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Optimising Existing Hydro Power Stations in Scotland with Floating Photovoltaics

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Signed: Darren MacIntyre Date:14/07/2020

Abstract

The UK has committed to ambitious targets relating to renewable energy technology and greenhouse gas reduction. Electrical power generation from non-polluting and sustainable sources plays an important role in this regard. Floating photovoltaic farms (FPV) have great potential when co-located with hydropower plant. Benefits include water preservation and higher power generation efficiency, no land costs, lower construction costs, reduction of algae, and lowering of natural methane emissions that come from standing bodies of water.

The market for FPV is dominated by nations where tropical or dry arid conditions prevail. The extent to which an FPV-PHS plant in the North of Scotland is feasible was assessed in this study.

Foyer PHS operational data was collected and analysed, then modelled in HOMER Pro with proposed FPV of 125MW and 250MW installed capacities overlaid, using generic bifacial and standard monocrystalline PV panels. Optimal generation with minimal reservoir surface coverage was found to be achieved from a 250MW FPV plant using bifacial 72-cell modules, as modelled in PVSYST 7.02. Technical feasibility analysis indicates 204934 MWh of electricity annually to the grid is achievable. Capacity of 9.36%; water conservation of 206,641,830kg; and potential annual CO_2(eq.) savings of 57,749 tonnes was calculated.

Financial analysis of FPV over 25 years, with discount factor of 6%, returns an NPV of -£49m and IRR of 3.26%, when the electricity strike price is £50. A negotiated discount of 15% and solar panel price updated, an NPV of £11.7m and IRR of 6.73% is achievable when the electricity strike price is £60.

Assumptions that FPV operational budget will be lower than conventional solar plant is disputed based on evidence of the highly detrimental impact of bird activity on FPV plants in the UK. The risk of fire resulting from panel stacking following severe weather is raised for the first time.

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Nomenclature

Symbol	**Description**	**Units**
AC	Alternating Current	
CAPEX	Capital Expenditure	
CB	Circuit Breaker	
CF	Capacity Factor	
CEC	Connection Entry Capacity	
CO_2	Carbon Dioxide	
COP	Code of Practice	
DC	Direct Current	
EBOS	Electrical Balance of Systems	
ENA	Energy Networks Association	
FPV	Floating Photovoltaic	
FiT	Feed in Tariff	
kW	Kilowatt	
kWp	Kilowatt Peak	
GW	Gigawatt	
GMPV	Ground-Mounted Photovoltaic	
HV	High Voltage	

IEEE	Institute of Electrical and Electronics Engineers	
IRR	Internal Rate of Return	
LCOE	Levelized Cost of ENERGY	
MW	Megawatt	
MWh	Megawatt hours	
NPV	Net Present Value	
OPEX	Operational Expenditure	
PV	Photovoltaic	
SBOS	Structural Balance of System	
SLD	Single Line Diagram	
SSE	Scottish and Southern Energy	
TEC	Transmission Entry Capacity	
UK	United Kingdom	
USD	United States Dollar	
Wp	Watt Peak	

1 Introduction

Across nations globally, consensus exists on the need to tackle greenhouse gas (GHG) emissions to limit global warming and impacts of climate change (UN Environment Programme 2019). The astronomical rise in the level of GHG carbon dioxide, raised global emissions total to a staggering 36573 metric tonnes in 2018 (Global Carbon Atlas 2019). Ranking as a top 20 contributor (ibid.), UK emissions totalled 365.7 million tonnes (Mt) of CO_2 in 2018 (Department for Business, Energy and Industrial Strategy, 2020) though 2019 emissions are predicted to be 3.9 percent lower at 351.5 million tonnes (ibid.). In 2019, carbon dioxide accounted for 81 per cent of total UK greenhouse gas emissions (Department for Business, Energy and Industrial Strategy, 2020).

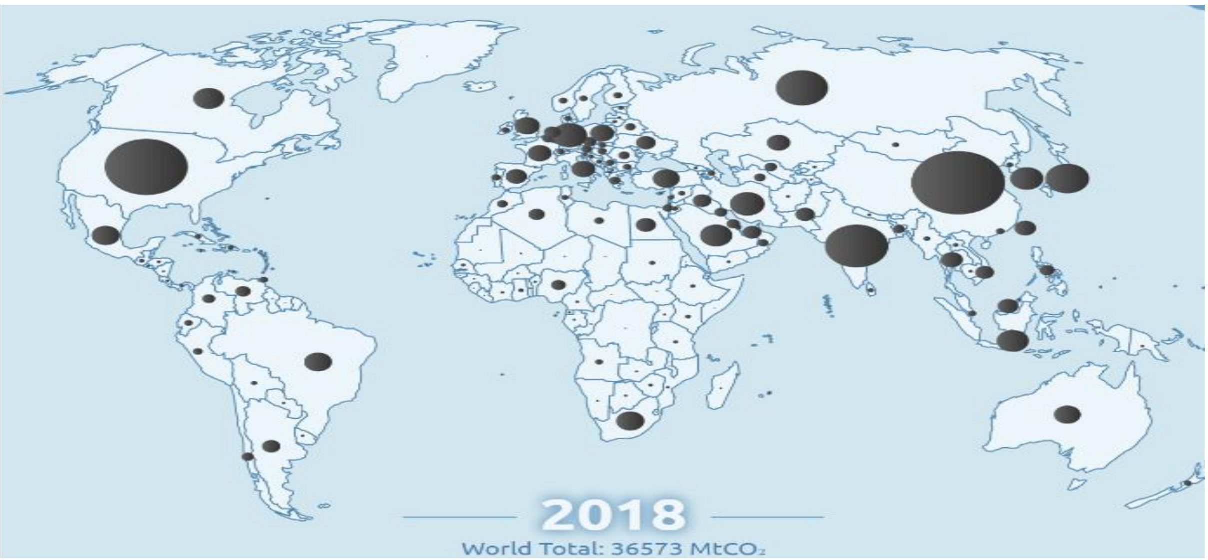
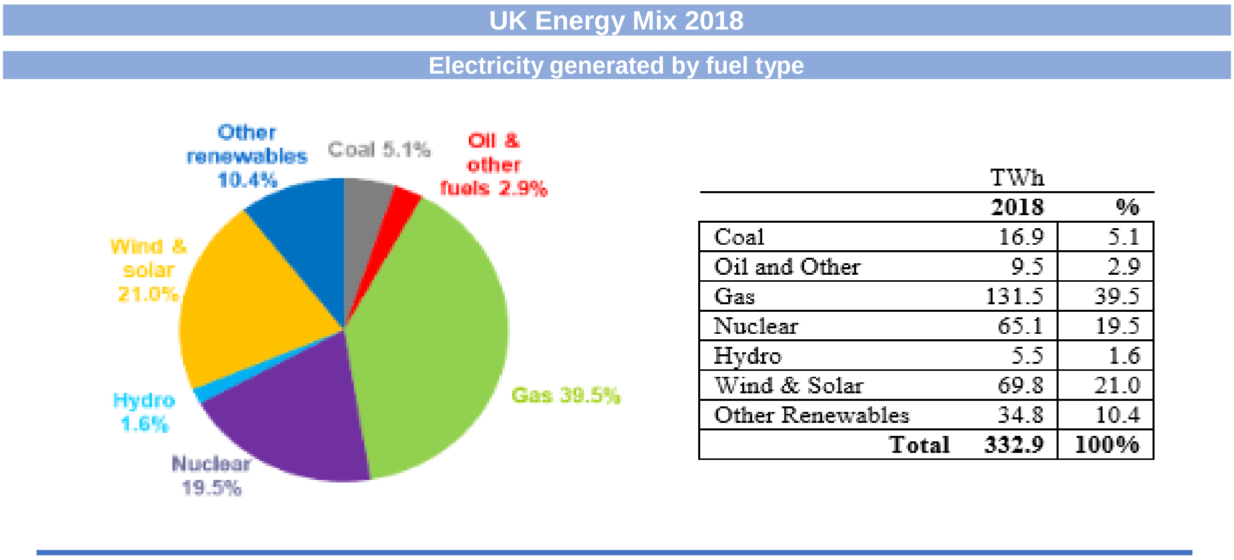


Figure 1 - Global CO_2 Emissions Map for 2018

International targets, agreed between world leaders, aim to strengthen the global response to the threat of climate change and lead to a reduction of greenhouse gas emissions. Electricity generated from fossil fuels is an important source of GHG released into the atmosphere. Impetus to increase electric generation from renewable sources becomes increasingly important if EU targets are to be achieved.

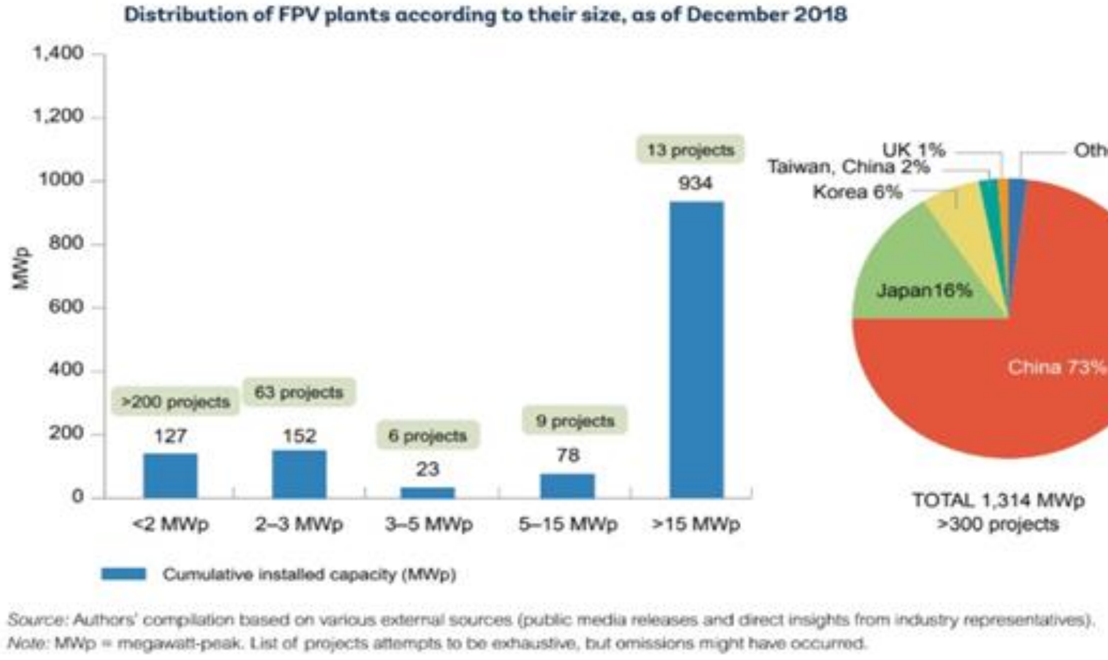
The Department for Business, Energy and Industrial Strategy (2019) report electricity generated from fossil fuels accounted for 47.5% of the UK energy mix in 2018 while renewables accounted for 33% (see Figure 2). An increase of renewable sourced energy generation is required to reduce CO_2 emissions and meet UK Government obligations.



	TWh 2018	%
Coal	16.9	5.1
Oil and Other	9.5	2.9
Gas	131.5	39.5
Nuclear	65.1	19.5
Hydro	5.5	1.6
Wind & Solar	69.8	21.0
Other Renewables	34.8	10.4
Total	**332.9**	**100%**

Figure 2 - UK Energy Mix in 2018 (Department for Business, Energy and Industrial Strategy 2019)

An interesting new application of solar photovoltaic technology is floatovoltaics, also known as floating photovoltaics (Bennington-Castro 2019). Floating photovoltaics (FPV) refers to solar modules placed on floating structures on the surface of a body of water, as opposed to traditional land-based ground mounted photovoltaic systems (GMPV). FPV may be deployed offshore and onshore (Bennington-Castro 2019). While the former has experienced the major challenges of operating in a marine environment such as increased cost of installations due to water depth, currents, high wave activity, salt mist corrosion, material stress and fatigue from constantly moving structures, and other important factors (Rosa-Clot and Tina 2017, p.21), the latter is in the nascent stage of market development having rapidly grown since 2014 (NREL 2019), with many large-scale deployments over recent years. In December 2018, around 287 projects of under 15MW capacity with total cumulative installed capacity of 380MWp had been deployed, along with 13 projects with capacities greater than 15MWp and total cumulative capacity of 934MWp installed (World Bank Group, ESMAP and SERIS 2018, p.58). Most projects deployed have been in Asia, although one percent of deployments were United Kingdom FPV installations (Figure 3 refers). Currently, the UK has built 6 floating plants, with capacities ranging from 50 kWp to 6.3 MWp (ibid.).



Source: Authors' compilation based on various external sources (public media releases and direct insights from industry representatives).
Note: MWp = megawatt-peak. List of projects attempts to be exhaustive, but omissions might have occurred.

Figure 3 - Distribution of FPV plants according to size, as of December 2018

1.1 Overview of UK FPV Plants

Costing £3.5m and operational since 2016, Godley Reservoir in Hyde is host to the second largest floating solar farm in the UK, having an installed capacity of 3MW (see Figure 4). Expected to power around 35% of the local water treatment plant needs , around 12,000 individual solar panels cover an area of 45,500 square metres, and generate 2.7 GWh per year of renewable, zero-carbon electricity (Hibbert 2016). Floating solar farms are advantageous to water companies as they provide an onsite power source without impacting land use (Spencer et al. 2019). By covering the surface area of the reservoir, solar arrays may reduce water evaporation, while the cooling effect of the water may increase the energy yield of the solar cells (Broom 2019; Spencer et al. 2019).

Figure 4 - QEII Floating PV plant

Figure 5 - Godley Floating PV plant

The 6.3MW installation lies on the surface of the Queen Elizabeth II reservoir (see Figure 4) which is situated in Walton-on-Thames, Surrey, and cost in the region of £6.5 million. It is connected directly into Thames Water's private network. The plant comprises of 61,000 floats on which 23,046 solar panels are secured, fixed in place with 177 anchors, secured by professional divers (Lightsource BP 2016). With coverage of the 57,000m2 surface area, the solar arrays generate 5.8 million kilowatt hours annually, enough to power 1,800 homes (ibid.). Supplying green, renewable solar electricity to the utility company via a Power Purchase Agreement (PPA), the QEII solar farm generates around 20% of the plant's energy needs which partially achieves Thames Water's ambitious bid to self-generate a third of its own energy by 2020.

All UK FPV installations have benefited from the UK Government's Feed in Tariff (FiT) scheme (Business Growth Hub 2015), which was closed in 2019 (Ofgem 2019).

1.2 The potential of hybrid solar-hydro generation

Currently few FPV plants have been co-located with hydroelectric facilities throughout the world. Scotland has many hydroelectric power stations on which FPV could be sited. The Introduction of FPV to existing hydroelectric power stations is a smart and dynamic means of utilising existing transmission entry capacity (TEC) of the national grids infrastructure, and the power station's electrical system. See Appendix 1 for full TEC.

In order to meet power stations' energy demand and reduce the need for import from the grid, FPV has the potential to provide localised generation with surpluses exported to the grid at times when the hydro power station has spare capacity. Using a case study approach, this project will investigate, evaluate, and report on the feasibility of FPV collocated with a Pumped Hydro Plant in Scotland.

