
Figure 16 Hybrid operation under constrained supply 25
Figure 17 Probability distribution 26
Figure 18 Change in discount rate 27
Figure 19 Change in Investment cost 27

List of Tables

Table 1 HP plants under the least cost development plan Source: The World Bank (2020) 7
Table 2 Hydropower inputs 18

Abbreviations

ADEC	Agence de developpement de l'electrification rurale
ARELEC	Autorité de régulation de l'electricité
BOT	Build own transfer
COE	Cost of Energy
FPV	Floating solar photovoltaics
GHI	Global horizontal irradiation
GSC	Global solar council
GW	Gigawatt
GWh	Gigawatt hour
GWp	Gigawatt peak
HM^3	Hecto cubic meter
HPP	Hydropower power plant
IEA	International energy agency
IRENA	International renewable energy agency
IPP	Independent power producer
ISES	International solar energy society
JIRAMA	Jiro sy rano malagasy
kWh	Kilowatt hour
kWh/m^2	Kilowatt hour per meter squared
LCOE	Levelized cost of electricity
LCOS	Levelized cost of storage
L/S	Litres per second
M	Meters
MM	Millimetres
MEH	Ministry of energy and hydrocarbons
M^3/s	Meters cubic per second
MWh	Megawatt hour
MWp	Megawatt peak
O&M	Operation and maintenance
PPA	Power purchase agreement
PV	Photovoltaics
SEforALL	Sustainable energy for all
STC	Standard test conditions
USc/kWh	United states dollar cents per kilowatt hour
W/ m^2K	Watts-per-Meter-Square-Kelvin
$/kWh	United states dollar per kilowatt hour

1 Introduction

The growth of renewable energy sources has been significant in the last decade mainly due to the need to transition to a more sustainable energy system, cut greenhouse gasses, and reduce dependency on fossil fuels. According to IRENA, (2020), the cumulative installed capacity for renewables by the end of 2019 stood at 2537 GW as shown in Figure 1. Solar accounted for over 50% of the expansion compared to the overall installed capacity in 2010 (IRENA, 2020). The increase in the deployed capacity of solar has been attributed to falling prices, rapid technological innovations, and progressive energy policies around the world. The cost of solar photovoltaic(PV) modules fell by about 90% between 2009 and 2018 (IRENA, 2019). Renewables are increasingly becoming the cheapest source of new power generation and in 2020, solar photovoltaics (PV) are expected to join hydropower (HP) in 2020 a as low-cost energy sources without requiring any financial assistance (IRENA, 2017).

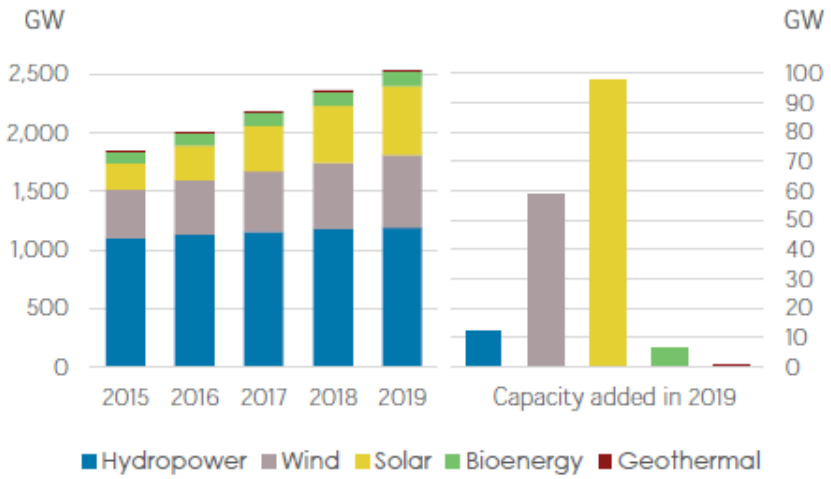

Figure 1 Cumulative installed capacity of renewable energy sources

One progressive policy that has increased the uptake of solar projects and catalyzed reduction in per unit cost of energy is the use of energy auctions. In 2017-2018, upwards of 50 countries used auctions to purchase approximately 97.5GWof renewables-based electricity, where solar PV accounted for more than half of the total volume (IRENA, 2019). Energy contracts also commonly known as power purchase agreements (PPA) are awarded to the bidder with the lowest price in an auction system ,consequentially, the cheapest solar energy projects based on the per unit cost of energy or the Levelized cost of energy(LCOE)[1] are prioritized. In 2018, the LCOE for solar PV fell steadily with a global weighted LCOE from all commercially available solar PV declining by 13 % (IRENA, 2019). This year, Abu Dhabi recorded the lowest auction price of 0.0135 $/kW (Bellini, 2020). This continues to show that solar PV can compete with

[1] Levelized cost of electricity is the present value of the price of the produced electrical energy ; expressed in units of cents per kilowatt hour, considering the economic life of the plant, investment cost and operation and maintenance cost .

other conventional energy sources in terms of cost thus can be deployed extensively to decarbonize the energy systems.

Despite this positive outlook of declining prices and an increase in installed capacity, solar PV percentage contribution in electricity production remains low, at only 2% (Center for climate and energy solutions, 2018). Fossil fuels still dominate electricity generation, for instance, Sub-Saharan Africa relies on expensive thermal plants as a back-up power source during capacity shortages which cost 0.50 $/kWh or more (Labordena, Patt, Bazilian, Howells, & Lilliestam, 2017). Sometimes the thermal plants make up a large share of their total installed capacity such as Madagascar where thermal plants percentage of the total capacity stands at 62% (The World Bank, 2020). The low usage of cheaper solar sources in electricity generation is due to their variable nature that poses grid integration and dispatchability challenges. (Alam & Sutanto, 2014). To reduce the contribution of costly fossil fuels in electricity generation, there is a need to find solutions to make solar PV dispatchable (Mahmud & Zahedi, 2016).

Several approaches have been proposed to remedy the grid intergration and dispatchability problem. These include demand-side management, interconnection, grid reinforcement , curtailment, energy storage and use of flexible energy sources (Mendoza, 2014). Demand-side management aims to match local demand and variable production. Its impediment is that there is low economic value and resistance from consumers to change their behavior patterns (Paterakis, Erdinç, & Catalão, 2017). Renewable energy curtailment contradicts the objective of increasing renewable energy supply. Energy storage technologies can be applied to balance high shares of solar PV and enable it to supply electricity on demand (Sepulveda et al, 2018). However, energy storage sources are expensive to deploy (Braff, Mueller, & Trancik, 2016).

This study reccommends the use of flexible conventional energy sources such as HP. HP is arguably one of the most flexible power sources as it can respond swiftly within seconds to demand variations and can store electricity over weeks, months, seasons or even years (Brown, 2011). It remains the most mature, reliable, and cost-effective technology available today (Brown, 2011). The LCOE for a large HP lies between 0.03-0.011$/kWh (IRENA, 2019) compared to thermal plants; 0.50$/kWh (Labordena, Patt, Bazilian, Howells, & Lilliestam, 2017). Therefore, a HP with a reservoir can be integrated and operated simultaneously with solar PV to ensure continuous and quality power supply at all times.

One of the most innovative solar PV technology is floating solar PV(FPV), which involves placing PV modules on water surfaces such as lakes, reservoirs and irrigation ponds. In 2020, the global installed capacity of FPV is slighly over 1.8 GW (ISES & GSC, 2020), Asia leads with 97% of the total capacity. The land saving potential of FPV (Trapan K, 2013) makes it especially attractive for regions such as Asia and Africa which have increasing energy demand and scarce land. FPV can be installed on a reservoir of a HP or another water surface and operated as a hybrid FPV HPP system.

Integrating and operating HP FPV as a hybrid system mutually benefits both power plants. FPV faces the grid integration challenges discussed above while HP can be unreliable in low rainfall or drought seasons resulting to severe power crises in especially HP dependent nations, frequent power rationing (Van Vliet, Sheffield, Wiberg, & Wood, 2016a) and switching to emergency and costlier IPP provided diesel generators (Karekezi, Kimani, Onguru, O, & Kithyoma, 2012). For instance, Madagascar has in the last 20 years experienced extreme weather events such as cyclones and severe droughts, which are becoming increasingly frequent and intense (USAID, 2016). These occurrences can potentially affect Madagascar's energy security in the future as research and physical evidence has shown that HP production is sensitive to climate change and dynamic rainfall patterns (Awerbuch & Yang, 2007).

This thesis analyzes the economic performance of integrating and operating a FPV and HP jointly as a hybrid system in Madagascar. Presently, there is no existing literature focusing on the potential of introducing utility-scale FPV or hybrid HPP FPV in the country. Existing studies focus on individual ground-mount solar PV energy systems (SEforALL, 2019) and HP (Newjec inc EJ, 2009, The World Bank, 2017) potential for electricity generation for the island nation. Madagascar's electricity sector emphasis on HP and solar PV technologies for power generation shows the possibility of hybrid HPP and FPV in the future

1.1 Objectives of the study

The general objective of the study is to examine the economic performance of introducing and operating a FPV with a hydropower plants (HPP) as a hybrid system, both to the IPP and the power utility in Madagascar. Specific objectives are

I. Analyze the LCOE for the individual FPV plant and HP
II. Assess to what extent hybrid HP and FPV can reduce reliance on thermal plants when operated and how that impact the cost of producing energy in Madagascar.
III. Assess if existing market conditions facilitate the operation of the two plants as a hybrid system

1.2 Research questions

The following research questions are addressed in this thesis

I. What is the LCOE of the HP and FPV and how is the cost of producing energy in Madagascar impacted when a hybrid HPP and FPV is under operation?
II. How can the market framework facilitate implementation of hybrid energy systems

1.3 Outline of the thesis

Section 2 provides some background information on Madagascar's general overview, electricity generation, energy sector institutional setup. Section 3 presents the case study, benefits, and limitations of FPV technology and hybrid HPP FPV.

Section 4 explains the theoretical framework while section 5 details the methodology and data used in the analysis. Results and discussion are presented in section 6. Finally, section 7 presents the conclusion.