1.3 Project Aims

1. Conduct a case study feasibility analysis of Floating PV collocated with a Pumped Hydro Plant in Scotland.
2. Highlight the different requirements of large-scale ground-mounted PV systems and FPV Farms.
3. Provide an overview of the impetus for change leading to the adoption of FPV.
4. Investigate the current market and future trends for FPV.
5. Assess the UK FPV market.

1.4 Project Objectives

The overall objective of this project is to study optimising existing hydro power stations in Scotland with installed floating photovoltaics to utilise the existing Transmission Entry Capacity.

The main objectives are:

1. Provide an overview of factors driving change in the energy sector of the economy and impetus for sustainable resources to be utilised in the ever-increasing demand for energy.
2. Describe the new application (FPV) of a mature technology (solar photovoltaics) operational on bodies of water as opposed to land.
3. Identify the rationale for adoption of FPV within the renewables energy sector.
4. Identify and describe the key differences between ground-mounted solar farms and FPV systems in terms of design, topology features, and constraints relating to component parts.
5. Identify the Benefits and Drawbacks of FPV.
6. Provide a brief history of FPV and the major deployments since inception in 2007.
7. Provide insight into the current market for FPV and future potential.
8. Provide a brief overview of the potential cost of components of FPV deployment and assess the degree to which location influences $/Wp costs.
9. Provide an overview of the UK FPV market.

10. Provide a case study feasibility analysis of co-locating FPV with Pumped Hydro in Scotland. Calculate savings of CO_2 emissions and water conservation. Analyse case study data and report findings. Discuss the implications of findings and offer suggestions for future research.

1.5 Case Study

Located on the banks of Loch Ness and controlled remotely from SSE's Renewable Operations Centre in Perth, Foyers Pumped Storage Power Station (see Figure 6 below) has the capacity to generate 305MW of electricity within 30 seconds. The power station houses two 150MW generators located in separate 50.2m deep elliptical shafts. A further 5MW of installed hydro capacity is also available. Hydroelectric energy storage is used by electric power systems for load balancing, stability, storage capacity, and ancillary grid services such as network frequency control and reserves (Kishor and Fraile-Ardanuy 2017, pp.48-51).

Figure 6 - Foyer's Pumped Hydro Station

Completed in 1975, the Foyers pumped storage scheme uses Loch Mhor Dam as its upper reservoir. Originally Loch Mhor Dam was built to provide a storage reservoir for the Falls of Foyers scheme, developed in 1896. Foyers pumped storage scheme involves two bodies of water at different heights and the movement of water between these reservoirs with electricity produced from generators driven by turbines that convert the potential energy of falling or fast-flowing water into mechanical energy. The water is released to create energy at a time when demand is high. During periods of low demand for power, turbine-generators operate in reverse as electric motor driven pumps, when electricity is used to pump water from the lower loch to the upper reservoir. A schematic representation of the system is provided in Figure 7 below.

Foyers facts (SSE, 2020)

- When Foyers is generating, water flows through two miles of tunnels and shafts from Loch Mhor through to the power station.
- When pumping, energy is drawn from the main transmission system at times of low load to drive two 150MW machines in reverse direction and pump water from Loch Ness up to Loch Mhor.
- The power station houses the two 150MW machines in separate 50.2m deep elliptical shafts.
- When generating at full load, 200 cubic metres per second of water – or 200 tonnes per second – is passed into Loch Ness.

A schematic diagram of the system is visually depicted in Figure 7 below.

Figure 7 - Schematic representation of Foyers Pumped Hydro Scheme

Water travels to and from Foyers through a near horizontal low- pressure tunnel 2743m in length, joining a vertical high-pressure shaft and tunnel, with a surge shaft above. The high-pressure shaft is 112.8m deep and feeds into a horizontal tunnel 117.3m long which then divides into two smaller tunnels 315.2m long - the last 95.7m sloping down to the turbines.

Two 150 MW (204,000 horse-power) Francis generation-motor sets, each weighing 914 tonnes, with 5m wide turbine blades, each occupy pits 36m in depth on the shore of Loch Ness, with 100 cubic metres of water passing through each turbine and out into the loch every second during generation. The turbines can be brought from a standstill to full power output in less than two minutes, which makes the station extremely responsive to demand. The new scheme became fully operational in 1975 (Gazetteer for Scotland, 2020).

1.6 Hybrid Hydro-Solar Plant

Co-generation of PHP and solar may provide added value through increased power generation while utilising existing infrastructure. Floating solar plant requires careful consideration of the geographical location and all its individual characteristics.

1.6.1 Loch Mhor

Latitude: 57.24480057, Longitude: -4.41858806

Figure 8 - Loch Mhor

Loch Mhor (Water Body ID 19935) is a large freshwater loch located in the Highlands of Scotland. It is generally shallow with low alkalinity and is situated at low altitude. Loch Mhor has a surface area of 428 hectares, a mean depth of 7.3m, and a maximum depth of 27.7m.

An excerpt from the Bathymetry Survey of the Fresh-Water Lochs of Scotland, 1897-1909[1], reveals its unique features:

“Loch Mhor is the reservoir for the British Aluminium Co.'s works at Foyers. In its construction, advantage was taken of two natural lochs (Garth and Farraline). By means of the dam at the lower end of Loch Garth, the surface of Loch Mhor may be raised to 20 feet above the original level of Loch Farraline, the upper loch. In summer the two lochs may subside to their original levels. The loch is still divided into two portions by a causeway 2 miles from the upper end, and a public road here crosses by a bridge, the water passing by a canal underneath. The loch is rapidly forming a beach by eating away the boulder clay of the fields. These raw cliffs of clay are exposed when the loch is below its high level, and portions are continually falling in. Loch Mhor is of very irregular form, narrow and elongate, running north-east and south-west in Strath Errick, the lower end some 2 miles south-east of Foyers. On the west the country is moorland, with low hills, and many patches of trees on the shore of the loch. On the east the hills are higher, rising to mountains at the distance of a few miles. The west shoreline is of a simple outline, with slight double sigmoid curvature. The east shore is much broken up, several bays and arms running south-eastward. The largest of these is in the middle of the loch, and runs three-quarters of a mile inland”

“The loch is nearly 5 miles in length, has a maximum breadth of nearly three-quarters of a mile, and a mean breadth of one-third of a mile. It has a superficial area of 12/3 square miles. The volume of water is subject to great variation, being estimated at the date of the survey (April 24 and 25, 1903) at 1134 millions of cubic feet. It drains an area of about 21 square miles. Few streams of any importance enter the loch. The largest are the Allt na Seabhaig, which formerly flowed into the river Gourag, but was diverted into Loch Garth when the dam was built.”

“When surveyed the surface was 638.5 feet above sea level. In accordance with its artificial origin, the greater part of Loch Mhor is very shallow; deep water is only found in the original natural lochs. Two-thirds of the whole area is less than 25 feet deep. The basin formed by Loch Farraline before the surface was raised was fully a mile in length and one-third of a mile broad, with a depth of about 40 feet. The breadth has been very little increased by the dam. The depth

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[1] Source: National Library of Scotland: Bathymetrical Survey of the Fresh-Water Lochs of Scotland, 1897-1909. Lochs of the Ness Basin Pages 408-409, Volume II, Part I.

is now 60 feet. The basin is simple, with uniform contours and gently sloping sides. The 25-feet contour encloses an area of two-thirds of a mile long by one-fifth of a mile broad. The 50-feet area is very narrow, a quarter of a mile long, and a little east of the central line. The basin of Loch Garth, which was 1 1/2 miles long by nearly half a mile broad, is of irregular shape. The main part of the loch was oblong, but a long, curved, narrower part branched off to the south. The depth is now 91 feet (the maximum for Loch Mhor). The 25-feet contour almost coincides with the shoreline of the original loch. The 50-feet contour encloses an area 1 1/4 miles in length and enters the narrow southern branch. This area is broad for half a mile at the north end, but from there south it is a narrow channel. The 75-feet area is one-third of a mile long, by one-fifth of a mile broad. The mean depth of the whole loch is 24 feet."

Subsequent chapters of this report will provide analysis of the potential of co-located pumped hydro power plant with floating solar photovoltaics on the Loch Mhor Dam.

2 Methodology

A brief overview of the problem area is provided in section one of this report which serves to contextualise the issue. Limited historic data is available on the application of FPV technologies and few studies of efficacy or economic viability exist given that: (1) FPV is a new technology applied over a period of less than 15 years with the majority of deployments spanning a 6 year period; (2) Consideration of multicomponent and environmental variables relating to solar arrays sited on water bodies has not been rigorously tested and reported; and (3) FPV is in the early stage of market life cycle. A comprehensive trawl of research along with extensive Internet database searches provided many relevant studies, tender documents, and announced projects, important information of FPV market size, trends, topologies, deployment costs, and stated installed capacities.

2.1 Report Structure

Section 1.5 of this study provides a comprehensive overview of the case study subject, Foyers Pumped Hydro Plant, including important technological aspects. Section 3 of this research sets out a literature review based on the aforementioned variables and concludes with a discussion of issues highlighted. In Section 4, the Results section, an analysis of the three key assessment categories of Technical, Cost, and Environmental Impact, is presented. This section encompasses an economic evaluation of the proposed system along with the quantification of the common suggested qualitative advantages and potential challenges of FPV.

The final section of this research is set out in chapter 5, the conclusions section, which seeks to synthesise knowledge gained throughout this process and evaluate the extent to which the research questions have been addressed. It will also attempt to position this work within the larger field of research and assess its value and contribution to the overall field of knowledge. Finally, the most important results will be highlighted and limitations and suggestions for future work stated.

2.2 Location

Location is a key determinant of the potential size, cost, and efficiency of an FPV plant. Accordingly, all SSE hydro assets were screened to establish the best possible site on which to base the model. Water body surface area, depth, water level variation, geological features, infrastructure, ease of access, and current function i.e. pumped hydro or hydroelectric, were investigated and evaluated using information obtained from SSE renewables, maps of locations, and bathymetry reports. The list of sites consider for co-location of FPV is available in Appendix 3 - Foyers Daily Generation (MWh) data for 2017

2.3 Software

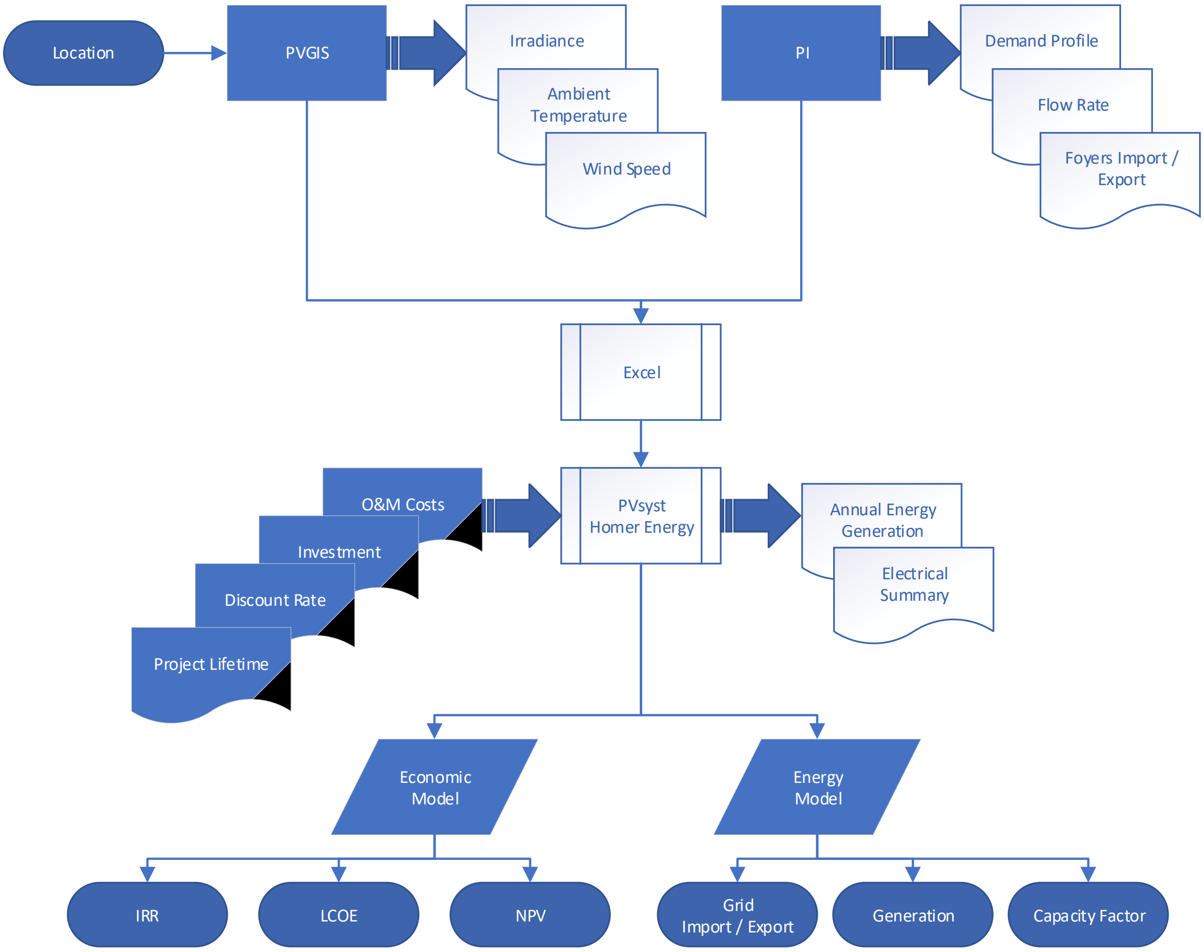


Figure 9 – Software

A variety of software applications were used to extract hydro import/export data, clean the data to ensure that it was free of irrelevances and incorrect information, before inputting the data to Homer Energy Pro and PVsyst modelling software. The schematic above provides a visual representation of the process undertaken in creating the model along with expected outputs (see Figure 9). The full range of software applications used for this research is recorded below with a brief overview of their role in this process. See Appendix 5 for work flow.

2.3.1 The PI System

The PI System is a suite of software products used for data collection, historicising, finding, analysing, delivering, and visualizing data. It is an enterprise infrastructure for management of real-time data and events.

Code of Practice (COP) meters the import and export data for each generator of a hydro plant. Annual energy demand data in half hourly sections was obtained through Pi, which allows users to collect large amounts of high-fidelity, time-series data from multiple sources. Data collected spanned the 5 years from 2015 through 2019. To achieve data that would be easily visualised half-hourly figures obtained were split into manageable chunks to be studied.

2.3.2 MS Excel

Data obtained from Pi was imported into MS Excel, organised into appropriate fields for manipulation, interrogation, and analysis. Data analysed was then visualised and presentation of data (both qualitative and quantitative) created in graphical format to facilitate greater understanding of content. MS Excel was used to classify, categorise and find relationships amongst data; understand the distribution and overlapping of data; determine patterns and trends, and detect outliers and other anomalies. Excel was used extensively for Cost analysis and Sensitivity scenarios in the Results section of this report. Cost in GBP per kW is based on the studies by numerous authors, press releases relating to new deployments of FPV, tender documents, and from personal communications with experts in the field.

2.2.3 PVGIS

PVGIS is an online research tool which focusses on solar resource assessment, photovoltaic (PV) performance studies, and the dissemination of knowledge and data about solar radiation and PV performance. The geographical location of Foyers Pumped Hydro plant was input to PVGIS to obtain the relevant irradiance, ambient temperature and wind speed data for the plant.

2.3.3 HOMER Energy Pro

HOMER Energy PRO software was used to create and simulate the planned hybrid hydro-FPV model. Based on input criteria, simulations of a viable system for all possible combinations of the equipment selected is obtained, offering the user maximum flexibility in options capable of meeting the desired outcome. Depending on how you set up your problem, HOMER may simulate hundreds or even thousands of systems. Homer PRO features an optimisation algorithm that significantly simplifies the design process for identifying least-cost options.

HOMER Pro is an excellent hourly assessment tool for hybrid renewable electric generation systems as it facilitates thousands of possibilities in a single run allowing the user to understand the impact of variables such as wind speed, fuel costs, etc, and understand how the optimal system changes with these variations.

Simulation of the current hydro generation profile along with 125 MW and 250 MW FPV plants, operating with bifacial and generic modules, facilitated a base for decision making regarding the on-going final capacity size and panel type to be used as Case 1, in the remaining sections of this study.

2.3.4 PVSYST 7.02

PVSYST 7.02 was used to model both the 125MW and 250MW FPV plant options selected for this research. Final analysis of potential energy generation output along with details of expected system losses were calculated and reflected in the report generated.

3 Literature Review

Floods, intensity and frequency of severe weather events, wildfires, melting icecaps, and other events, have focused attention on climate change (Palmer et al., 2017) and the need for action (IEA, 2019). Global response to the threat of climate change, as set out in the Paris Climate Agreement (2015), signed by 197 countries, commits nations to “strengthen the global climate effort” and work towards limiting global temperature rise this century to less than 2°C above pre-industrial levels; preferably lower at around 1.5°C (IPCC, 2018) which will require “rapid, far-reaching and unprecedented changes” (ibid.). Heat-trapping greenhouse gasses produced by combustion of fossil fuels during electricity generation, is a significant contributor to Carbon Dioxide (CO_2) emission levels in the atmosphere (IPCC, 2018). Despite nations’ commitments to lower CO_2 emission targets, with many governments working towards a net zero target, energy-related CO_2 emissions rose to a high of 33.1 Gt in 2018, a rise of 1.7% although these figures are based on higher energy demand as consumer demand increased world wide by 2.3% (IEA, 2019). Whereas lower emission levels were recorded in Germany, Japan, Mexico, France and the United Kingdom in 2018. Asia, China, India, and the United States increased the amount of coal used for power generation recording 10Gt CO_2 (see Figure 10) which accounted for 85% of the net increase in emissions (ibid). Given that in 2018, the Power Sector accounted for around 65% of global CO_2 emissions growth (IEA, 2019), the impetus for Energy Companies to increase electricity generated from renewable, sustainable sources is high.

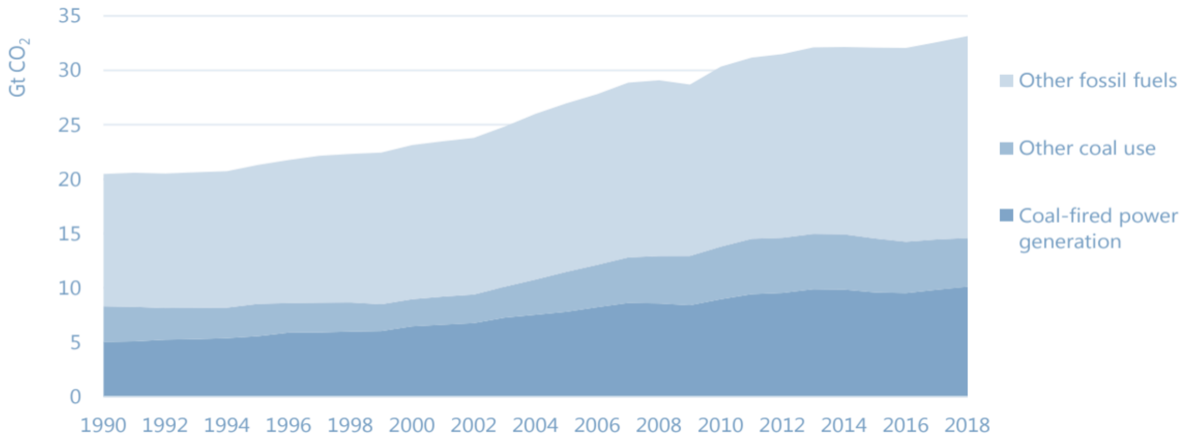


Figure 10 - Global energy-related carbon dioxide emissions by source, 1990-2018 (IEA, March 2019)

Increased levels of CO_2 emissions from electrical power generation, as a result of higher consumer demand and increased use of fossil fuels, provide the impetus for expansion of power generation from renewable sources. Recent advancement of key technologies through components' development, increased efficiencies, design optimisation, and new application of current technologies, all factor into the benefits of adoption. The drive to provide a cost-effective means of harnessing efficient, clean, abundant renewable sourced energy has never been stronger. Currently the Renewable Energy Technologies Market (see Figure 11) is dominated by three key technologies: Renewable Hydropower (44.7%); Onshore Wind (23.4%); and Solar Photovoltaic (22.9%); with an additional 2.2% mixed Hydro Plants reported (IRENA, 2019).

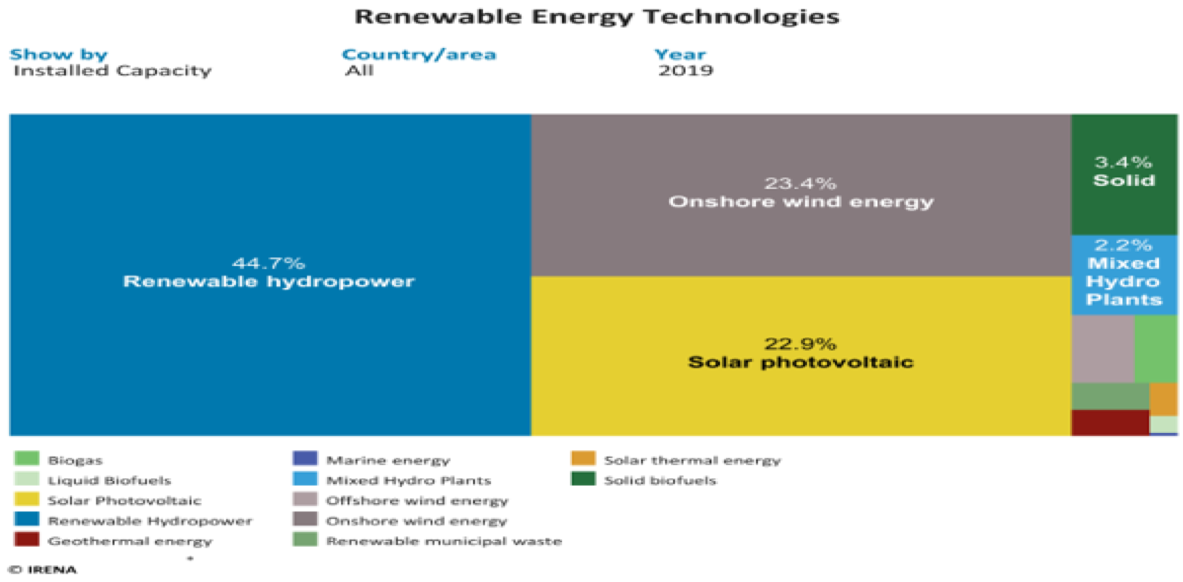


Figure 11 - Renewable Energy Technologies: Global Market Installed Capacity in 2019 (Source: IRENA, 2019)

Since its inception in 2007, after a slow start, FPV has been deployed globally with significant numbers of large capacity installations from 2015 onwards. Given the size of the hydropower sector, collocating solar photovoltaics through installation of an FPV system to increase power generation output seems appealing, as sharing of infrastructure would significantly reduce the CAPEX of such a project. To date few hydroelectric plants have invested in this technology despite deployments of FPV worldwide. Diversity of water bodies utilised for FPV installations make investment comparisons difficult. Analysis of the key variables relating to FPV deployment and their impact on both cost and success is vitally important. Location, project size, water body type, required components, environmental impacts, topology, design, and safety, are important factors when investigating feasibility of FPV projects.

3.1 The Global Market for Solar Photovoltaic

The global Solar PV market in 2019 was valued at $154.3 billion and generated 124.6 GW of power (Navigant Research 2019). The Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE, 2019) cite the Compound Annual Growth Rate (CAGR) of PV installations between year 2010 and 2018 to be 36.8% though growth is expected to slow slightly over the next few years to a CARG of 30.7% from 2019 through 2026 (The Express Wire, 2020) with a predicted capacity of 4766.82 GW by 2026 (Fortune Business Insights, 2019). Demand shift to clean energy along with technological advancements such as thin-film technology provide impetus for market growth (Fortune Business Insights, 2019). Key factors driving the market are electrochemical solar cells, dye sensitizers, ultra-thin wafer solar cells, and anti-reflection coating (ibid.). The Solar market comprise four key categories: Domestic rooftop; Commercial/Industrial rooftop, Utility-scale ground mounted; and floating PV. The Solar Energy Research Institute of Singapore (SERIS), a World Bank Group, report that by the end of 2018, FPV had a global cumulative installed capacity of 1.3GW (2019, p11). In 2019, FPV accounted for 1% of global solar demand (Wood MacKenzie Power and Renewables, 2019).

3.2 Floating PV: Technology Overview

Figure 12 - Floating PV applications

Floating photovoltaic (FPV) systems, also referred to as floatovoltaics, is an emerging technology application in which solar photovoltaic (PV) systems are sited directly on a body of water (Spencer et al., 2019) as opposed to the traditional land-based alternatives such as ground-based and roof mounted solar PV. Water bodies used as sites for FPV include both off-shore and on-shore locations. The latter category consists of dams; lochs; industrial water ponds; quarries / mine lakes; irrigation reservoirs; desalinization; water treatment sites (Kent County Council, n.d.); aquaculture farms; canals; and retention ponds amongst others (Spencer et al., 2019). Pioneer and market leader Ceil &Terre (2020) assert that FPV is “particularly suitable for water and energy-intensive organizations – industries and farms – for which land and water are valuable. Irrigation reservoirs, hydroelectric dams, water treatment surfaces or drinking water sites, quarry lakes or tailing ponds, aquaculture ponds or even floodplains" (see Figure 12). The World Bank Group and SERIS report (2018) claim a conservative estimate of global potential for this technology is over 400GW.

3.3 FPV System

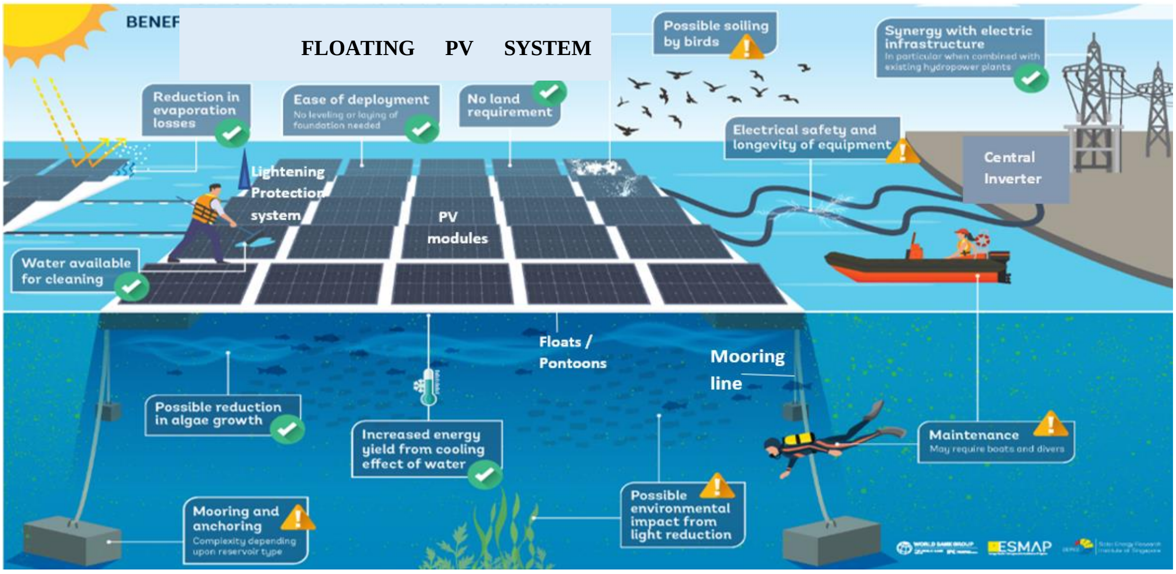


Figure 13 - Floating Photovoltaics System: Benefits and Challenges (Adapted from World Bank image, 2019)

The major differences between ground-mounted PV and FPV systems relate to the mounting structure and securing methods. Ground based systems use racks or frames attached to ground based mounting supports which hold solar modules in place. Dependent on the specific site, mounting supports may be pole mounts embedded directly into the ground; foundation mounts, such as concrete slabs or poured footings; or ballasted footing mounts, such as steel bases or concrete that use weight to secure the solar module system in position and do not have need of ground penetration (Nguyen, 2017). FPV differs insofar as mounting requirements necessitate accommodation of the different operational environment and the necessity to float. Figure 13 provides a schematic illustrating the important components of an FPV system along with the possible benefits and challenges of such a system. Base structures currently available are a float system with optional platforms to ease access for maintenance purposes (one large membrane serves as a platform for all solar modules to be installed) and an alternative pontoon architecture (many pontoons linked together to support the solar modules) originally designed to support much larger infrastructure (Parnell, 2018). The CAPEX of such investment, especially from the structure component, is on average 10-20% higher than a ground-mounted system (A Jiménez, personal communication, 24 February 2020). An FPV system for power generation typically consists of PV modules installed on top of the floating structure; inverter to convert DC output of PV solar panels into a utility frequency AC that can be fed into a commercial electrical grid; mooring system that adjusts to water level fluctuations while maintaining its position, underwater cables to transfer generated power, substation and distribution line (see Figure 13). The major benefits of FPV farms are no land costs; improved efficiency of photovoltaic modules due to lower temperatures as a result of the cooling effect of water; higher power generation efficiency, water conservation, lower construction costs, reduction of algae, and lowering of natural methane emissions that come from standing bodies of water. The key drawbacks of FPV are higher cost of the base structure, higher costs relating to anchorage and mooring systems, and increased cost of maintenance. A comparison of the features of FPV and ground-mounted systems is provided in the Table 1 below.