2 Background

2.1 General overview of Madagascar

Madagascar is an island nation located in the South-West Indian Ocean circa 400km from the east African coast. With an area of 590,000km^2, it is the second largest island country with a population of 26 million people and approximately 80% of the population live in extreme poverty (The World Bank, 2019). The primary economic activity is agriculture and the main exports are minerals and vanilla. Despite the nation's richness in natural resources and being a major tourist destination in Africa, it remains one of the poorest countries in the world. The World Bank predicts that the economy will grow by 5.3% in 2020, this is attributed to an increase in public investment. However, there are concerns that Madagascar's overall growth over the medium term or the long-term will continue being hampered by inadequate infrastructure, poor governance, and limited human capital development

2.2 Electricity sector in Madagascar

The total available installed capacity is 467 MW, primarily made up of 34% HPP and 62% thermal power plants (The World Bank, 2017). This capacity is predicted to increase to 800MW by 2023 when planned power systems are developed (SEforALL, 2019). Figure 2 shows the generation capacity contribution of individual technologies to the electricity sector. Due to poor maintenance and obsoleteness of the HP power plants, the available HP capacity can be lower (The World Bank, 2017). Therefore, the sector relies on generally expensive fossil fuels. Consequentially, the cost of producing energy is high at 0.29$/kWh, which is among the highest in sub-Saharan Africa (The World Bank, 2020)

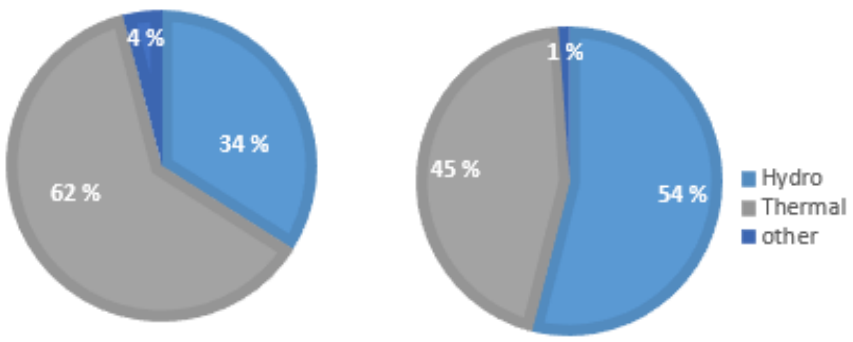

Figure 2 Available capacity versus generation in Madagascar source; Castalia

The Malagasy people's primary source of energy is firewood and its derivates (The World Bank, 2018). Due to high poverty levels and high electricity connection fees, only 24% of the population in Madagascar has

access to electricity (The World Bank, 2018). Specifically, 60% of urban residents compared to 5% of rural dwellers are connected to the national grid leaving most of the population with no electricity access despite highly subsidized electricity tariffs. The average total annual consumption of electricity per capita for Madagascar is among the lowest in Africa (Power Africa, 2016)

Madagascar grid network is encompassed of three high voltage interconnected transmission networks: Antananarivo, Fianarantsoa and Toamasina interconnected network. The electricity infrastructure is limited and most of the power generation facilities are obsolete and cannot meet the growing electricity demand. Therefore, power outages, load shedding and planned curtailments are common in Madagascar.

2.3 Electricity sector institutional set-up

The power sector of Madagascar has various organizations that perform different roles and have contractual and financial interrelationships as shown in Figure 3. The Ministry of Energy and Hydrocarbons (MEH) is the government organization responsible for setting energy policies, strategy, and planning. It also coordinates the energy sector and monitors the power utility electricity sector activities. Under this ministry, there are two administrative entities which are the rural development agency and the electricity regulator.

The rural Electrification Agency or Agence de Développement de l'Electrification Rurale (ADER) is responsible for implementing projects that are aimed towards universal energy access, especially in the rural areas. (SEforALL, 2019) and operates about 130 isolated mini-grids in the country alongside JIRAMA. The electricity sector regulator or Autorité de regulation de l'Electricité (ARELEC) oversees tariffs, technical standards, and market entry.

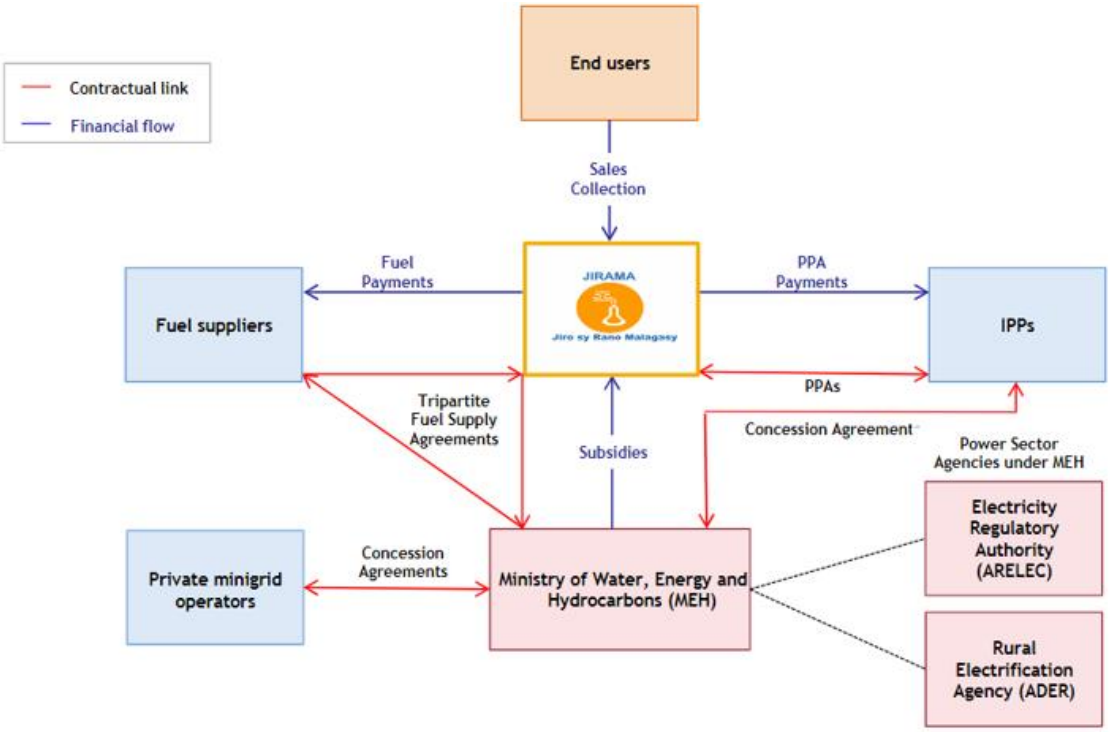

Figure 3 Madagascar power market Structure source: The World Bank(2020)

Jiro sy Rano Malagasy (JIRAMA) is a state-owned power utility vertically integrated[2] company established in 1975 and its main function is to transmit and distribute electricity to the end users. It operates approximately 82.2% of the power producing sites and grid infrastructure covering the main urban centres of Antananarivo and Fianarantsoa (Ministry of Energy and Mines (MEM) and WWF, 2012). Though it does not have a market monopoly, it is the sole off-taker of all grid-connected power plants in regions where it operates mainly due to long term contracts. Recently, JIRAMA has suffered operational difficulties and financial problems which resulted into insolvency and sluggishness in expanding the grid throughout the country (SEforALL, 2019)..

In 1999, the government introduced a policy for public and private partnerships to allow the IPP's to contribute to electricity production under special contractual arrangements, commonly PPA after JIRAMA was unable to invest sufficient infrastructure to serve all regions (Praenea, et al., 2017). Currently, there are more than 10 IPPs in Madagascar who develop and operate approximately 12.8% of the total installed capacity (Power Africa, 2016),

2.4 PPA

PPA secures the payment stream for a Build-Own Transfer (BOT) or concession project for an IPP (The World Bank , 2020) , whereby power utilities enter long term power purchase contracts with IPPs at a fixed electricity price. These types of contracts are designed for specific energy technologies and can vary between energy system types. PPA contract defines system capacity and power quality which is to be made available and delivered by the IPP within established terms and conditions. Ideally, an independent engineer is contracted by the buyer to ascertain the capacity level and reliability of the power plant after completion and before plant commissioning. Normally, a producer is obliged to provide a certain period forecast of the anticipated monthly generation and any scheduled outages.

The payment terms may differ according to country and technology source. Generally, the charging mechanism is a pass-through arrangement; the price charged for the power consist of a charge (availability charge), to cover the project company's fixed costs(including a return on equity for the IPP) plus a variable charge to cover the project company's variable costs (The World Bank , 2020). The availability charge is calculated based on the availability of the plant, while the variable charge is connected to the quantity of supplied electricity

2.5 Solar PV and HP in Madagascar's electrification plan

In the short term, Madagascar plans to double the country's electricity generation capacity by 2023 and ensure that at least 50% of the population has access to electricity with socially acceptable prices

[2] Vertical integrated electricity firms occur when a utility owns and controls production, distribution, and transmission. The level of control may differ depending on the degree of integration.

(SEforALL, 2019). In the medium term, the government in their electrification strategy has laid out plans which could increase the electrification rates to 70% by 2030. The New Energy policy; initiated in 2015 outlined three strategies; least cost grid extension, increasing decentralized renewable energy solutions and provide rural populations with affordable lighting solutions (The World Bank, 2019). So far, HP and solar PV projects have been earmarked under this low-cost electrification strategy.

HPP remains a priority power generation source now and in the future as shown in Table 1. HP's theoretical estimated potential is at 7800MW and currently, only 2% of the resource has been exploited (Beguerie & Blanchard, 2009). In Madagascar's electrification strategy, the World Bank, (2020) outlines and analyzed 15 HP plants with a capacity between 2MW to 300MW which could be developed under the least cost development plan.

	HP Projects	**Capacity (MW)**	**Generation (GWh)**
Committed plants	Andekaleka	34	140
	Mado	2	9
	Mahitsy	22	86
Candidate plants	Antafofo	160	1220
	Antetezambato	142	908
	Antetezambato extension	60	376
	Fanovana	9	62
	Lohavanana	120	915
	Mahavola	300	1870
	Ranomafana	93	393
	Sahofika	192	1685
	Sahofika extension	108	635
	Talaviana	21	143
	Tsinjoarivo	21	115
	Volobe	120	717

Table 1HP plants under the least cost development plan Source: The World Bank (2020)

The utilization of Solar PV in Madagascar is low despite having abundant solar resources. Its average global horizontal irradiation is 2000 kWh/m² which is among the highest in the world. To increase the electrification rate to 70% by 2030, Madagascar aims to electrify 42% of her population through solar PV technologies (République de Madagascar - Ministère de l'Energie et des Hydrocarbures., 2015) consisting mostly of hybrid solar mini-grids and solar home systems. Actual or planned utility-scale PV plants under consideration are not well documented.

3 Case study

3.1 HP project

The HP project under consideration is to be installed in Madagascar and will be generating electricity for the Tomassini and Antananarivo interconnected network. The project will consist of six horizontal axis Francis turbines with a rated power of 20MW, 6 generators rated at 24 MVA and 6 transformers, totaling an installed power capacity of 120MW. The HPP operates as both a run-off river and has a reservoir that can store energy and ensure a steady supply during peak periods or dry seasons.

Production from HP is highly dependent on existing hydrological conditions. The project area has a sub-tropical climate, with heavy rainfall and cyclones with some dry months. Figure 4 shows the area specific cumulative average monthly rainfall. The total annual rainfall is 2700mm with January, March and December receive the highest rainfall while September and October are the driest months.

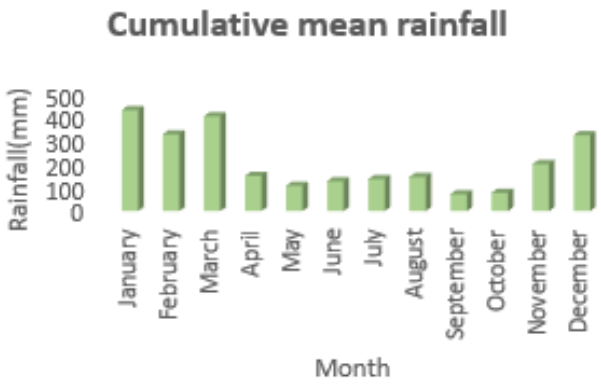

Figure 4 average monthly rainfall source. SN Power

3.1.1.HPP's PPA

The HPP in this study is a built-own and operate project under a 35-year PPA between the IPP and JIRAMA. In the PPA contract, the IPP is obliged to deliver a certain quantity of firm energy, also primary energy, on an annual basis. The contracted energy quantities are primary (up to580GWh), secondary (up to 580 GWh), secondary (between 580GWh and 745GWh) and tertiary (above 745GWh), annually. The energy categories were sorted according to historical hydrology characteristics and available technical production potential. Therefore, 580GWh has a 95% availability guarantee and attracts a PPA price sufficient to cover 85% of fixed costs, while the secondary and tertiary energy gets a half and a quarter of the primary energy price, respectively.

This is a 'take or pay' kind of contract where JIRAMA is obliged to buy the energy produced or pay otherwise. In case the annual production is less than 580GWh due to hydrological reasons, JIRAMA takes the hydrological risk and in case of supply side curtailment, the dispatch centre in its discretion would ask the producer to reduce power output.

3.2 FPV project

The FPV project will be developed on an irrigation pond that is located near the airport and it will supply electricity to the Antananarivo grid network. The FPV project is to be operated jointly with the HP as a hybrid energy system With over 1.8GW installed capacity globally, FPV technology has had a steady increase in popularity in many parts of the world such as Asia, Europe, and America. However, deployment has remained low in sub-Saharan Africa despite a few countries having carried out theoretical feasibility studies (ISES & GSC, 2020).

FPV plant normally has a floating platform where the PV modules are placed and offer buoyancy needed for the system to float on its own; the mooring system which holds the floating platform in place by minimizing lateral movement and ensuring the system is able to withstand the variability in the water level (Oliveira-Pinto & Stokkermans, 2020), inverters which are either placed on land or on top of floaters and an under-water electricity cable. **Error! Reference source not found.**shows main components of an FPV system.

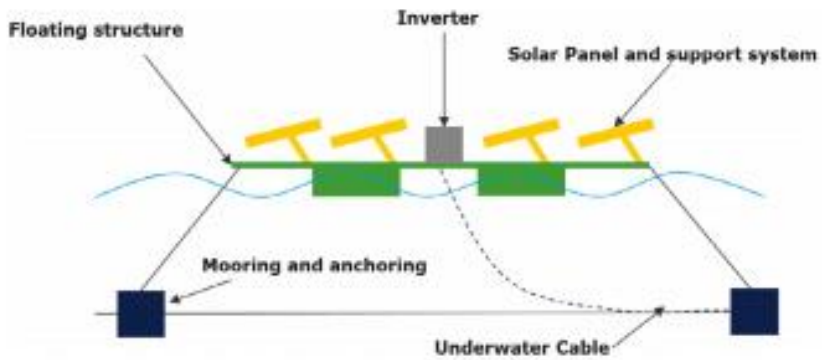

Figure 5 Main components of a FPV system source: Oliveira-pinto & Stokkermans(2020)

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3.2.1 Why FPV?

The choice of FPV technology is primarily influenced by Madagascar's need to exploit cheap local energy resources and have a sustainable energy supply (The World Bank, 2020). The IPP also desires to balance electricity supply during low rainfall and extreme drought seasons which negatively impact HP production (Gernaat, Bogaart, & Vuuren, 2017). FPV plant will be installed in Antananarivo, which is a high energy demand center and will also have access to a distribution network which will reduce the need for investing in transmission infrastructure.

Deploying FPV technology saves limited land resources (Trapani & Redón 2015) and allows for large scale deployment of solar PV technologies. One limitation of developing solar PV projects around the world has been the need for large tracts of land, approximately 1.6 hectares per each MW installed (Kabir, Kumar, Kumar, Adelodun, & Kim, 2018) and thus competes with other land uses such as agricultural and tourism (Liu, Krishna, Lun, Reindl, & Zhao, 2018). Furthermore, due to land scarcity, purchasing land is costly hence FPV can positively impact project viability by saving this cost.

FPV system has a higher energy production compared to ground-mount systems especially those located in hot climates whose production efficiency is reduced by the thermal drift effect[3]. The water acts as a cooler for the solar modules thus the efficiency increases by 11% (Choi ,2014), 2% (Ho, Chou, & Lai, 2015), and 7% (Ioanni, et al., 2016). An Increase in production due to the cooling effect between water and air (Choi, Choi, & Lee, 2016) is yet to be sufficiently documented.

Installing an FPV plant on an existing irrigation surface has innumerable benefits as it aids in converting unexploited surfaces into profitable and value adding commercial solar projects (Sahu, Yadav, & Sudhakar, 2016), generates power and helps to reduce evaporation losses by as much as 33% for freshwater bodies and up to 50% (Choi, 2014) or 90% (Taboada, et al., 2017) for man-made facilities whilst deterring algal growth thus improving water quality indirectly (World Bank Group, 2019.)

FPV is new and its components especially the mooring and anchoring structures make the technology to be more costly compared with terrestrial systems. (The World Bank & SERIS, 2019), which could result in a 30% increase in investment cost (Gisbert, et al., 2013). However, a few FPV projects have recorded LCOE that does not differ much from that of ground-mount fixed-tilt systems. For instance, Oliveira-Pinto & Stokkermans, (2020) published an LCOE value of between 0.0503 $/kWh and 0.0962 for three different FPV projects, values that are comparable to 0.09$/kWh published by the 5MW FPV in Seychelles (Bellini, 2020).

Generally, most FPV plants have been deployed on freshwater surfaces. However, oceans cover approximately 70% of the earth's surfaces which offers significant untapped potential. Utilizing ocean surfaces for FPV is in its initial stages though it increases the complexity of installing this technology due to the salinity of ocean water. Floaters must have the ability to withstand corrosion as they are highly exposed to salty water (George & Patel, 2019) whilst the mooring and anchoring systems should be able to withstand storms to maintain optimal orientation and tilt (Choi, Lee, & Lee, 2013). However, manufacturers have developed robust solutions for the ocean environment and the number of off-shore FPV projects installed is growing steadily.

2.6.2.1 FPV project area climate characteristics

Solar PV production is affected by temperature and solar irradiation. These parameters directly affect the efficiency of solar cells which decreases with an increase in temperature and increases with the amount of solar irradiation. Even though an increase in irradiation results in an increase in cell temperature, the efficiency gain due to increment in solar irradiation is greater than the effect of increased temperature. The

[3] Thermal drift effect is the changes in the normal operation of a device due to internal heating caused by variation in external ambient temperature

average temperature received in the project area is between 22 and 15 degrees. The area also records higher and lower temperature values as shown in Figure 6

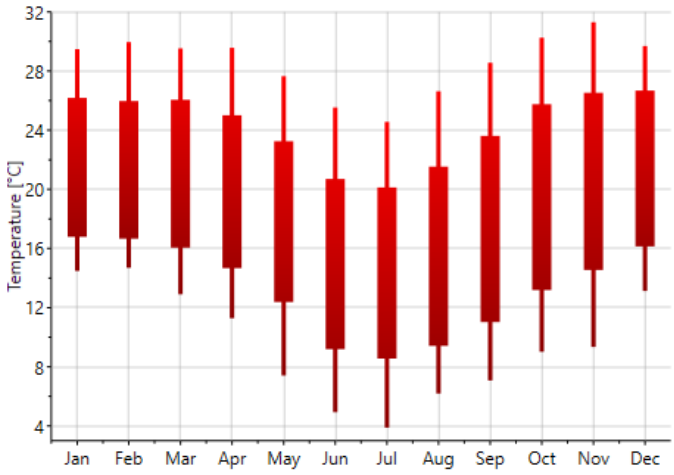

Figure 6 Average monthly temperature source:Meteonorm

The average annual solar irradiation recorded in the area is 1947 kWh/m^2. The level of irradiation is highest in October and lowest in June as shown in Figure 7, thus solar energy production is expected to be higher in October in comparison to other months as an increase in radiation leads to an increase in solar cell efficiency.