Table 1 - FPV vs Ground-Mounted PV (Cazzanigaetal, 2018; Château et al., 2019; Clot, 2018; Ferrer-Gisbert et al., 2013; Liang and Liang, 2017; Liu et al., 2017; Nguyen, 2019; Rosa-Clot and Tina, 2017)

	FPV	Ground-Mounted PV
Land	No land requirement. Exceptionally beneficial where land costs are high, or land availability is limited.	Sited on land which is costly.
Module Efficiency	Improved efficiency of photovoltaic modules due to lower temperatures as a result of the cooling effect of water. Approximately10% increase in yield.	Loss of efficiency when ambient temperature is high due to thermal drift.
Excavation	Cabling and excavation: no support foundation and cable trench excavation required as regular cables supported by buoys or cables submerged in waterproof conduit.	Support foundation and cable trench excavation required. Soil and water conservation may be impacted.
Shadow	Less impact from shadowing as water surfaces are generally open resulting in more uniform solar	May be impacted by shadow. Less uniform solar irradiation and illumination time therefore less

	irradiation on panels and longer illumination time. Higher power generation.	efficiency of photovoltaic modules and lower power generation.
Water Evaporation	Less water evaporation due to component coverage across a range of temperatures. Improves water quality.	High level of evaporation during times of high ambient temperatures
Algae	Reduced algae as sunlight is blocked by solar photovoltaic modules.	N/A
Cost	Higher Cost of base structure of around 20%	Lower cost of structure
O&M	Dependent on design. When sited centrally on a water body boats and divers are required periodically to perform maintenance which increases costs. Designs which provide appropriate spacing of modules and incorporate aisles significantly reduce maintenance costs associated with replacement modules, cleaning, and inspection. Less dust accumulates on FPV panels making the requirement for cleaning less frequent. PV panels must meet the highest waterproof requirements when sited on water. Compared with ground PV, less damage occurs cleaning.	Accumulation of dust impacts efficiency and energy generation potential. Regular cleaning required.
Natural Environment	Compatible with aquaculture (site specific: careful site selection for FPV panels may be beneficial). Installation of FPV on fishponds has been found to have a 'moderate negative impact on fish production', due to a reduction in dissolved oxygen levels in the water. Minimises some of the natural methane emissions that come from standing bodies of water. Less visual impact on the landscape.	Loss of habitat. Disturbance to biological soil Significant visual impact on the landscape.
Construction	Construction time is less than Land-based systems. Labour costs are lower. FPV plant can be completed and operational within 6 weeks.	Longer construction time with higher labour costs than FPV plant.

3.4 Floating Photovoltaic Market Analysis

The attractiveness of FPV is evident in locations such as China, Japan, Taiwan, India, South Korea, and Singapore, amongst others where large ground mounted photovoltaic (GMPV) arrays are not possible due to land availability constraints, high land costs (Chandran, 2019) or unsuitable topography (World Economic Forum, 2019). Unlike GMPV, FPV can be deployed on otherwise unused bodies of water such as flooded gravel pits and industrial water bodies. In 2019 the market for FPV was around 1% of the solar photovoltaics market (Figure 14 refers). It is predicted to more than double by 2022, reaching 2.4% of annual global demand (Cox, 2019). Contributing to this trend of increased floating solar capacity, is the year on year growth rate of 85% for average global project size during the period 2015-2019 (ibid). Based on tenders and project announcements, the average project size in 2020 will be around 14MW rising to 21MW in 2021, and 219MW in 2022 (Wood MacKenzie, 2019).

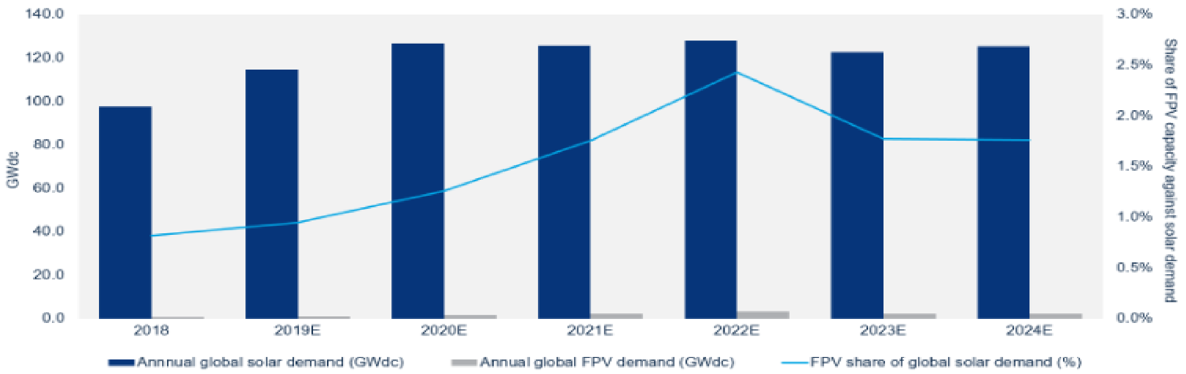


Figure 14 - Annual global floating solar installations as a percentage of annual global solar installations 2018-2024 (Wood Mackenzie Power & Renewables)

Home to the third largest FPV plant in the world, the Yamakura Solar Power Plant (see Table 2), Japan had a cumulative installed capacity in 2019 of 130.59MW across 73 sites (Figure 15 refers). China had around 55% of Japan's installed cumulative capacity at 78.36MW across 6 sites, two of which are currently the largest FPV plants in the world - the 40MW Sungrow Huainan Solar Farm and 20MW Xinyi Solar Plant (see Table 2). With 11 FPV plants, South Korea had the third largest cumulative installed capacity of 22.71MW in 2019. On average, South Korea's FPV plants are smaller, the largest of which are the 3MW Otae Province and Jipyeong Province plants. The United Kingdom has just under 10MW cumulative installed capacity across three sites, the largest of which, ranked seventh largest in the world, is the 6.3MW Queen Elizabeth II Floating PV Farm.

Table 2 – World's Largest FPV Sites in 2018 (Solar Asset Management Asia, 2019)

Rank	Size (MW)	Water Body Name/Type	Country
1	40	Sungrow Huainan Solar Farm - Huainan City	China
2	20	Xinyi Solar Plant - Huainan City	China
3	13.7	Yamakura Solar Power Plant	Japan
4	10	Pei County	China
5	7.5	Umenoki	Japan
6	6.8	Hirotani Ike Floating Solar Plant	Japan
7	6.75	Jining GCL	China
8	6.4	Queen Elizabeth II Reservoir	UK
9	3	Cheongpung Lake	South Korea
9	3	Otae Province	South Korea
9	3	Jipyeong Province	South Korea
9	3	Sujang Reservoir Solar Par	South Korea

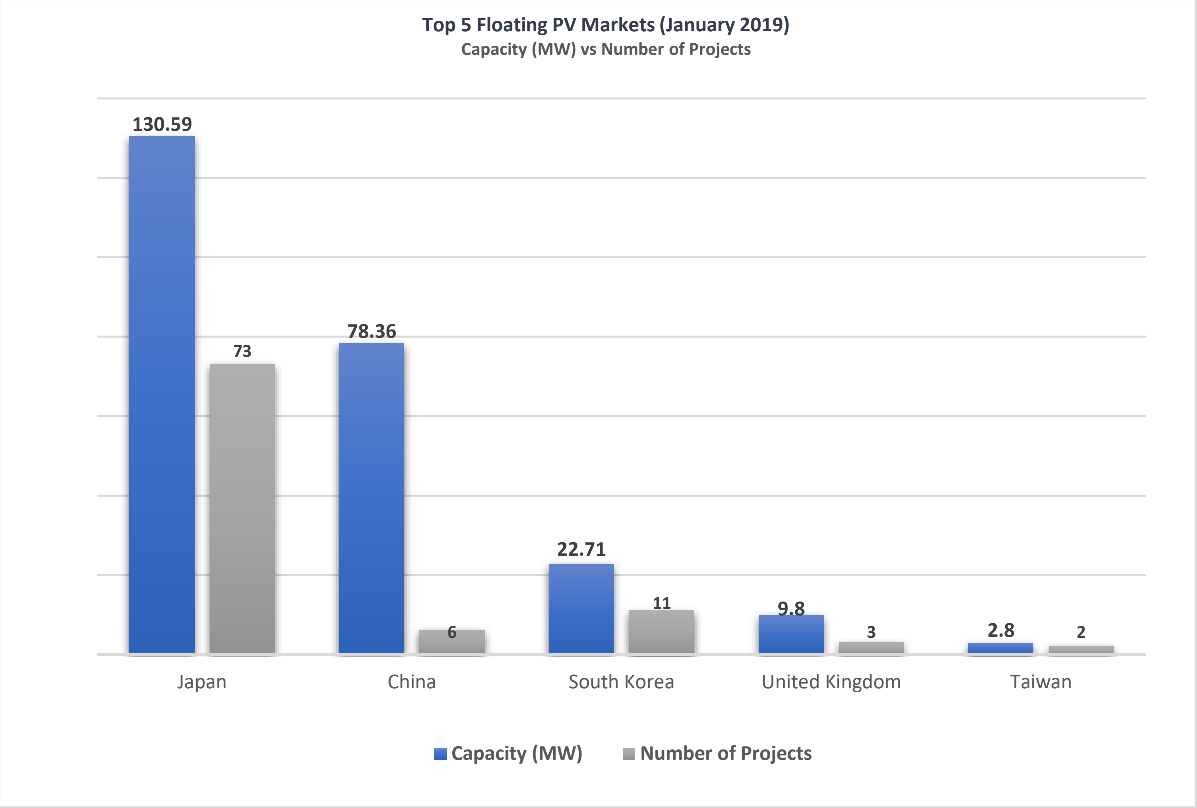


Figure 15 - World's Largest FPV Markets (January 2019): Cumulative Installed Capacity MW, and number of projects per nation. (Wood Mackenzie Power & Renewables, 2019)

3.5 Distribution of FPV plants according to size as of December 2018

Global FPV capacity has rapidly expanded since 2015, mainly as a result of larger sized deployments. Figure 16 below gives details of major FPV installations deployed in China, India, Japan, Portugal and the UK between 2014 and 2018. Larger project size is a trend expected to continue for the foreseeable future and by 2022 is expected to reach 3.2GWdc of cumulative installed capacity (Wood MacKenzie, 2019). In China alone, within a period of two years, the largest FPV plant size has grown from 20MW installed capacity in 2016 to 150MW in 2018. Similarly, the markets in India and Japan have grown from an average project size of 0.5MW in 2017 to 5MW installed capacity in 2018 for the former, and the latter increased from 2MW in 2015 to 13.7MW in 2018. Asia is the clear market leader and will continue to be so for the foreseeable future with south east Asia powering growth.

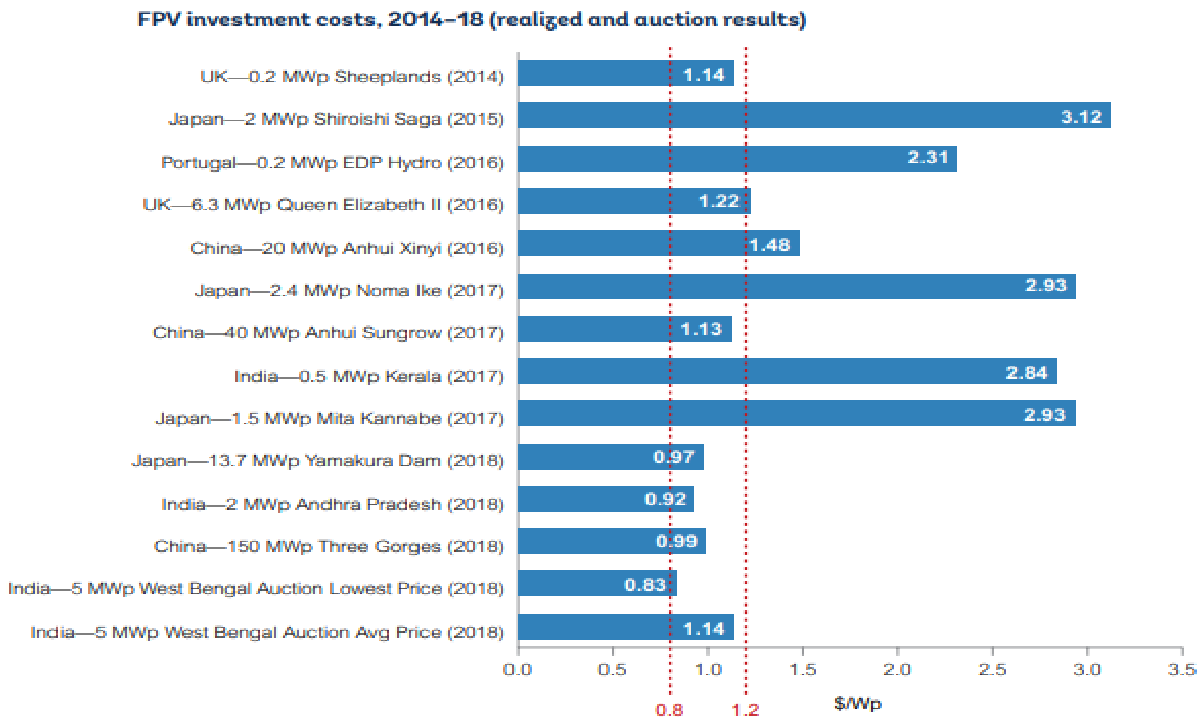


Figure 16 - Investment cost of floating PV (2014-2018) (World Bank, Sun meets Water, p93)

Larger sized projects see significant reduction of investment cost, due in part to economies of scale (see Figure 16). Data presented pertaining to investment costs suggests that in 2016, US dollar per watt (USD/Wp) costs varied from a low of $1.22/Wp in the UK to a high of $2.31/Wp in Portugal. Investment costs reported for 2018 show a significant reduction with USD/Wp costs dropping to $0.83/Wp for a 5MW FPV plant in India; $0.97/Wp in Japan for the 13.7MW Yamakura Dam Project; and $0.99/Wp for the 150MW Three Gorges FPV farm in China.

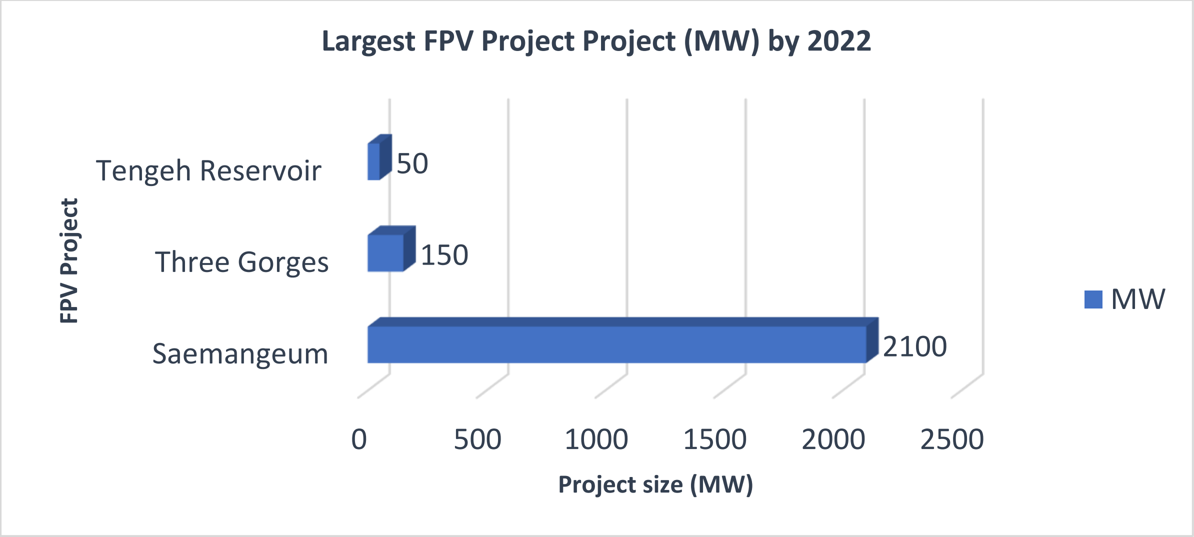


Figure 17 - Largest FPV Projects (MW) by 2022

The trend towards larger deployments is predicted to continue. Tenders and project announcements for the period 2020 to 2022 suggest an average global project size of 14MW in 2020, 21MW in 2021, increasing to 219MW in 2022 (Wood MacKenzie, 2019). The three largest deployments by 2022 are predicted to be the 50MW Tengeh Reservoir; the 150MW Three Gorges FPV farm, and the 2.1GW Saemangeum Plant in South Korea (Figure 17 refers).