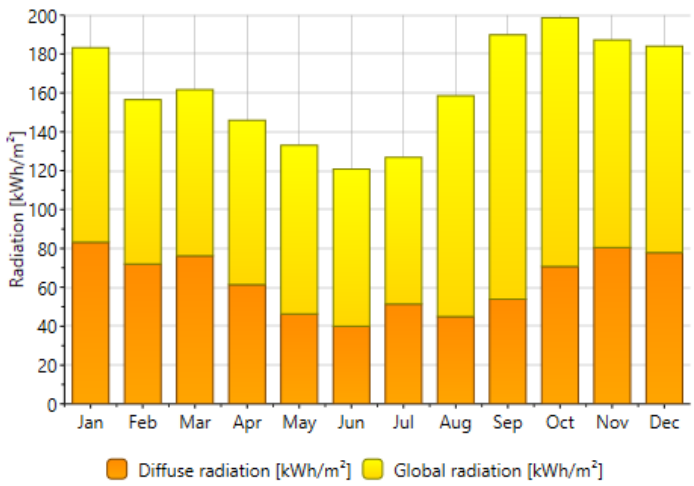

Figure 7 Average monthly solar irradiation Source: Meteonorm

3.2 Integration of HP and FPV energy technologies

To achieve universal energy access and sustainable energy supply, power systems are transitioning towards high levels of variable renewable energy sources which require improved energy efficiency and reliability (King & Van den Bergh, 2018). Meanwhile, energy systems are highly exposed to climate variability (Liu, et al., 2019), making it more difficult to predict climate-related renewable energies. Combining and operating these energy systems jointly is effective in promoting sustainable energy supply (Hua, Ma, Lian, Pang, & Yang, 2019). Among the various renewable technologies, HP with a reservoir stands out as a reliable and mature renewable energy source that can be used to complement variable renewable energy sources such as solar PV (Li & Qju, 2016). The deployment of hybrid FPV and HP systems around the globe is in infant stages. It is evident today that there is more theoretical work on how to optimize

production from hybrid HP-FPV for various scales, resource conditions and regions (Li, et al.2019, Ioannis, Sandor, Fabio, Thomas, & Katalin, 2016) and economic feasibility of HP-FPV hybrid plants (World Bank Group, 2019.) than the physical installations.

Integrating hybrid HP and FPV power can mitigate seasonal and daily constraints that both technologies face individually (Kougias et al.2016). HP with a reservoir can be used to control factors such as voltage regulation, synchronization, response to voltage, and frequency disturbance caused by connecting solar to the grid (Kropopski 2006). Meanwhile, FPV can complement the HP during the dry season and in daily operation to ensure that HP produces optimally during peak and dry season. The complementary roles are limited as FPV constrain the operation of a HP because a minimum level needs to be maintained to avert stranding the FPV structures, similarly to HP flow constraints that may also impact the revenues (Anindito, Rosa- Clot, Rosa- Clot, & Tina, 2019).

According to online publications, the total production for FPV-HP hybrid systems can double when 3-4 percent of large reservoirs are covered with FPV panels (World Bank Group, 2019.) or increase by 34% when 2.4% an average water basin is covered with modules (Cazzaniga et al. 2019). Increased production shown by the HPP FPV hybrid system is relevant for countries like Madagascar which have a steady growing demand and require a secure energy supply.

To adopt the least-cost technology combinations, it is essential to assess their LCOE and how it is impacted when the hybrid system is under operation. Zhenchen, et al. (2019) used the LCOE to determine the economic feasibility of large scale hydro-solar hybrid power including the long-distance high voltage for three hydropower stations located in Africa. They conclude that with a HP solar PV hybrid with a capacity ratio of 1:1 and transmitted on high voltage, the bundled LCOE is 6.72 USc/ kWh, which is 1.92 USc/kWh less than dispatching HP separately.

4 Theoretical Framework

4.1 Cost minimization

The neoclassical theory of production postulates that firms maximize profits and minimizes costs subject to certain technological constraints (Varian, 2000). A firm must minimize production costs to maximize profit. In the short run some factors of production such as capital are fixed while in the long run, all production inputs are variable as a firm may invest in new power plants, increase the installed capacity of the existing energy system or retire some operation. Deciding whether inputs are fixed or variable is empirical and firm specific.

For a cost minimization problem, the producer minimizes the cost function given a certain production function. The cost equation is a function of the inputs and their prices, while the production equation is a

function of the output level and the market price. Due to 25 years project lifetime for the hybrid energy system with fixed capital and variable labour. I consider a short run cost-minimization problem below.

$$Min_{\{L,K)}wL + rK_0 \qquad 1.0$$

Where L and K is labour and capital while w and r, wage and return on capital

$$s.t\ Q \geq\ F(L, K_0) \qquad 1.1$$

Where Q is output

$$L \geq 0, K \geq 0 \qquad 1.2$$

The production function $s.t\ Q \geq\ F(L, K_0)$ shows the technology of the firm that gives the maximum level of output that can be achieved for each input combination. To change the output, the producer needs to install more power plant capacity which will result in a cost increase. Changing the installed capacity of FPV is made easier by the modular nature of solar PV systems.

The solution to the short run cost minimization problem is derived by taking the first order conditions and the result is conditional factor demands which are expressed as a function of output level, Q and input costs, w, and r. The conditional factor demands are the optimal choice of factors of production, needed to achieve a certain level of output at

When the conditional factor demands are substituted in the objective function, it gives a short run total cost (CT) function, which shows the minimum cost of producing a given output level Q, given input prices w, r

$$CT_{SR}(Q, w, r)\ =\ wL(Q)\ + rK_0 \qquad 1.3$$

5 Methods and data

5.1 Methodology

Energy and electricity models are developed for power system analysis, operation and investment decision support (Ringkjøb, Haugan, & Solbrekke, 2018). They adapt a top-down (economics approach) or bottom-up (engineering approach), whereby the former analyzes the macro-economic relationships and long-term changes while the latter looks at detailed technical descriptions of the energy systems (Ringkjøb, Haugan, & Solbrekke, 2018). When examining the integration of intermittent renewable energy sources, both long term changes and technological characteristics are invaluable thus models can be captured in hybrid approaches (Fortes, Pereira, Pereira, & Seixas, 2014)

This paper adopts Hybrid optimisation model for electric renewabes (HOMER Pro) which works by combining engineering and economics concepts in a way to optimize production and consumption at the lowest possible cost (Homer Energy, 2020). HOMER Pro is the most common tool that can simulate a hybrid energy system on an hourly basis and categorize feasible hybrid systems based on net present costs

(Sinha & Chandel, 2014).The model is popular among researchers for optimizing different energy systems combinations such as run-off HP and FPV (Vasco, Silva, & Beluco 2018).

I use the model primarily to calculate total energy production for HP and FPV, total investment and operation and maintenance cost(O & M) and the per unit cost of energy for the individual energy systems over the project lifetime. I feed into HOMER pro the HP variables, available head, design flow rate, minimum and maximum flow ratio, turbine efficiency, losses, and stream discharge flows. HOMER Pro then calculates the electrical output from hydro turbines using the following mathematical formula (Homer Energy, 2020)

$$P_{hyd} = \frac{\eta_{hyd} \cdot \rho_{water} \cdot g \cdot h_{net} \cdot Q_{turbine}}{1000\ W/kW} \qquad 1.5$$

Where :

$\boldsymbol{P_{hyd}}$ = power output of the hydro turbine [kW]
$\boldsymbol{\eta_{hyd}}$ = hydro turbine efficiency [%]
$\boldsymbol{\rho_{water}}$ = density of water [1000 kg/m^3]
$\boldsymbol{g}$ = acceleration due to gravity [9.81 m/s^2]
$\boldsymbol{h_{net}}$ = effective head(m)
$\boldsymbol{Q_{turbine}}$= hydro turbine flow rate

I import into HOMER Pro a custom-made FPV hourly production profile which I import from PVsyst. I add a yearly load profile and the grid to cover the unmet demand. Due to a lack of real data related to the technical, economical, and operational characteristics of the existing energy systems in Madagascar, it limits in-depth modelling of each energy system as a lot of assumptions must be made. A sample of an optimization schematic in Homer Pro is shown in Figure 8

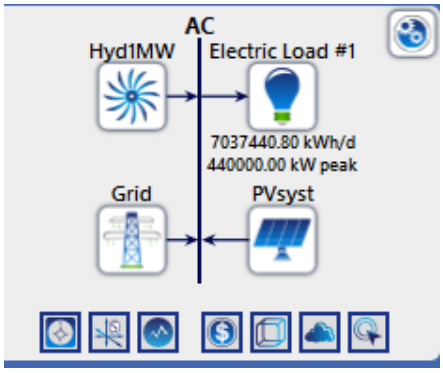

Figure 8 HOMER Pro schematic

I feed into HOMER pro detailed economic data: FPV and HP capital cost, O&M, replacement cost and discount rate. Then, the model optimizes production and consumption using the technological, resource constraints and economic inputs and sorts the results into several configurations of system combinations together with their costs. It works like a merit order matrix, meeting demand by utilizing the cheapest technologies first then expensive energy source in ascending order.

I use the LCOE method to analyze the energy cost of HPP and FPV. The LCOE formulae mirror the long ran average cost in producer theory as they both measure per unit cost of producing output and they are

based on the assumption that the producer chooses input combinations to produce a level of output at the lowest possible cost. The LCOE method has been applied extensively in the literature (Astariz, Vazquez, & Iglesias, 2015, Manzhos, 2013), financial institutions and governments alike (HM Government Department for business, 2016). to value energy systems, to determine whether to finance energy systems or when evaluating policy decisions concerning differential support of energy technologies. The LCOE is analyzed by HOMER Pro as the cost of energy (COE) for individual and combined energy systems. The LCOE is defined mathematically as:

$$\boldsymbol{LCOE} = \sum_{t=1}^{n} [(l_t + M_t)/(1+r)^t] \,/\, \sum [(E_t/(1+r)^t] \qquad 1.6$$

It = investment expenditures,
Mt **=** operation and maintenance cost
Et **=** electricity generated
r **=** discount rate
n**=** expected lifetime of the power

The investment expenditure and O&M costs over the project's lifetime are calculated based on discounting from a reference date and then divided by discounted energy production. The LCOE calculations carried out in this study are real LCOE because I use real discount rates which are not revised for inflation. Predicting inflation rates is complex and is laden with a high level of uncertainty thus real LCOE estimates are preferred as they offer sufficient financial details for this study.