3.6 Non-Standardised Cost of FPV

Important characteristics of an FPV plant are the location; planned capacity; exposure to extreme weather conditions; the extent to which water level varies; depth of the water body; current; wave activity; exposure to high winds, typhoons etc; and environmental constraints. These variables will impact component selection and overall costs of deployment. When compared to ground-mounted PV arrays, where the largest cost relates to module price, the structural balance of an FPV system and soft costs can exceed the cost of the modules. In common with GMPV, capacity of the FPV project is a critical factor as economies of scale are realised in terms of the lower $/Wp price offered on larger projects.

In terms of cost, PV modules present less of an obstacle than other components as there are several module options available for both GMPV and FPV applications. Currently dual glass modules are most popular for FPV systems – depending on the racking solution selected, these may be framed or frameless. The cost of modules and inverters used for GMPV and FPV systems is the same. Significantly more costly is the electrical balance of systems (EBOS) of an FPV plant, of the same size and location, with costs on average 13% higher than a ground-mounted system. This is partly due to the requirement for marine grade cabling.

The structural balance of system (SBOS) includes the floating structure along with the mooring and anchoring system. It costs, on average, five times more for an FPV application than it costs for a ground-mounted array of the same size in the same location. Where there is increased water level variation or where the water body is significantly deeper, costs may be considerably higher.

Labour costs may be on average 6% higher as a proportion of all-in system cost for FPV applications than a ground mounted system of the same size and in the same location. Other soft costs such as design and engineering can vary significantly from 1% up to 15% depending on the simplicity or complexity of the proposed system. The cost variance for other categories of soft costs such as supply chain and logistics, are largely dependent on distance from the manufacturing location of all products to the site. Due to bulkiness rather than weight, higher delivery/shipping costs will be incurred where floating structures include pontoons filled with air due to the larger area utilised in transit. Deliveries across borders, from country to country, is expensive as will transit costs within the destination country to the site itself, especially if remote. The lack of land acquisition costs for FPV applications can reduce developer costs by on average 26% when compared to a ground-mounted solar array of the same size and location. A further consideration relating to SBOS costs is proximity to vendors which impact competition and price pressure. For example, costs may be higher in the US than in other countries as there are less floating structure vendors operating there. European markets have more solar vendors and are likely to experience more cost reductions as a result of increased competition compared to the US.

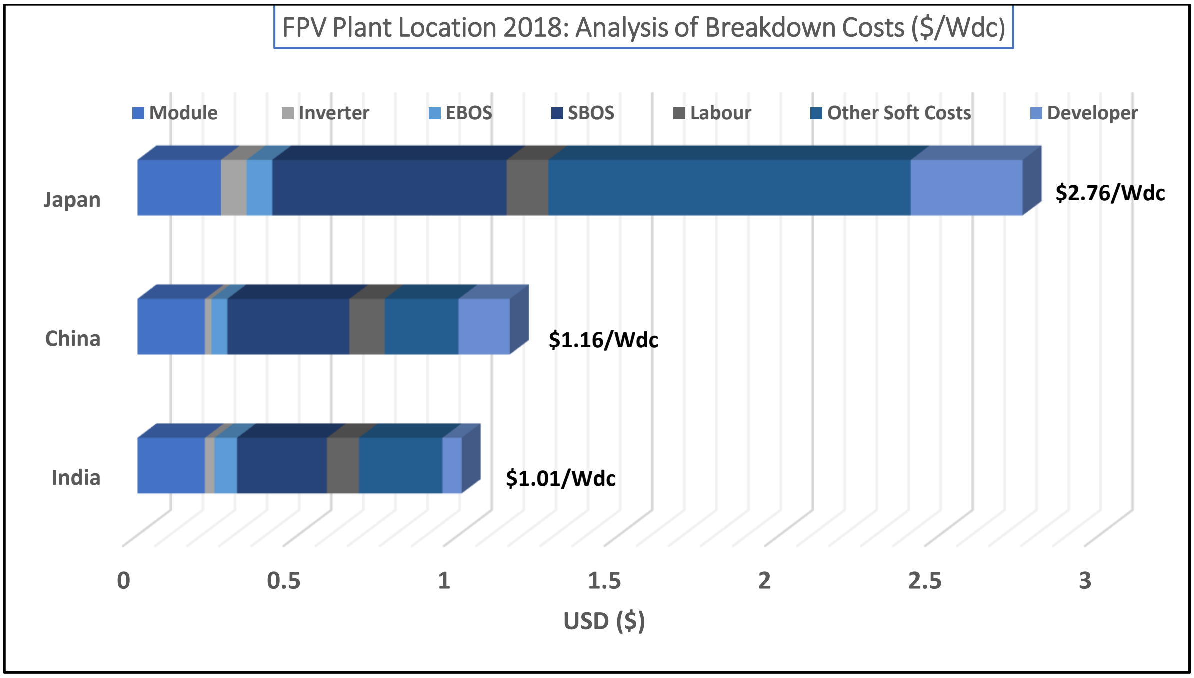


Figure 18 - FPV Plant Location (2018): Analysis of Breakdown Costs ($/Wdc)

In 2019, China had the lowest all-in cost ($1.16/Wdc) of all major floating solar markets in Asia apart from India ($1.01/Wdc). This was due to lower labour and soft costs available in India and China throughout 2019. As China's FPV project size is typically larger compared to countries such as Japan, benefit from economies of scale contribute to a lower $/Wdc figure for all-in construction costs than is the case for Japan. While China benefited from economies of scale and low labour costs, Japan had higher all-in costs ($2.76/Wdc) in 2019 due to smaller average project size, higher component costs, and higher labour costs (see Figure 18).

Japan had higher supply chain and logistics costs, which increased the overall soft costs. Whereas China and India have little opportunity to reduce costs further, Japan's soft costs have the potential to fall as permitting costs lessen, and design and engineering practices become more streamlined to yield lower all-in costs in future.

During 2018, India experienced some of the lowest FPV all-in construction costs of any country in the world, however the costs of the floating structure and the mooring and anchoring were high relative to other cost categories. Logistic costs were also higher partly due to the more remote locations in which deployments were sited and partly due to the cost of transport of materials into the country.

3.7 South East Asia Market

Hosting the largest capacity plants in the world, Asia accounts for the highest percentage of FPV deployments worldwide (World Bank, 2019). From 2020, Southeast Asia is set to contribute to the growing trend towards high capacity plants having announced many large-scale projects. Development plans are currently underway in Thailand and Vietnam for large-scale floating PV installations, with smaller utility-scale floating PV developments being proposed in Indonesia, Singapore, and Myanmar (ET Energy World, 2019). Thailand's planned construction of 2.7GW of floating solar - many on hydro dams, has construction start dates ranging from 2020 through 2037, is set to be a key contributor in this market. A listing of individual projects, capacity, and their completion dates is provided in Figure 19 below.

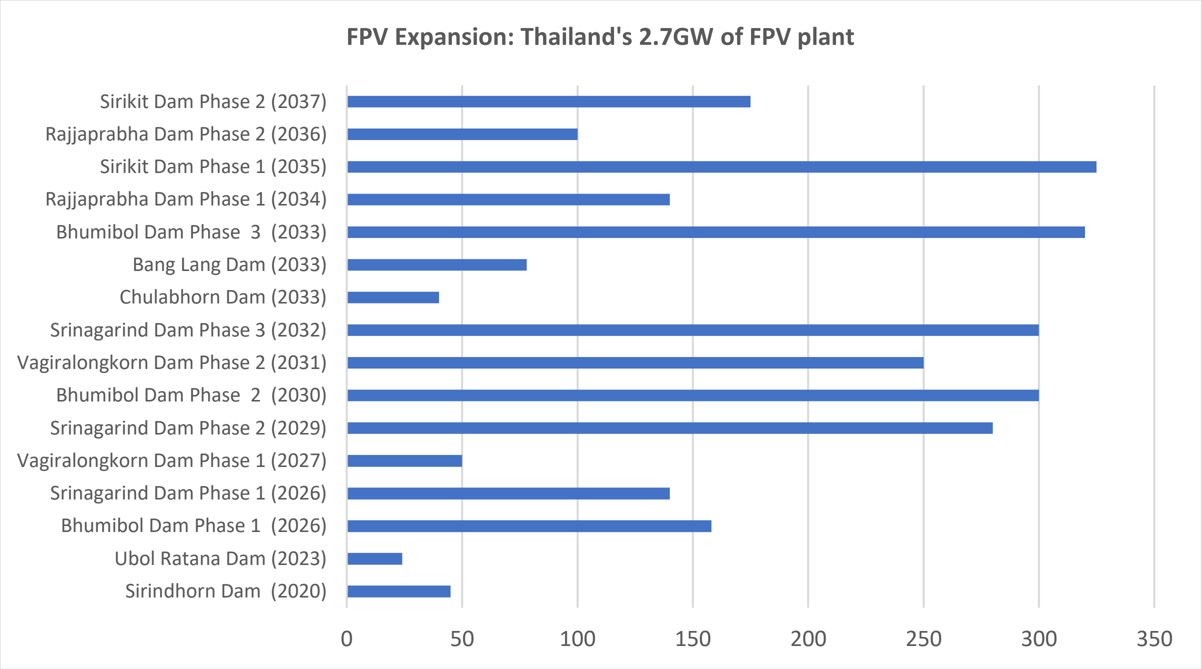


Figure 19 - Expansion of FPV in Thailand (2020-2037)

Due for completion in 2023, Ubol Ratana Dam in Khok Sung in the Ubol Ratana district of Khon Kaen province in Northern Thailand will become home to the first hydroelectric power project developed in Thailand’s north-eastern area of Isan. Thailand’s National Energy Policy Council revealed the first two projects would be built for $1 million per megawatt (Bellini, 2019).

3.8 Geographical Adoption of FPV Plant

Figure 20 - Map of FPV Deployments (Ceil &Terre)

The extent to which FPV has been adopted across geographical areas differs significantly. Climate, land scarcity, physical features of the land area, water conservation needs, and infrastructure, all factor into investment decisions. The sun shines consistently and intensively in many parts of Asia making it an attractive market for solar applications (Quansah et al., 2016). Africa too is endowed with significant amounts of renewable energy resources of which solar holds enormous untapped potential (ibid.).

There is a growing market for FPV in South America where the need to provide clean energy from sustainable sources, reduce evaporation from dams and challenged water reservoirs, save valuable agricultural land, and reduce deforestation, making floating solar applications particularly appealing. IRENA (2019) predict a significant fall in the levelized cost of electricity (LOCE) for solar PV to around 1.4 cents to 5 cents per kWh by 2050 from its average price in 2018 of 8.5 cents. Highlighting the trend towards lower priced electricity is the average electricity price of 2.7 cents per kWh Colombia was awarded in a recent solar and wind auction (IRENA, 2019).

Europe has yet to invest substantially in FPV technology, though following small-scale installations of under 1MW in Italy and Belgium in 2017, several projects have been commissioned and subsequently launched. To establish viability of FPV, in the Spanish region of Extremadura, a 1.125MW demonstration project was created to evaluate different panel configurations and technologies along with different flotation structures. In 2018, the UK was the seventh largest FPV market in the world with installed FPV capacity of 9.8MW. Since then, the Netherlands have installed a 14.5MW floating array near Zwolle, a 2MW facility in Watercooler, an 8MW floating plant in Tynaarlo, and are currently constructing a 27.4MW array on an artificial lake near Zwolle (Enkhardt, 2020). Portugal is home to the first project in Europe to co-locate FPV and hydroelectric plant. France is currently home to the largest FPV plant in Europe, with 17MW of installed capacity at the Omega 1 site, launched in October 2019.

3.9 Location

Multidimensional elements of FPV plant make design of systems a specialist competence. While site location determines important design options available to the developer, capacity is contingent on the dimensions of the water body and preferred level of coverage. Geographical features of the location provide for assessments of potential shadow on panel efficiency; optimal tilt; requirements of mooring and anchoring system (bottom anchorage, shore anchorage, or combination); advantages and constraints of access routes for delivery of components, FPV build and post-construction O&M requirements; routing of electrical cables; environmental and ecological impacts; overall costs; and many more variables. Importantly, electrical power generation from solar applications vary across the globe as the actual level of solar irradiance is contingent on latitude and local climatic conditions (Ekins-Daukes, 2009). Table 3 below illustrates the range of decisions developers have made over recent years with respect to site location, capacity, FPV cover of water body surface area, and scope of responsibility placed on the developer.

Water body coverage ranged from 1% in Portugal’s 218kW plant to 63 percent on Japan’s Sasakuacho 1.259MW plant. Average coverage of the water bodies reported was 33% while median coverage was 43%. The main purpose of the water bodies recorded were irrigation, industrial, water treatment, artificial lake, agricultural pond, and hydroelectric plant. Six plants required bottom anchoring systems, six opted for bank anchoring systems, and one hybrid system used a combination of both. Scope and responsibility of the developer varied from site to site with the full range of services recorded as project development, project engineering (anchoring design and design of the floating array), construction and procurement, construction supervision, financing, and operation and management (O&M). In the case of Omega 1 FPV plant, financing through crowdsourcing was supplemented by investment from Natixis Energéco and the municipality of Piolenc. This symbiotic relationship between Developer and local community may provide a sustainable business model for future developments.