The drawback of LCOE as a methodology of comparing energy sources is that it is highly sensitive to discount rates and uncertainty of future costs (Manzhos, 2013). Additionally, the method does not consider the impact of changes in the value of electricity throughout the day or the difference in the value of energy between dispatchable and intermittent generation (Snieckus, 2017)

The fundamental limitation of using HOMER Pro model in this study is that it lacks a direct component for modelling HP with a reservoir thus has no water balancing and dispatch function which the paper's area of interest. A possible solution is to adopt a HOMER pro based methodology that was developed by Fausto & Alexandre, (2014) which modifies a battery as a pumped HP. This approach is later adapted by Canales A, Beluco, & Mendes (2015) in optimizing a HP with a reservoir. Online publications about this methodology are sparse thus I do not employ it in the analysis. Lastly, HOMER Pro model is not suitable for modelling several energy systems as it has primarily been used in studies optimizing small scale on-grid and off-grid islanded community-based energy systems.

5.2 Reservoir modelling

There is no open access software or tool available to researchers and students for optimizing hybrid FPV plus HP with a reservoir. Researchers have developed their own mathematical codes and algorithms (Sterl, et al., 2018) or use existing models such as stochastic dual programming (Brandi, et al., 2016, Li, et al., 2019,) to assess the complementarity of HPP FPV operation. Therefore, the Excel-based model that I use optimizes HP dispatch targeting peak periods which generally have high energy production costs. FPV's production profile is imported into the model as a custom file. due to FPV's non-dispatchability, firm power is achieved from the hybrid plant by adjusting production from HP based on the assumption that HP can perfectly complement the stochastic output from the FPV.

The model optimizes production from HP using equation 1.5 subject to the following physical and operational constraints as suggested by Li, et al., (2019) and modified to fit hourly decision intervals. Due to hourly FPV production profile and monthly stream flows, it theoretically limits the time resolution analysis.

$$S_{i+1} = S_i + \Delta T_t[l_t - Q_t - El_t] \qquad 1.7$$

S_i and S_{i+1} are the reservoir storage before and after the *i*th period, in m³, respectively. l_t is the inflow in m³/s , Q_t is the water release in m³/s, El_t is the loss caused by evaporation and leakage, all in the *i*th period. *t* is the time period and ΔT_t denotes the number of hours in the *i*th period (m³/s) (Li, et al., 2019)

$$\underline{S_t} \ll S_t \ll \overline{S_t} \qquad 1.8$$

$\underline{S_t}$ and $\overline{S_t}$ represents the lower and upper reservoir limit in the *i*th period

$$\underline{Q_t} \ll Q_t \ll \overline{Q_t} \qquad 1.9$$

$\underline{Q_t}$ and $\overline{Q_t}$ indicate the lower and upper limits for water release

$$\underline{N_t} \ll N_t \ll \overline{N_t} \qquad 2.0$$

$\underline{N_t}$ and $\overline{N_t}$ indicate the lower and upper limits for HP output (MW) respectively, where the upper limit $\overline{N_t}$ equals the maximum installed capacity (Li, et al., 2019)

I feed average monthly stream flows and hourly energy costs for peak and off-peak periods in the model. The cost assumptions are 0.10 $/kWh (IRENA, 2017), 0.29 $/kWh (The World Bank, 2020) and 0.50 $/kWh (Labordena, Patt, Bazilian, Howells, & Lilliestam, 2017) for the night, daytime off-peak and evening peak period, respectively. The varying energy costs reflect the real expenditure incurred by the power utility in meeting the daily load. The assumption is that cheaper and stable energy sources are used for baseload, off-peak periods, while expensive thermal and diesel power plants are additionally used during peak periods in the evening. Comparable to the HOMER pro model, I do not have sufficient technical and price characteristics for existing HP plants hence they are not included in the modelling.

The main objective of the optimization is to assess how much water from HP can be saved to peak periods and quantify the extent to which the thermal plants are substituted. Additionally, quantify this reduction in relative terms using the hourly cost of production in Madagascar and comparing the LCOE of the hybrid plant and thermal plants.

5.3 Data

I used primary and secondary data sources for this thesis. The IPP availed project related official documents for the HPP project. I undertook discussions about the project scope, operation, and Madagascar's energy sector with the IPP. HPP project related data: reservoir properties, turbine type, hydrological and predicted monthly energy production between 1901 and 2013.

The IPP provided economic data; investment and operation costs which were denoted in euro. I use the exchange rate of 1 Euro to 1.136 dollars (XE, 2020) as dollars are used by most power utilities in sub-Saharan Africa and international energy organizations like IRENA and the World Bank to denote energy costs and electricity tariffs

The secondary data sources were reports from international organizations' publications and conferences. (IRENA, 2019, The World Bank & SERIS, 2019, ISES & GSC, 2020,) and reviewed journal articles such as Oliveira-Pinto & Stokkermans, 2020,). These secondary sources were relevant in establishing Madagascar's energy sector, determining FPV technology status, energy costs, investment, and operation costs. Data from Multiconsult Norge AS helped in developing a realistic daily demand profile for Madagascar and is similar every day of the year. This limits its accuracy because usually weekends and holidays record lower demand and the demand profile does not take this into consideration. The demand profile was useful in establishing the total percentage contribution of the hybrid system to the energy sector and determining peak period energy needs

I simulate a simple FPV system on PVsyst[4] version 7.0 to generate total annual and average hourly production values. The software is used by researchers and students to design solar PV systems (PVsyst, 2020) and is the most bankable and acknowledged tool of optimizing land-based system. The main challenge with simulating FPV in PVsyst is that the software has not incorporated the thermal effect to show heat exchange between solar PV modules and water (Oliveira-Pinto & Stokkermans, 2020) thus the predicted production can be theoretically lower as it does not reflect the efficiency gain published by Choi, (2014) or Ioanni, et al., (2016).

Lastly, I import meteorological data from Meteonorm software, version 7v 7.3.3 which is relevant for FPV simulation.

[4] PVsyst is one of the oldest photovoltaic software that is designed to be used by architects, engineer and researchers for simulating and optimizing solar PV systems. The software was developed by scientists at the University of Geneva in Switzerland. More information on the website www.pvsyst.com

5.3.1 HPP with reservoir

The IPP plans to install a 120MW hydropower system with the following technical characteristics listed in *Table 2*. This data is relevant in calculating the total annual production.

Variant	Detail
Type/design	Francis
Available head (m)	127
Design flow rate(/s)	110000
Maximum flow ratio (%)	110
Minimum flow ratio (%)	14
Efficiency (%)	91

Table 2Hydropower inputs

Production from the HP with the reservoir is dependent on reservoir size, hydroelectric properties in Table 2, and stream discharge flow in Figure 9. The volume at the normal reservoir level is 15.8 million $hm^{3,}$ and the mean annual discharge is 103 m^3/s.

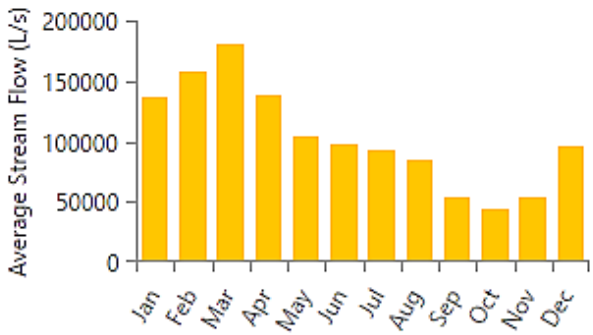

Figure 9 Average monthly stream flow

5.3.2 FPV simulation

The IPP proposes a 70MW grid connected FPV plant which I simulate on PVsyst. First, I define the geographical site using the area coordinates and altitude values and import the meteorological data from Meteonorm. I select the albedo[5] value of 5% which is in the range recorded by Liu, Krishna, Lun, Reindl, & Zhao, (2018) of between 5% and 7% at Singapore's FPV testbed.

I choose system components where I use monocrystalline Longi Solar 450Wp PV modules. Dual glass structure modules are preferred for FPV projects as they provide greater protection of the cells from water damage, reduce probable chemical erosion thus minimizing potential induced degradation. I select 4200 kW SMA sunny inverters, central inverters are preferred for a large PV plant. The inverters used in the actual project should be able to offer ancillary services. *Figure 10* shows a sample of what a completely specified system looks like in PVsyst.

[5] Albedo effect is used to examine a surface ability to reflect sunlight on a scale of 0 to 1. It measures how much light that hits a surface is reflected without being absorbed.

Parameters for detailed losses, thermal and soiling losses are set to default as provided by the software. Thermal losses are dependent on mounting, I assume a large footprint high density polyethylene Ciel et Terre floaters which have a standard tilt of 12 degrees and are known to have a low cooling effect gain which is closer to a well-ventilated inland system (Oliveira-Pinto & Stokkermans, 2020), thus I choose a default constant loss factor 20.0 W/m^{2}k. Lastly, not much is documented on the soiling of FPV systems thus I assume soiling factor 2%, default value in PVsyst.

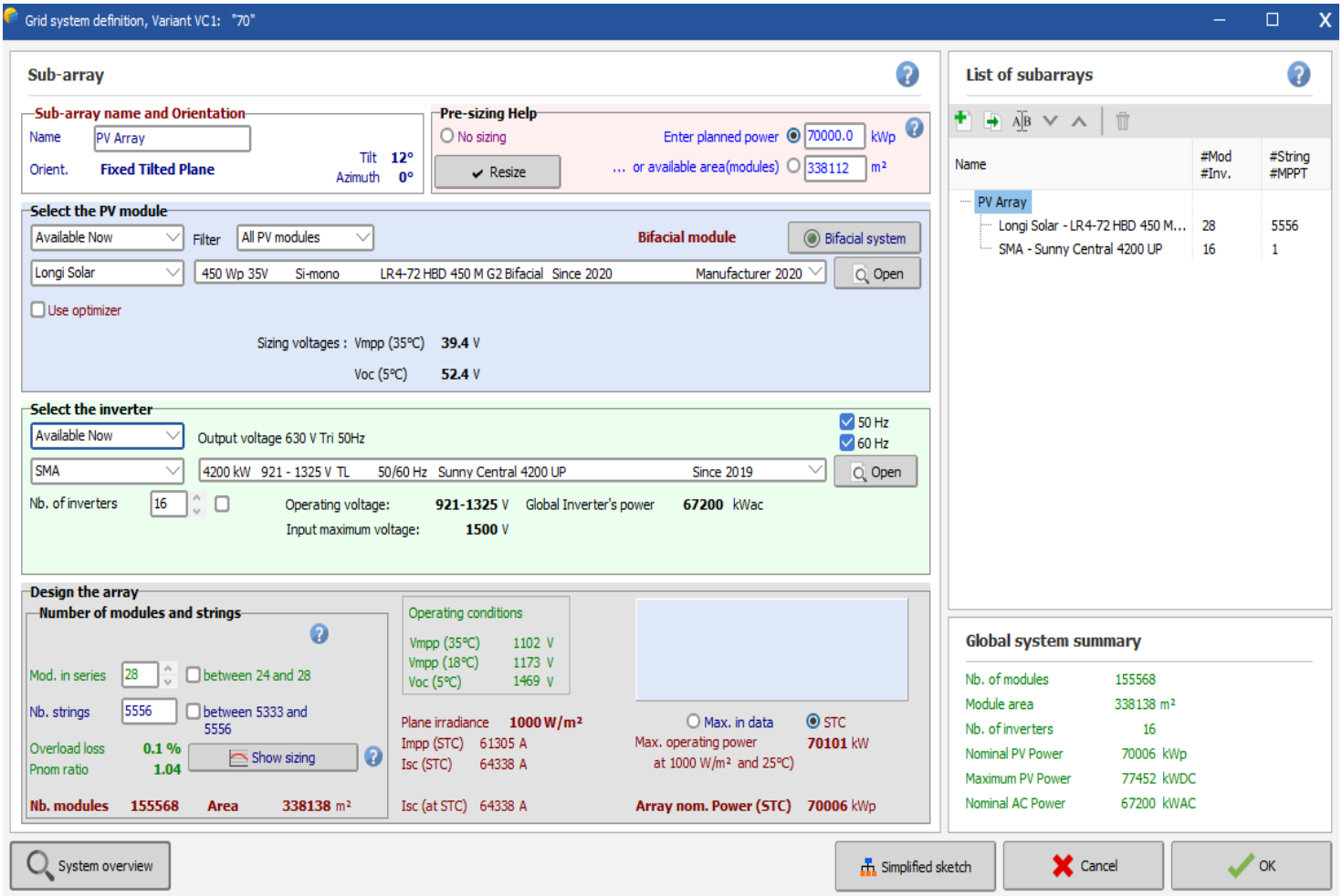

Figure 10 FPV simulation

5.3.3 Madagascar's daily load profile

The annual demand in Madagascar is predicted at 2480GWh in 2024 (The World Bank, 2020), thus I adapt a daily demand profile retrieved from a previous assignment by Multiconsult Norge AS in 2015 and modify to fit the predicted demand increase in 2024 when the hybrid plants are expected to be commissioned. In the analysis, the load profile is scaled down to reflect a demand factor of 66%. The demand curve is similar for each day of the week with two peaking periods as shown in Figure 11

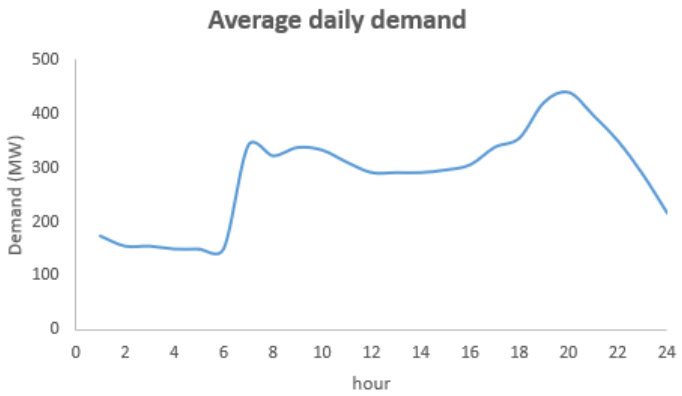

Figure 11 Average daily demand

5.3.4 Average hourly energy cost

The cost per hour shown in Figure 12 is chosen based on average costs for the different energy technologies that generate electricity in Madagascar. The assumption is that cost of energy rises as demand increases as higher energy technologies are used to meet the load. Madagascar relies mainly on HP and thermal plants thus 0.10$/kWh is an average HP energy cost (IRENA, 2017),0 29$/kWh is the average energy cost in Madagascar (The World Bank, 2020) where I assume that demand is met by a combination of all the technologies with HP covering a large percentage of the demand. The last price is 0 50$/kWh which was published by Labordena, Patt, Bazilian, Howells, & Lilliestam, (2017) representing the average cost of energy for diesel plants, the assumption is that during evening peak periods, thermal and diesel plants are increasingly used to meet demand.

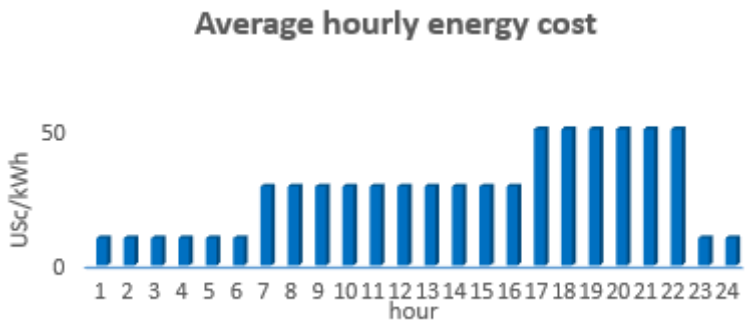

Figure 12 Hourly energy cost

5.3 5 Hybrid system cost

5.3.5.1 Investment costs

Investment costs, commonly known as capital expenditure for energy systems is dependent on total installed capacity, technology, location, and the suppliers. FPV components costs include pontoon or separate floats, mooring systems, PV modules, inverters, labor costs, underwater cables, and electrical connections. The costs of FPV may vary depending on region to another depending on water level variation, wind load tides, distance to shore , local regualtion and bathymetry (Paton, 2020). Cost of PV modules and inverters have decreased significantly in the past years, they however still make up a huge share of the total investment.

FPV projects have published investment costs of between 480 and 1100$/kW (ISES & GSC, 2020). I assume an investment cost of 1000 $/kW for the FPV.

The capital cost of HP system comprises of cost of turbines, generators, sub-station, engineering, and construction. The total installed costs for large HPP range from 1000 -3000 $/kW (IRENA, 2020). Depending on the location and needed infrastructure, some projects may fall below or above this price range. The cost of HPP which is retrieved from the IPP's official documents is 4865 $/KW.

5.3.5.2 Operation and maintenance costs

Recurring labor and material costs that are essential to keep a system running are valued. Energy system components must be routinely inspected and serviced to maximize energy production and prevent system breakdown. Solar PV maintenance includes cleaning PV modules, active monitoring, inverters inspection, critical and non-critical repairs. Specifically, the FPV system is in the aquatic environment hence attract biological life resulting in frequent routine maintenance such as checking wire connections and components for moisture accumulation (Oliveira-Pinto & Stokkermans, 2020). Therefore, I assume an annual O&M of FPV at 5% of the investment cost, which is higher than that of terrestrial systems which are calculated at 1.5% (Jager-Waldau, 2018).

O&M activities for HPP include the refurbishment of mechanical and electrical parts like a turbine, generator rewinding, overhaul and investment is control systems. The annual O&M cost for the HP plant is $7million for the first 5 years and $5million from the sixth year onwards.

5.3.5.3 Replacement costs

This is the cost of replacing an energy system component at the end of its lifetime. This cost may vary from the initial cost due to a change in technology price over time. Inverter for solar PV energy system is replaced once in its lifetime. I discount the initial inverter costs at year 15; thus I use 38 $/kW. I do not add HPP replacement costs as the turbines and generators can operate throughout the project lifetime.

5.3.5.4 Discount rate

The discount rate differs widely across countries and technologies depending on the level of risk. Generally, the cost of capital is higher in developing countries and most renewable energy projects are developed using private finance (Steffen, 2018), making information about financing cost unavailable to researchers (Donovan, 2012). This paper adopts 12% as the discount rate for solar PV and HPP for the base case. I perform sensitivity analysis using different discount rates for the FPV as shown under the sensitivity analysis sub-section

5.3.5.5 Project Lifetime

The useful lifetime for a PV plant is 25 years, while HPP's is 35 years based on the PPA signed between the IPP and JIRAMA. However, this is a hybrid project thus its lifetime depends on the useful lifetime of the FPV which is 25 years.

6 Results and Discussion

6.1 LCOE

The assumption is that all energy produced by the HPP and FPV is fed to the grid thus valued in the LCOE calculation. The systems are in different locations, therefore transmission constraints related to substation capacity is irrelevant. A 70MW FPV system with a total annual production of 139GWh; a yearly degradation factor of 0.5%, the investment cost of 1000 $/kW, annual O&M at 5% of the investment cost, discount rate at 12%, has a resulting LCOE is 0.089$/kWh. While the HP has an annual production of 745 GWh, an investment cost of 4865 $/KW, O&M of approximately 1.3% of the investment cost, resulting to an LCOE of 0.10$kWh. The LCOE for the hybrid FPV HPP is 0.105$/kWh, which is less than the published LCOE for thermal plants of 0.50$/kWh (Labordena, Patt, Bazilian, Howells, & Lilliestam, 2017).

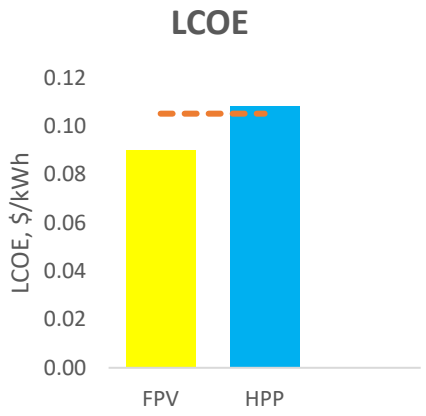

Figure 13 LCOE

The LCOE for FPV falls within the range published by Oliveira-Pinto & Stokkermans, (2020) and (Bellini, 2020) and is not far off from that of terrestrial solar plants (IRENA, 2017). Some publications have recorded lower LCOE of 0.04 and higher, of 0.14 $/kWh (ISES & GSC, 2020) for various FPV plants around the world. This variation is dependent on assumptions made on discount rates, investment and O&M costs. For instance, investment costs for FPV technologies ranged between 480 $/kW and above 1000 $/kW (Paton, 2020). Investment costs vary from one site to the other and are greatly influenced by bathymetry, water salinity, proximity to shore and local regulations.