Table 3 – Development projects

Name, size, and connection date	Surface area	FPV Cover	Module data	Main purpose	Anchorage and Mooring system	Scope of responsibility
ASIA						
Sugu 4,023kW Taiwan **2018**	8.81ha	15%	13,410 modules **300W** 60-cell	Industrial reservoir	Hybrid anchoring on shores and bottom	* Project Development * Project engineering Anchoring design Floating Array design *Construction and procurement * Financing * O&M
Tano IKE 2,548 kW **2018**	5.7ha	44%	8942, **285W** 60-cell modules	irrigation	Bottom anchoring	* Project Development * Project Engineering Anchoring design Floating Array design *Construction & Procurement Construction supervision *Financing *O&M
Iwano IKE 2,596 kW **2018**	4.87ha	48%	8800 modules, **295W**, 60-cell, double glass	irrigation	Bottom anchoring	* Project Engineering Anchoring design Floating Array design
Ichinomiya IKE 2,242 kW **2018**	6.93ha	31%	6498 modules **345W** (72-cell)	irrigation	Bottom anchoring	* Project Development * Project engineering Anchoring design Floating Array design *Construction and procurement Construction supervision * Financing * O&M

Tano IKE 2,548 kW January **2018**	5.7ha	44%	8942 modules, **285W** 60-cell	irrigation	Bottom anchoring	* Project Development * Project engineering Anchoring design Floating Array design *Construction and procurement Construction supervision * Financing * O&M
Sasakuacho 1,259 kW (over 2 sites). **2018**	0.92ha	63%/61%	3564 modules, **355W** 72-cell	irrigation	Bottom anchoring	* Project Development * Project engineering Anchoring design Floating Array design *Construction and procurement Construction supervision * Financing * O&M
Hyoshiga IKE 2,703 kW **2019**	6.07ha	45%	10010 modules **270W** 60-cell			* Project engineering Anchoring design Floating Array design
EUROPE						
United Kingdom						
Sheeplands 200kW **2014** **Max depth: 6.1m level variation 6.1m**	1.49ha	14%	800 Modules **250W** 60-cell		Bank anchoring	* Project engineering Anchoring design Floating Array design *Construction and procurement Anchoring system supply
Polybell 471kW **2015** **Max depth: 3.9m level variation 3.9m**	4.73ha	11%	1848 modules **255W** 60-cell		Bank anchoring	* Project Development * Project engineering Anchoring design Floating Array design Electrical design

						*Construction and procurement Construction supervision
Godley 2,991kW **2016** **Max depth: 9.9m level variation 9.9m**	5.83ha	48%	10494 modules **285W** 60-cell	Water treatment	Bank Anchoring	* Project engineering Anchoring design Floating Array design *Construction and procurement Anchoring system supply Anchoring system installation
Queen Elizabeth II 6,338kW **Max depth: 18.4m level variation 18.4m**	128ha	5%	23046 modules **275W** 60-cell	Water treatment	Bottom Anchoring	* Project engineering Anchoring design Floating Array design
Portugal						
Alto Rabagao 218kW 2016 **Max depth: 90m level variation 30m**	2212ha	1%	840 modules **260W** 60-cell	Hydroelectric	Bottom anchoring at 60m with 30m water level variation	* Project engineering Anchoring design Floating Array design Electrical design *Construction and procurement Construction supervision
Italy						
Pontecorvo 343kW **2017**	0.88ha	43%	1320 modules **260W** 60-cell	Irrigation	Bank anchoring	* Project engineering Anchoring design Floating Array design
Belgium						
Hesbaye Frost 998kW **2017**	2.96ha	35%	3120 modules **320W** 72-cell	Industrial site	Bank anchoring	* Project engineering Anchoring design Floating Array design

Netherlands						
Azalealaan 1845kW 2018	3.34ha	47%	6150 modules **300W** 60-cell	Agricultural Pond	Bank anchoring	* Project engineering Anchoring design Floating Array design *Construction and procurement Anchoring system supply Anchoring system installation
France						
Omega 1 17MW 2019	17ha	Not specified	47000 panels **360W** 72-cell	Artificial Lake - former quarry	unknown	Bouygeus Energies & Services Design anddevelopment Production and Delivery Construction Operation
USA						
Orlando Utilities 2017	1.22ha	2.9%	100 modules 315W 72-cell	Irrigation reservoir	Bottom anchoring system	* Project engineering Anchoring design Floating Array design *Construction and procurement Anchoring system supply Anchoring system installation PV module and Inverters supply

The solar module power output option selected for each installation is recorded in Table 3 above. Options varied from 60-cell panels of 250W-300W to 72-cell panels of 320W-360W. A 360W panel generates up to 20% more electricity than a 300W panel of the same size in the same location. As power output decreases with increasing cell temperature, ambient temperatures above 25^{o}C result in less efficient panels and lower power output. Every degree above standard test conditions specified for a 330W panel may result in reduced efficiency of around 0.258%. However, current research suggests a significant benefit of floating solar arrays in terms of their increased generating capacity due to the cooling effect of water, which lowers module temperature. Estimates of power gains vary though an increase of between 10% and

20% (Spencer et al, 2019) over ground-based system of the same size in the same location are frequently cited (Goswami et al. 2019; Sahu et al., 2016).

The concept of heat islanding and its impact on the environment is well documented in literature (Masson et al., 2014; Cortes et al., 2015; Barron-Gafford et al., 2016; Goswami et al. 2019). Large-scale ground-mounted solar power plants raise temperature which creates a heat island effect like that around urban or industrial areas. Alternative siting of plants to available unused water bodies within the vicinity could mitigate this rise in temperature, reported to be around 3-4 °C higher than surrounding area (Barron-Gafford et al., 2016).

3.10 Investment considerations

The last two decades has seen a significant increase of demand for: (1) energy from renewable and sustainable sources; (2) a solution to the increasingly limited availability of land for utility scale projects; and (3) the high level of need for water conservation. Until recently deployment of FPV, which addresses all three requirements was regarded as "hardly economically viable" (Barbuscia, 2018).

As with conventional photovoltaic systems, the cost of floating solar plant comprises of both CAPEX and OPEX costs. On average CAPEX is between 10% and 20% higher than a ground-mounted system of the same size in the same location (Jiménez, Personal communication, 20 February 2020). Many factors impact elements of both cost categories. The major considerations are outlined below.

3.11 Module efficiency

One of several variables impacting efficiency of a solar cell or panel is surface temperature; an increase of surface temperature can significantly compromise power generation output (Mehrotra et al., 2014). Placing solar panels on a body of water mitigates this issue as the cooling effect of the water reduces overheating and increases power output. Many estimate the possible gains of modules floated on water bodies to be in the region of between 5% and 22% (Abdulgafar, Omar, and Yousif, 2014; Bahaidarah et al. 2013; Choi 2014; Majid et al. 2014; McKay 2013; Rosa-Clot et al. 2010; Sacramento et al. 2013; Sacramento et al. 2015; Sahu et al., 2016;). Other important considerations relate to shadow (Sahu et al., 2016), module tilt angle and its orientation with horizontal plane (Salih, 2014) and potential soiling (Hamhuis et al., 2017); all capable of decreasing power output. A well-designed plant allows for optimised positioning of modules to minimise shadow and maximise exposure to solar irradiance. Key findings of a study of Singapore Tengeh Reservoir testbed, set up to evaluate a variety of Floating PV applications and technologies, concluded that (1) module temperatures depend on floating structures as well as locations within the floats; and (2) bifacial modules do not outperform mono-facial modules on water, however in the long-term bifacial may perform better than mono-facial due to slower water ingress as a result of the dual glass structure (Haohui et al, 2017). Performance ratios (PR) were found to be around 15% higher than roof-top systems in Singapore (ibid.). Factors influencing PR (corrected for DC cabling loss) were frequent inverter fault, significant downtime, and severe soiling due to bird droppings.

3.12 Water conservation

Sheltering large expanses of water from the sun in places like Australia, Brazil, China, India, Japan, South Korea, California, and the UK, provides both energy and environmental benefits (Warburg, 2016). Floating solar arrays provide a canopy which protects the water surface, by reducing airflow and absorbing solar radiation that would ordinarily be absorbed by water, resulting in reduced levels of evaporation and conserving water (Spencer et al., 2019). The extent to which water is conserved is reported in a study conducted by Santafe et al. (2014) in finding that water conserved from FPV cover amounted to an annual saving of 5000 m^3, equating to 25% of the reservoir's storage capacity. Similarly, Haohui et al. (2017) report approximately 1000 litres per metre squared per year saved on a Spanish reservoir due to the testbed FPV plant. Sharma and Kothari (2016) state a potential of 909.05-GW power generation with an annual saving of 16233 billion litres of water exists if FPV power plants were installed on large reservoirs in India.

Experts claim that FPV systems achieve water evaporation reductions of ~80% (Jiménez, Personal communication, 20 February 2020).

3.13 Environmental impact - Ecosystem

The consequence of blockage of solar rays by FPV structures is a reduction of the photic zone in the reservoir. This limits the gas exchange in the reservoir-atmosphere interface which impacts the local fauna and flora (Sahu et al. 2016; Pearce et al. 2017). FPV coverage of the aquatic environment limits algae growth and improves water quality (Sharma and Kothari, 2016). Nonetheless, Liu et al. (2017) point out that the effect of reduced algae growth on fish living in the reservoir is currently unclear.

The level of coverage is an important factor. Sharma and Kothari (2016) report coverage of minimum 20 % of total reservoir surface area can be considered to have negligible impact on environment.

Fishing and boating activities may also be impacted (Trapani et al. 2013; Trapani and Santafé, 2015; Sahu et al. 2016). Given that these activities are likely to be a revenue source, mitigation strategies are required. Careful consideration of the level of reservoir coverage and required topology to minimises impacts is essential. Two possible mitigation strategies are free-floating structures; and installation of LED lamps below the photovoltaic panels where the need for a high degree of surface coverage is a factor (MaKay, 2013; Cazzaniga et al. 2017).

3.14 Risk Assessment

Until recently, floating PV was considered a niche market in the US. Despite having the potential to install 2116 GW of floating PV, by the end of 2017 the US had deployed only seven FPV projects, a small fraction of the 198MW of global installed capacity. The major barrier to increasing FPV in the US has until now been the high-level risk associated with the technology's operation and manufacturing. According to NREL (2019) there is an expectation for the market to grow, especially in areas that are land-constrained and where conflict between solar and farmland exists. An Estimated 2.1 million hectares of land could be saved if water bodies were used for solar installation (NREL, 2029).

Risk covers all areas of a project, during all phases of development – the scoping and evaluation phase, and pre-construction, installation, operational, and decommissioning phases. There are risks associated with both tangible and intangible aspects of investment. Thorough identification of risks, accurate risk assessment, and effective risk management strategies are essential to all large-scale projects. Project Management is key to maximizing potential.

3.15 Discussion

An emerging technology, FPV plant is an application in which solar photovoltaic (PV) systems are sited directly on a body of water. There has been significant interest in effectiveness of such systems over the last five years, resulting in numerous published papers focusing on various aspects of FPV. Solar PV has been around for many years and has been well researched since it was first deployed on roof-tops, ground-based siting, and utility scale applications, therefore effectiveness is evidenced. Most components required of FPV have been tried and rigorously tested for many years and significant advances made. The key difference between GBPV and FPV is the mounting structure and the mechanism by which it is secured within its operating environment. This aspect of FPV plant has developed over the short period since inception in 2007. Key vendors have developed competencies in these specific areas by developing floating bases of different design, along with their associated attachments and mechanisms for mooring and anchoring.

Base structures and anchoring and mooring systems have not been rigorously tested for a sufficient period to conclusively determine their efficacy. Impacts on the environment and aquatic ecosystems are also unknown. Environmental impact assessments (EIA) are a necessary tool to determine possible impacts on a variety of spheres which affect project costs and ultimately project viability over time. Following several small proofs of concept deployments, pilot studies, and testbed installations, small to medium-scale projects were deployed from around 2013 onwards. From 2016 to the present day, the FPV market has grown significantly, primarily in Asia through large-scale deployments, however little if any actual reliable data is yet available on which to base investment decisions. Nevertheless, data reported from researchers of Singapore’s Tengeh Reservoir FPV testbed site provide interesting findings not yet covered in the many FPV studies undertaken to date which highlights the difficulties experienced by live systems, suggesting that profitability of FPV may not be as high as current expectations suggest. The six key findings were:

- Constant movement puts challenge on cable management and maintenance of connecting parts.
- Component quality is important for reliable operation.
- High humidity environment leads to more insulation resistance issues.
- Animals insects and biofouling may need to be addressed for operation and environmental considerations.
- Proper system design, workmanship and good O&M practices are important.
- Active cooling brings around 2% gain in NRG yield on high irradiance days.

Issues raised related to design, pre-construction, installation, and operational phases of the project suggest that issues surrounding components' quality were often observed, and in some cases were not fit for purpose. Examples include: (1) the loss of buoyancy some floats suffered due to foams shrinking and absorbing water; (2) Electrical boxes and cabinets were generally exposed resulting in mild corrosion from water ingress. This is an important health and safety issue; (3) damage occurring during the pre-construction phase where float walls were punctured from nails and dragging over rough surfaces.

The importance of investing in design services, high quality components, a skilled workforce, and ongoing high level of O&M services, is of critical importance to those investing in FPV plants. Project Management is a key element in maximising the potential of a successful outcome as many of the challenges cited would have been avoided or mitigated.

3.16 Unexpected health and safety risks and concerns

The Operations and Maintenance (O&M) function plays a critical role over the lifetime of an FPV plant. Significantly more demanding than a GMPV plant, the operating environment of FPV can pose more challenges to O&M personnel, including health and safety issues. Firstly, access pathways may be partially blocked by poorly sited combining boxes or other equipment; secondly, submerged MC4 connectors pose an additional problem; and thirdly, bird soiling is a serious issue.

High humidity environments and proximity to water cause damage to cables and connections making these areas hazardous. Low insolation leads to possible electrical leakage to the ground which poses a danger to staff and has the potential to cause damage to equipment. Inverters on the testbed have regularly suffered delay in start-up which led to “non-negligible loss” of energy production ((Wang et.al., 2020, p380, ln9).

Water ingress causes numerous challenges for both electrical and non-electrical components. There is a greater requirement for repair, replacement, and regular cleaning services than would be the case for a ground mounted system. Consequently, the costs allocated to O&M will be higher.

One major challenge requiring regular attention is that of bird soiling (see Figure 21). Shading effect, hot spots, reduction of current, accelerated degradation, and consequently significant reduction of energy generation can be attributed to bird soiling. In one instance a 10% reduction of electrical output was recorded at the testbed site, seriously impacting revenue.

Figure 21 - Bird Soiling at Sheeplands Floating Solar Plant

Overall FPV investment is currently expected to have a cost premium of 10-15% over GMPV systems in the short-term, though is expected to fall in the coming years (Wang et.al., 2020, p380).

3.17 Impact of Typhoon Faxia on Kyocera’s 13.7 MW floating project

Recent press coverage of the impact Typhoon Faxia had on the Kyocera’s 13.7 MW floating project at the Yamakura Dam has highlighted possible vulnerabilities of this technology (see Figure 22). The 120mph winds the typhoon brought to the coastal city of Chiba resulted in enormous damage to the plant. Firefighters identified the cause of the fire as heat generated by the strong heat produced by panels stacking up (Bellini, 2019a). Important insights of this incident are that (1) Connections between modules are insufficient to withstand excessively high winds; (2) Structural support mechanisms suffered severe failure; (3) heat generated by modules has the potential to catch fire. The latter point has some significance for concerns regarding birds trapped in gaps between modules that subsequently die, their bodies having potential to cause heat spots on the surface of the panel.