LCOE for HP falls within the range reported by IRENA (2017) of small scale HP in developing nations. FPV plant has a lower LCOE than HP's and this can be the hybrid project lifetime is shorter than what is used for individual HP in the PPA. FPV and HPP LCOE is both lower than the average energy cost in Madagascar which is 0.29$/kW (The World Bank, 2020) and that of thermal plants; 0.50 $/kWh (Labordena, Patt, Bazilian, Howells, & Lilliestam, 2017). Individual HP and FPV record low energy costs supporting prediction by IRENA, (2017) that solar PV would join HPP as a low-cost energy source in 2020.

A possible study area is to analyze how the LCOE for individual energy systems vary under supply side curtailment or transmission constraints when the HPP and FPV are connected to the same substation. The

decision variable would be to assess the potential of developing a FPV which when added to the HP make the hybrid system's rated power is higher than that of the existing transformer and analyze the utilization rate of the system and the possible economic implications

6.2 Contribution to Madagascar's energy supply

At the time of commissioning in 2024, the hybrid system total annual production will be 884GWh, which covers approximately 40% of Madagascar's energy demand. This is a significant addition to the overall energy sector and will substantially reduce the cost of energy as the hybrid plant cost is expected to considerably reduce based on hybrid system low LCOE of 0.105 $/kWh. FPV contributes approximately 6% of total energy supply while HPP contributes the remaining 34%. Using the LCOE figures above and the percentage share of the HPP FPV in Madagascar's energy mix, the cost of producing energy reduces by approximately 18%.

Madagascar uses thermal energy during peak and off-peak periods, however, periods with high energy demand have a higher share of thermal plants. To reduce the cost of energy, it is important to introduce and operate energy systems that can offer supply electricity during all periods and especially during peak periods where IPPs which charge a premium price for electricity. Therefore, in the analysis, I assess how much the hybrid plant contributes to peak and off-peak periods on a rainy and dry season day. Lastly, I analyze the operational pattern of the hybrid plant when Madagascar is saturated with more low-cost energy sources or the IPP operates in a more liberalized market.

6.2.1.Hybrid operation on a rainy day

FPV production is weather dependent hence cannot be relied on for load peaking, on the other hand, HPP is a firm and flexible technology that can be used for baseload and during peak periods. On a rainy day, HP operates at full capacity both when operated separately or jointly as shown in Figure 14 and there is less flexibility to save water for peak periods. The IPP must operate the HPP optimally at each hour or spill water otherwise, the operation algorithms can vary depending on the month as some months like January and December receive higher rainfall than February for instance. Therefore, the HPP can be used throughout the day to balance production FPV production and ensure steady supply during the day. Furthermore, if the total demand does not increase at the growth rate of 5% annually as predicted by the World Bank (2020), the percentage contribution from the hybrid plant will increase substantially.

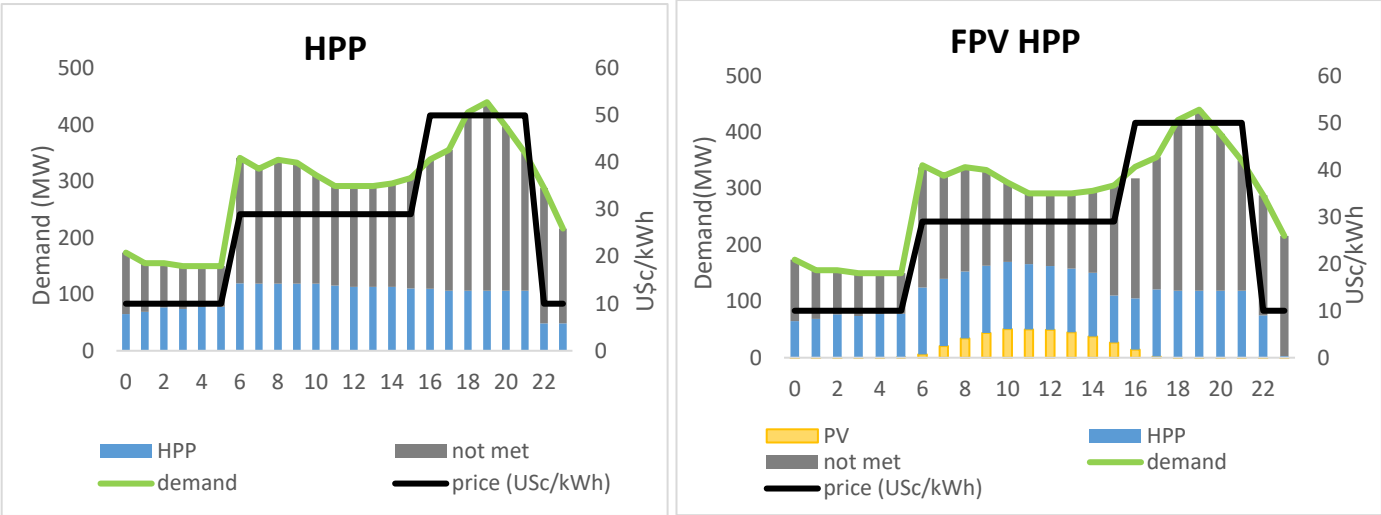

Figure 14 Hybrid operation on a rainy day

6.2.2 Hybrid operation on a dry day

For this analysis I assume a day in October, which is a dry month with low HP and a higher FPV production. The HPP operates at a lower capacity when compared to its operation on a rainy day. HP can be used as a firm energy power source or balancing FPV and for peaking as shown in Figure 15. The daily production from HPP drops by approximately 54% on a dry day, this is not constant for all dry months as the hydrological conditions vary. FPV production is higher on a dry day than a rainy day by approximately 14%, due to clear skies, thus can cover some of the load previously met by HP plants during the rainy season. The total contribution of the hybrid system to daily demand is circa 22% compared to 40% on a rainy day

In terms of scheduling the HP, the IPP can increase HP utilization in the evening periods when demand is high and rely upon FPV during the day to reduce the thermal share.

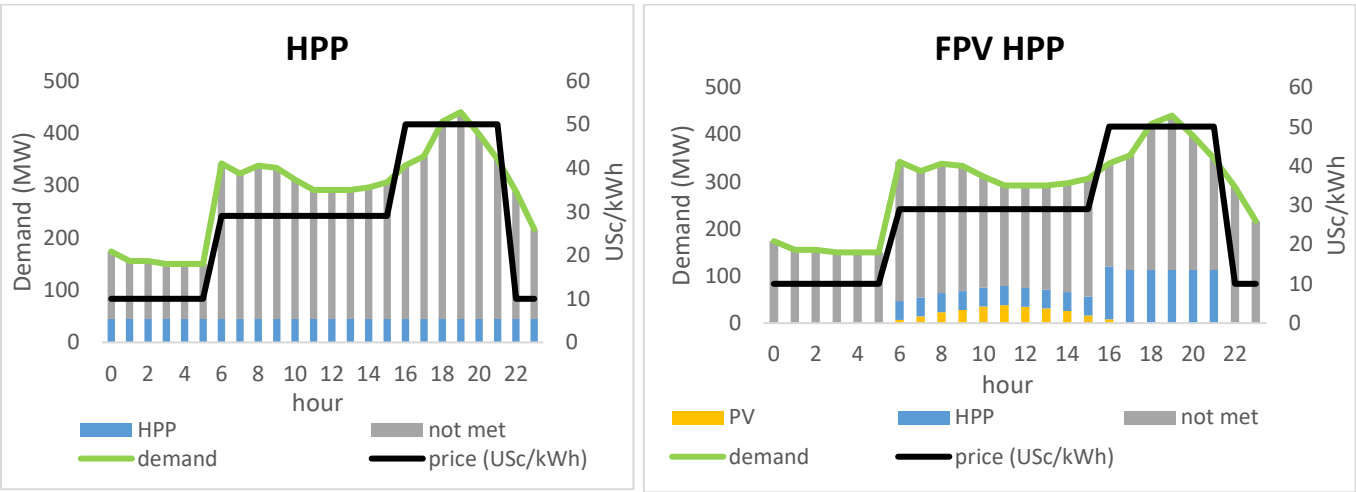

Figure 15 Hybrid operation on a dry day

FPV covers slightly above 6% of the daily total demand, which is a direct replacement of energy sources which can cost five times thus offering a direct financial saving for the power utility. Thus, the power utility

in the short-term may need to contract more thermal plants to cover the unmet load, in the medium and long term investing in more HP and FPV power plants are necessary.

6.2.3 Hybrid operation under constrained demand

This analysis offers an insight into how the hybrid plant energy supply changes when the energy sector is saturated with cheap energy sources. The total demand load to be served by the hybrid system is scaled down to 130MW peak as shown in Figure 16. The HPP operates at a lower capacity and almost all the demand is met in all hours when it is operated jointly with the FPV compared to when it operates alone. The total production from HP operating separately and jointly with FPV is 1.7GWh and 1.5GWh, respectively. FPV plays a pivotal role in ensuring that the daytime demand is met thus enabling HPP to operate optimally during the evening peak, off peak night, and early morning.