Figure 22 - Impact of Typhoon Faxia on Kyocera’s 13.7 MW floating project

3.18 Points to consider

An important aspect of FPV deployment is the extent to which state sponsorship and subsidy have contributed to investment as ultimately this impacts profitability. Although the market is moving towards non-subsidy solar, investment to date has attracted generous feed in tariffs (Fit) or generous state funded grants. The main market is for FPV is currently Asia. China holds around 60% of the market for solar photovoltaics, has low labour costs, and has invested heavily in FPV. In neighbouring countries, the cost of importing components from China is low and climate conducive to high levels of energy generation from FPV plant. The US has great potential to invest in this market though no significant investment in FPV has yet been made to remoteness of providers and lack of vendors in the American market.

Europe also has potential to benefit, the question is, to what extent is FPV economically viable in Northern Europe?   in many countries has attracted

4 Results

Results are divided into three main categories for the purpose of clarity of presentation. Sections relating to Environmental Impact; Cost Analysis; and Energy Analysis are presented below.

4.1 Environmental Impact

4.1.1 Water Evaporation

Floating solar arrays naturally cause shading of the reservoir's surface, and with it, a drop of water temperature. The amount of water lost through evaporation is therefore reduced during warm weather conditions, although the rate of evaporation is directly linked to the size of area covered by the floating platforms. For utilities, this is lost revenue. Evaporation of water from a water surface is dependent on a combination of factors: water temperature, air temperature, air humidity and air velocity above the water surface. With a reduction in water evaporation of around 70% predicted, an estimated annual savings of 206,641,830kg will be made, which equates to an additional annual revenue of £1.47m

4.1.2 Greenhouse Gas Emissions: UK CO_2(eq.) emissions due to electricity generation

In calculations, kWh to kilograms (kg) of carbon released is based on Greenhouse gas reporting: conversion factors from Department for Business, Energy and Industrial Strategy. The conversion factor is 0.28307 kg CO_2 saved for each kWh produced from a carbon free source. The factor is based on the carbon emissions generated by the current UK power stations per kWh generated. This factor includes other greenhouse gasses such as methane and nitrous oxide which are converted to their carbon dioxide equivalents, so the value is kg CO_2 eq. per kWh (RenSMART).

Table 4 - Emissions due to electricity generation

Kilowatt hours (kWh)	Conversion factor	UK CO_2 (eq.) kg
204,013,000	0.28307	57,749,959

The potential annual CO2(eq.) savings of 57,749 tonnes is achieved as a result of the operation of a 250MW FPV plant operating from Foyers Pumped Hydro site.

4.1.3 Land

Foyers Pumped Hydro plant is situated in the north of Scotland, an area renowned for its natural beauty. Visibility of an FPV plant is significant though proper mitigation measures will minimise this. Floating PV arrays have less visual impact than an alternative ground-mounted PV system. When not suitably mitigated the PV installation will have a negative landscape effect and result in a downgrading of the area as a tourist destination, the consequences of which include a reduction of revenues generated by the hospitality industry operating within that region. The FPV installation will have significantly less visual impact if care is taken during the design phase of the project to ensure topology design is optimised and mitigation measures seek to avoid, reduce or offset negative impacts. As the reservoir is situated around one metre below the nearby road, arrays will not be on eye level. In areas along the roadside where the arrays are more visible, appropriately selected plants and hedges may be planted.

Suitable siting of floats across the 5-mile long and three-quarters of a mile-wide reservoir, with its uniform contours and gently sloping sides (National Library of Scotland, n.d.) will minimise visual impact. Early design consideration must be given to possible negative landscape effects in order to optimise plant efficiency while minimising visibility and incorporating fitting mitigation strategies.

4.1.4 Pre-Construction and Construction Phases of Planned FPV Plant

The plant shares the hydro infrastructure, therefore minimal damage to land would be necessary during pre-construction and construction phases of the project. Support foundation and trench excavation are not required as regular cables are supported by buoys or cables submerged in waterproof conduits (Sahu et al., 2016; Santafe et al., 2014; Spencer et al., 2019). Additionally, the short period during which construction will be underway minimises inconvenience to local communities and visitors alike. As FPV plant can be completed and operational within 6 weeks, the duration of construction is short.

4.1.5 The Natural Environment

The proposed FPV plant covers approximately 30% of the reservoir surface producing shadow that impacts the extent to which sunlight can penetrate the water, thereby hindering destructive algae growth over that area (Woody, 2011). Although algae can be of benefit to the water ecosystem, excess causes problems insofar as high levels of algae restrict light penetration through the water, limiting the growth of plants. Moreover, by reducing algal growth the potential of water pollution is minimised (Haas et a., 2020). Dependent on the placement of the floating structures, sufficient space between panels will be necessary to ensure light is able to hit the water thereby minimising the impact of widespread shading. Good design and appropriate topology can minimise impact on the natural environment and maximise potential benefits . Consultations with SEPA, RSPB Scotland, and wildlife experts are necessary to ensure minimal impact on aquatic life as well as avian and mammalian species.

Given that fishing on the reservoir provides a revenue stream for SSE it is important to consider the implications of a reduction of sunlight penetrating the loch insofar as the possibility that it will result in a reduction of the biomass of filamentous algae and organic matter fish stocks feed on and organisms of the aquatic ecosystem (ibid.). Areas which are excessively shaded alter the ecology of the floral and faunal communities in reservoirs and ultimately impact the reservoir’s biodiversity. FPV covered area of the reservoir will require restrictions on access and use for recreational activities.

Sunlight and oxygen will continue to be distributed through natural convection cycles over the remaining, unaffected 70% of the reservoir.

4.1.6 Restricting algae growth

Control for algal blooms and biological fouling reduces maintenance requirements as cleaning is required less frequently. Moreover, growth of algal blooms impact component efficiency therefore reduction or elimination reduces maintenance costs over time. A further operational benefit of FPV is the increased level of dissolved oxygen in the water, a crucially important water quality indicator essential to the health of aquatic ecosystems (Sharma and Pica, 2014). Low concentration levels of dissolved oxygen result in stress which when sufficiently severe, may cause the deaths of large fish (EPA, 2012). Water quality indicators also include pH, temperature, salinity and nutrients (nitrogen and phosphorus). All indicators are important however habitat temperature is a major determinant of fish health, notably their survival, growth and reproduction. The habitat temperature is unlikely to alter sufficiently to endanger fish stocks however shading may impact primary productivity which effects species diversity and nutrient cycling.

4.1.7 O&M

Dependent on the final design of the FPV plant O&M costs will be comparable with GMPV systems. Poorly designed plant will incur significant additional costs due to higher labour and service costs for example, when sited centrally on a reservoir, boats and divers are required periodically to perform maintenance which increases costs. Designs which provide appropriate spacing of modules and incorporate aisles significantly reduce maintenance costs associated with replacing modules, cleaning, and inspections as well as the health and safety risks involved when staff must climb over combiner boxes to access arrays.

PV panels must meet the highest waterproof requirements when sited on water, many generic panels comply with this requirement. Although less dust accumulates on FPV panels than GMPV arrays, theoretically making the requirement for cleaning less frequent, the extent to which bird soiling has emerged as a challenge was unanticipated. Recent reports highlight additional operations and management costs incurred through bird soiling, nesting, and damage resulting from bird activity. Bird droppings cause an instant reduction of output. Moreover, soiling results in the creation of hotspots within the solar panels, causing the solar panel as a component to break-down and eventually fail. Additionally, bird mortality is a common problem on FPV plants as electrocution resulting from contact with damaged wiring is a common occurrence.

According to Clean Solar Solutions Ltd. (2019) between 10% and 20% loss of efficiency, as a result of bird soiling, is a realistic estimate of the impact on a financial model that depends on a relatively high PR.

Birds access arrays in a variety of ways, some land on the reservoir and climb onto the panels causing possible microcracking of the panel surface. Dry twigs, bird droppings, or birds themselves, all create electrical current when they contact PV components, electrical connections, and equipment. FPV structures carry a significant risk of fire as when a fault occurs, due for example to birds pecking at wiring or a component, the DC part of the system may arc causing the nesting material to ignite and fire to spread.

Bird soiling also poses a risk to human health as they carry different types of airborne disease and spores.

Measures to inhibit bird activity must be incorporated during the design stage of the project and include bird deterrent features which should be reflected in the CAPEX expenditure. Bird deterrents have the potential to reduce bird activity by around 75% as reported at Sheeplands Farm in the UK (see Table 5).

Table 5 - Sheeplands Farm Business Case

Business Case – Sheeplands Farm Floating Solar Panels	
Business Case	Sheeplands Farm, Wargrave, Berkshire, UK
Application Content	Floating Solar panels on reservoir
Problem Definition	Soiling of the panels resulting in energy loss and damaged panels
Pest Bird Species	Seagulls and Ducks
Time of Year with bird problem	All year round
Laser projection area	3 acres (1.2ha)
Bird numbers before Agrilaser	100s
Bird reduction after Agrilaser	75%

4.1.8 Decommissioning

Recycling of PV panels must be fully considered during the design phase of the project to include collaboration with recycling units to ensure appropriate eco-design.

Following decommissioning of PV plant, special care must be taken to ensure PV panels are disposed of appropriately as they contain heavy metals such as cadmium and lead that may be released into the environment through landfill leachate. The risk of land, water and air pollution is high. Some solar panels also contain rare elements, such as gallium and indium. Their loss through indiscriminate solar panel disposal could result in permanent depletion of these substances in the future.

From a regulatory perspective, PV panel waste is classified in many nations under the general waste category. However, at EU-level, under the Waste Electrical and Electronic Equipment (WEEE) Directive, PV panels are defined as e-waste. The UK PV panel waste management is currently regulated by this directive, as well as other legal frameworks. Optimising recycling of solar panel components is a growing industry. Development of new recycling technologies has been evident in recent years with some claiming up to 96% recycling efficiency and promises of improved efficiency in coming years.

Floating platform manufacturers highlight eco-friendly characteristics of their products. For example: compliance with fresh and natural water environments; neutral or positive environmental impact; reduction of evaporation; preservation of ecosystems; easy to dismantle; and recyclable materials.

As the proposed FPV site located at Foyers Pumped Hydro facility would minimally have a lifespan of 25-30 years, further development of these technologies will be available at the point of plant decommissioning.

There are two main types of solar panels, requiring different recycling approaches. Both types—silicon-based and thin-film based—can be recycled using distinct industrial processes.

4.1.9 RISKS

FPV is a new technology with a limited track record and must therefore be perceived as higher risk than a GBPV system. Moreover, the lifetime costs of floating solar remain uncertain as most plants have a projected lifetime of 25-30 years, while the earliest installation of FPV was in 2007. Similarly, uncertainty surrounds the long-term environmental impacts of FPV and its effect on ecosystems makes predicting both negative and positive impacts assumptions rather than scientifically proven fact.

Solar photovoltaics operation on a reservoir requires contractors with unique technical design skills and expertise to adequately plan the construction and operation of such plant including all aspects of electrical safety, type of mooring and anchoring appropriate to this unique site, along with the operation and maintenance requirements which is more complex given the movement of water and potential risk to employees. There are many new entrants to the pontoon and float supply industry which has placed downward pressure on price to the extent that there is no longer a disparity in cost when compared to a GBPV system. Nevertheless, quality is essential in this environment therefore contractors with a strong track record should be prioritised.

Table 6 - Risk Matrix

1 -2	Low
3 - 4	Medium
5 - 6	High

Foyers Floating PV			
Descriptor	Impact Severity	Probability	Total(P x I)
Safety	2	2	4
Environmental / SEPA Conditions	1	2	2
CAPEX	3	4	12
Engineering / Asset Integrity	2	2	4
Total			**22**

4.2 Energy Analysis

To ensure data integrity, data was collected for a five-year period from 2015 through 2019 and initially scrutinised. The first two years of data was found to be highly fragmented and was therefore eliminated from this research. The subsequent data sets were further scrutinised in order to identify the optimum data set on which to base this study.

Through Code of Practice (COP) meters, import and export data were collected for each generator at Foyers Pumped Hydro plant. Figure 23 (2019), Figure 24 (2018) and Figure 25(2017) provide graphical representations of the data. The lines of the graph depict the levels of electricity exported to the grid in MWh from generator 1 (FOYE~M1_EXPORT) and generator 2 (FOYE~M2_EXPORT) over a one year period, along with the levels of electricity imported from the grid in MWh from generator 1 (FOYE~M1_IMPORT) and generator 2 (FOYE~M2_IMPORT) over the same period. A similar pattern of export generation and electricity import for pumping is evident over the first 10 months of 2018 and 2019. An exceptional event, in terms of an outage lasting from the beginning of November until the end of December occurred in 2019 which resulted in zero MWh export generation and zero import electricity for pumping for the duration of the outage (see Figure 23).

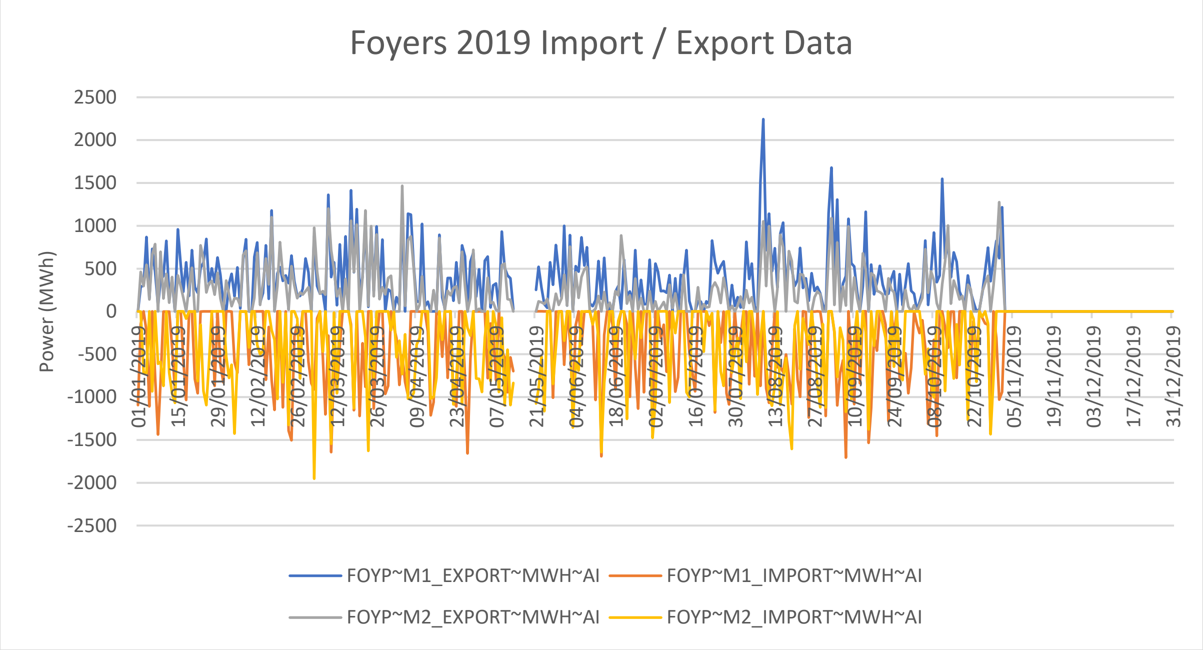


Figure 23 - Foyers 2019 Import / Export Data

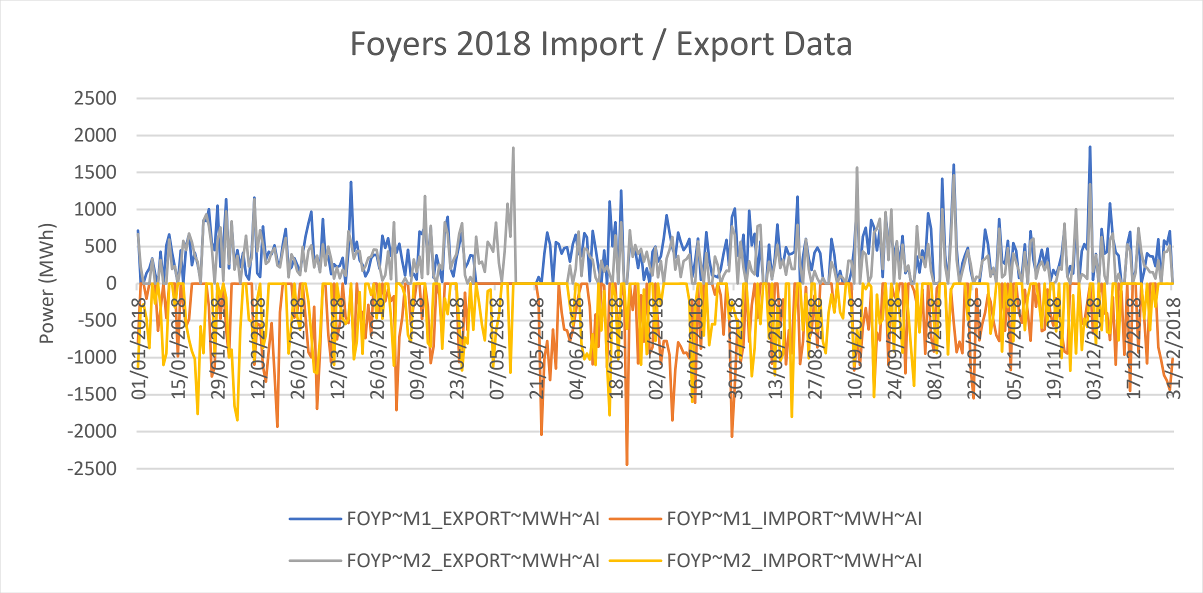


Figure 24 - Foyers 2018 Import / Export Data

Comparison of 2017 electricity import, and export patterns reveal higher level of import than subsequent years (see Figure 25).