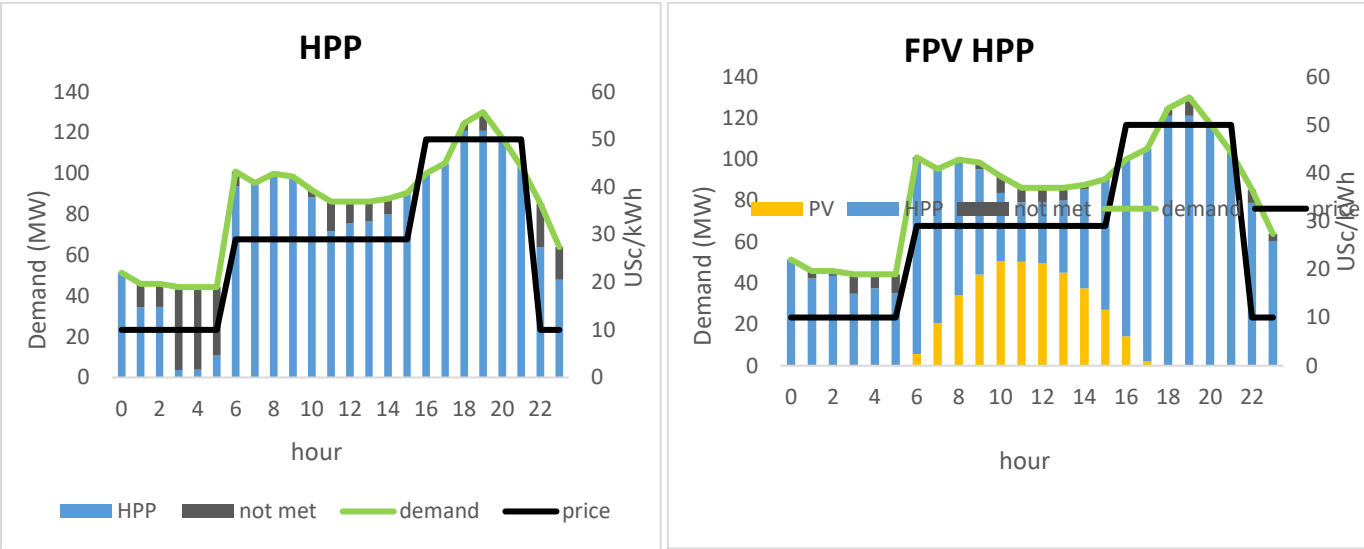

Figure 16 Hybrid operation under constrained supply

This is irrelevant for Madagascar's energy sector in its present state as it needs cheaper energy and constraining supply from renewable energy sources can result in an undesirable investment in fossil fuels. In a liberalized market or a market flooded with cheap energy sources, the IPP can save water for other periods or enter bilateral contracts with the IPP to offer balancing and reserve services. The operational strategies of such kind of arrangements are beyond this paper, however, I presume the IPP will be keen on maximizing revenue thus increasing HP production in hours with a high energy value.

6.3 PPA arrangement

The assumption is the two power plants are a hybrid power system owned by one IPP hence can be contracted under one PPA. This alters the technical and potential commercial characteristics of the existing PPA as the installed capacity increases to 190MW and the two plants have different LCOE as shown above. This changes the contractual arrangement between JIRAMA and the IPP, and they can contract the FPV separately or add it to the existing PPA. For instance, the IPP is 95% certain of supplying 580GWh from HPP annually, hence receive a tariff that is sufficient to cover 85% of the IPP's investment costs. The tertiary and secondary energy price is low and covers other costs. It is not economically feasible to contract

the FPV production under the secondary and tertiary energy tariff as their price is lower than the FPV's LCOE.

I assess the FPV's production probability distribution in PVsyst, the findings are that FP's 95% production guarantee is 133GWh a year as shown in Figure 17. When added to HP's 95% secure generation potential, the total firm energy increases to 713GWh, which can be contracted under the primary tariff. The remaining 6 GWh of FPV production can be placed under secondary and tertiary purchase prices. Negotiations between the IPP and the power utility are necessary to establish the possibility of contracting the two power plants separately or under one power purchase arrangement. The power systems can be operated as a hybrid to derive the benefits which are interspersed in this document.

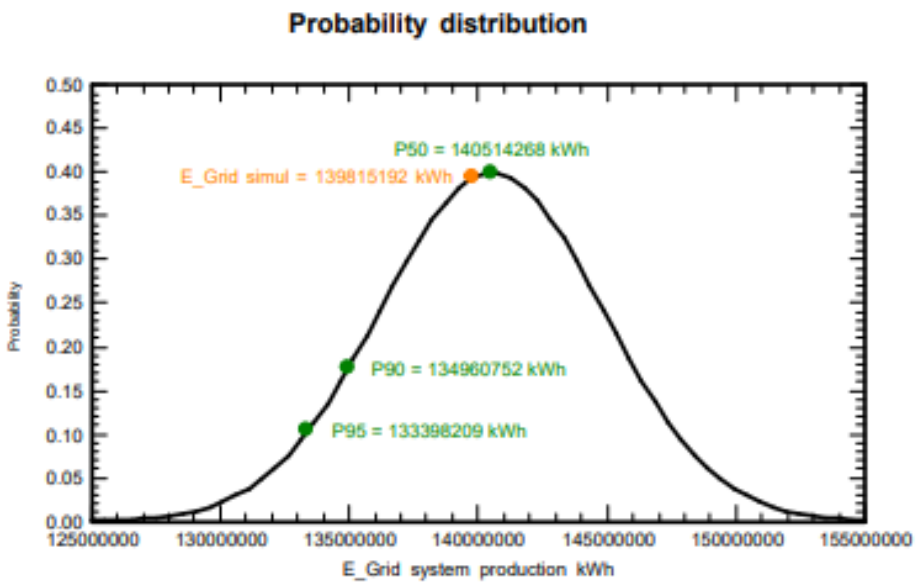

Figure 17 Probability distribution

For efficient operation, an IPP can install a sky camera to detect cloud movements and ensure that HP is ramped in time to pick the load from the FPV when the clouds cover the sun which can reduce direct horizontal irradiation by 50% thus affecting production (Alam & Sutanto, 2014)These fluctuations in production can be predicted and possibly resolved by looking at time series data, but their exact time of occurrence is unpredictable (Kleissl, 2013).

A study can be carried out on strategies an IPP can undertake when deciding the production timelines. The decision variables are dependent on reservoir size and energy storage potential, the costs of spilling water and the marginal losses of not receiving the secondary and tertiary energy tariff.

6.4 Sensitivity analysis

LCOE is an appropriate tool for comparing energy technologies but it is also highly sensitive to the parameters which are used in its calculation. The most important parameters that influence the LCOE are the component prices, discount rate and the inflation rate. The developer must choose realistic assumptions for these inputs of these and perform a sensitivity analysis to incorporate the market risk and uncertainty in the

cost. I conduct a sensitivity analysis for the FPV, as it is a new technology with a steep learning curve. The component prices and risk factors are bound to change when FPV is deployed on a large scale. .

6.4.1 Change in discount rate

The LCOE is highly sensitive to the discount rate. Different discount rates can be applied to different technologies as they may face differing risk profiles. Some argue that a risk-free discount rate is the most appropriate for comparing technologies. Therefore, a developer needs to make realistic assumptions that are sometimes constrained with the cost of financing. In this sensitivity analysis, I introduce discount rates between 9% and 13% to analyze how the LCOE of FPV changes as shown in Figure 18. The LCOE changes linearly and it is between 0.076 and 0.0933 $/kWh.

Figure 18 Change in discount rate

6.4.2 Change in Investment cost

Cost of components such as modules, inverters, mooring and anchoring structures take up a large share of the investment costs. As reported by IRENA (2018), the prices for solar PV modules and inverters have been reducing drastically since 2010, thus are not expected to reduce drastically low because they have been historically low. On the other hand, prices for anchoring and mooring systems are considerably high and are expected to decrease when FPV deployment increases. I consider a price decrease of 5 % ,10%, 15 % and 20%. The LCOE varies between 0.07 and 0.08$/kWh as shown below in Figure 19.

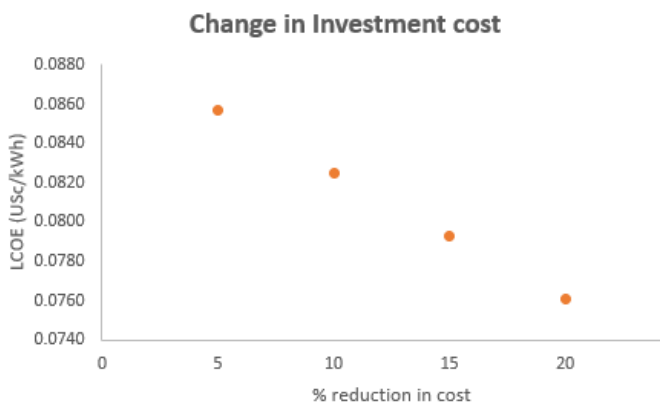

Figure 19 Change in Investment cost

7 Conclusion

This paper presents the economic performance of integrating and operating FPV and HP as a hybrid system in Madagascar. The LCOE for individual energy systems was assessed and was found to be between 0.07 $/kWh and 0.108 $/kWh which leads to an 18% reduction in energy costs. The weighted LCOE for the hybrid system is 0.105, lower than the published cost of energy from thermal and diesel plants, and the average cost of producing energy in Madagascar. It is evident that the hybrid system is cost-effective and fits Madagascar's universal energy access goal.

The superiority of operating a hybrid HPP FPV jointly system is further supported in this analysis by comparing it to operating separate HPP or FPV system . Primarily, HPP FPV has higher firm energy production of 713 GWh up from 580GWh when HP is operated alone, which increases the percentage contribution of secure renewable energy to Madagascar electricity sector, reduces reliance on expensive carbon-intensive thermal plants for offering base power and peaking power especially on rainy days. Additionally, HP has a small reservoir which is effective for daily peaking and load following when FPV is under operation thus easing FPV grid integration. However, its size limits energy storage for a long period thus in the dry period, FPV compliments the HPP by covering some of its load. However, Madagascar should prioritize the fast development of more HP and FPV plants under the least cost electrification plan for a steady supply of cheaper electricity in dry months.

The high cost of producing electricity in Madagascar and low investment in infrastructure has culminated into very low electricity access, which in turn has limited economic development and has resulted in a vicious cycle of stagnation in electricity demand and poverty. Deploying low-cost energy technologies such as HP which are listed under Madagascar's electrification strategy and integrating them with FPV can stimulate demand as electricity access becomes affordable to the population which in will increase funding in infrastructure. This will offer a pathway for a low-carbon electricity sector and act as a catalyst for an optimal liberalized electricity market. Furthermore, developing HP and FPV technologies which are in Madagascar's electrification plan and operating them jointly will result to greater utilization of the grid infrastructure while limiting grid imbalances which is revolutionary for variable energy growth.

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