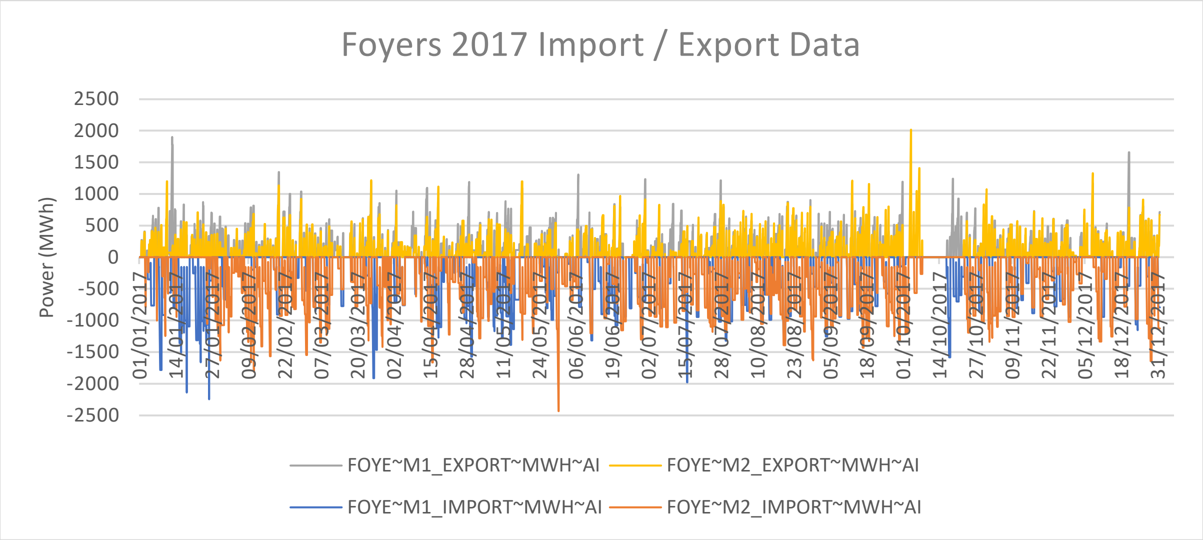


Figure 25 - Foyers 2017 Import / Export Data

Table 7 below presents a summary of electricity import and export in MWh over the three-year period from 2017 through 2019. Total export for 2019 amounted to 205,863MWh; in 2018 the export total was 243,100MWh; and in 2017 a total export figure of 125,689MWh was recorded. Total import for 2019 amounted to 242,576MWh; in 2018 the import total was 273,040MWh; and in 2017 a total import figure of 264085MWh was recorded. See Appendix 3 for larger graphic.

Table 7 - Foyers Import / Export 2017 - 2019

Year	Export (MWh)			Import (MWh)			Outage (days)	Daily Average Export (MWh)	Daily Average Import (MWh)
	G1	G2	Total	G1	G2	Total			
2019	124025	81838	205863	123740	118836	242576	61	677	797
2018	135513	107587	243100	150755	122285	273040	8	681	765
2017	75925	49764	125689	145425	24737	264085	9	353	741

Comparison of outage periods recorded for 2017, 2018, and 2019, were 9 days, 8 days and 61 days respectively. While average daily export over the same period varied significantly between the most recent years and 2017. There was an average daily export of 677MWh in 2019; 681MWh recorded in 2018; and in 2017 a significantly lower figure of 353MWh was recorded. Average daily import figures were similar over all three years with 797MWh (2019), 765MWh (2018) and 741MWh (2017) documented.

The origin of the disparity between 2017 figures and subsequent years may be attributed to weather conditions during 2017, the 5th warmest year on record since records began in 1908, which may explain the low export and high import figures recorded during that period. On that basis 2017 was not selected as a baseline case for this study. Also eliminated was data recorded for the operating period 1 January 2019 through 31 October 2019 on the basis that only partial data was available as a two-month outage would skew the model. Over the remainder of this study the 2018 data set is used for the model and will represent Case 0MW FPV plant.

Subsequent to the selection of annual import and export data to be used in this study, the process of modelling data obtained from Foyers Pumped Hydro plant for the year 2018 was processed as follows:

1. Location coordinates of Foyers Pumped Hydro plant was input to PVGIS which generated irradiance, ambient temperature, and wind speed data for the site.
2. Pi generated Foyers Pumped Hydro (FPH) demand profile, flow rate, import and export data.

3. Data obtained from steps 1 and 2 were imported to Excel and Homer Pro software for analysis and modelling.

Input variables investment cost, project lifetime, discount rate, O&M costs, and their associated attributes were input to HOMER Pro software which produced an annual energy generation and annual electrical summary report. To establish technical feasibility of hybrid hydro-FPV generation potential, grid import and export patterns, capacity factors, and electrical generation potential were simulated.

4.2.1 Technical Analysis: Initial Analysis of Foyers Pumped Hydro Plant

The image below (see Figure 26) provides a graphical representation of the current pattern of electricity export to the grid and import from the grid during 2018. Although generating at full capacity at some points over the year, Foyers Hydro generation had spare capacity, especially over the spring and summer seasons. This would suggest that technically, co-generation of Hydro and FPV holds potential.

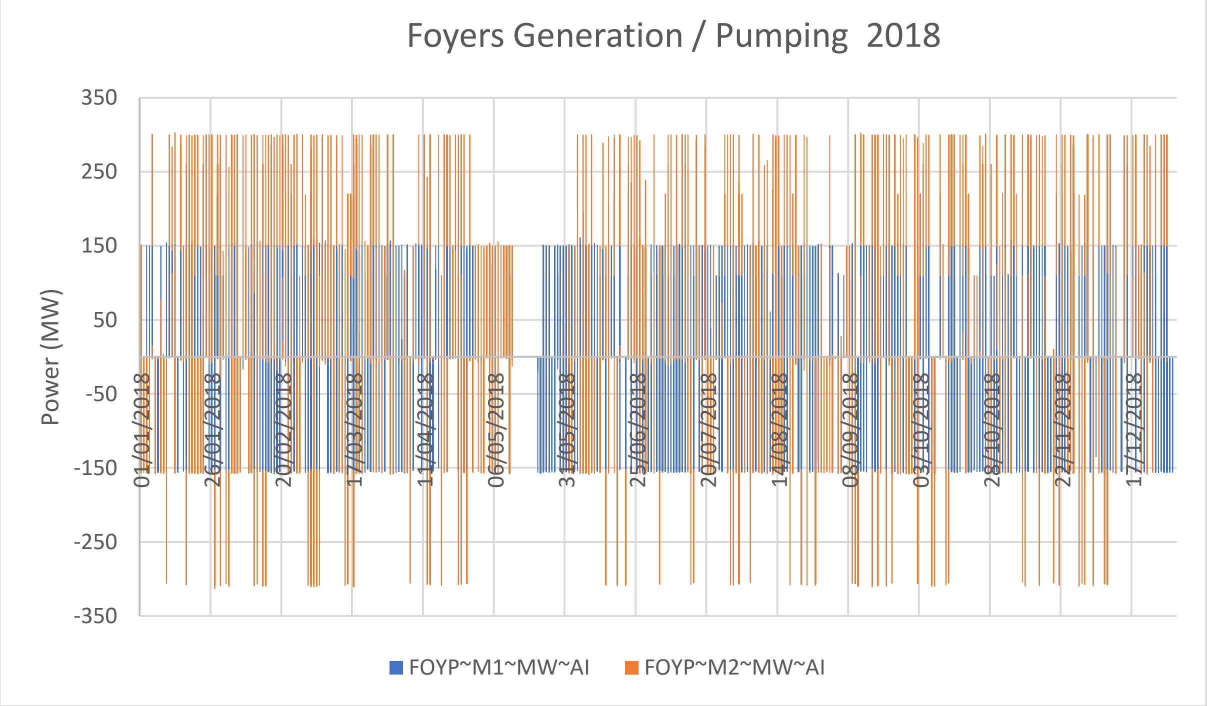


Figure 26 - Foyers 2018 Generation / Pumping

4.2.2 Hydro Generation with FPV overlaid

A graphical representation of generation and pumping patterns of Foyers Hydro Plant overlaid with 125 MW and 250 MW FPV installed capacity plants and their outputs, is presented in Figure 27 below. The 125 MW and 250 MW capacity FPV plants were modelled with generic monocrystalline 440W 72-cell modules which are indicated respectively by pale blue and green lines, and 72-cell monocrystalline 440W bifacial modules, depicted by the grey and yellow lines respectively. Output of Foyers generator 1 is characterised by a mid-blue line while generator 2 is indicated by an orange line. The dashed line is representative of current maximum TEC agreement level. At numerous points over the year the TEC limit is breached.

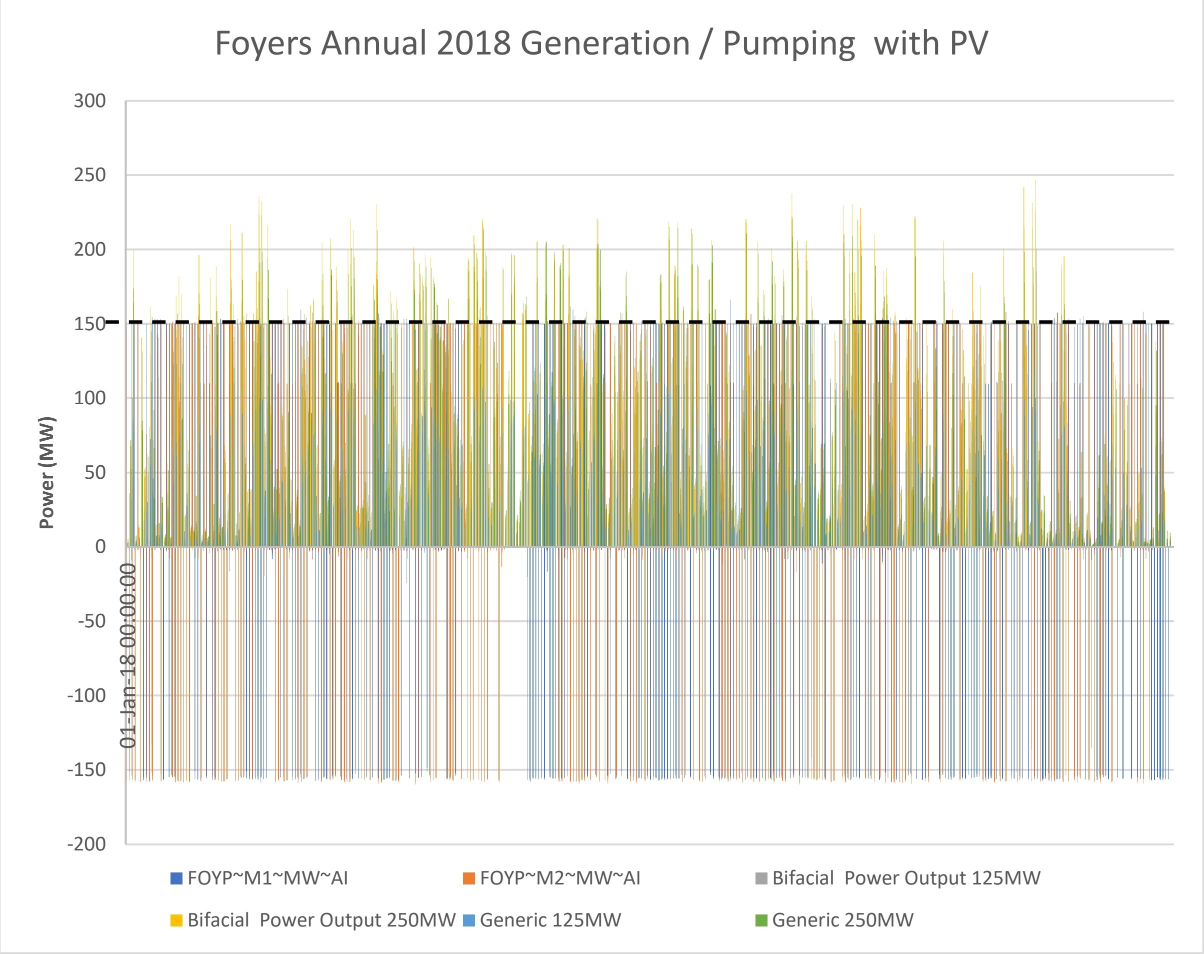


Figure 27 Foyers Annual 2018 Generation / Pumping with PV

Minor change to control settings would enable generation from FPV to be prioritised over hydro generation, conserving hydro generation potential for periods where solar irradiation is low. Additionally, FPV generation could power pumping requirements at Foyers reducing the need for import of power from the grid. Figure 28 and Figure 29 below illustrate the patterns of electricity generation possible during a single week of January and June 2018, illustrating the synergetic benefits of FPV-hydro cogeneration. Figure 29 below depicts the potential of FPV on an average day in June 2018 highlighting the greater efficiency of 440W bifacial modules over the alternative generic 440W monocrystalline cell technology.

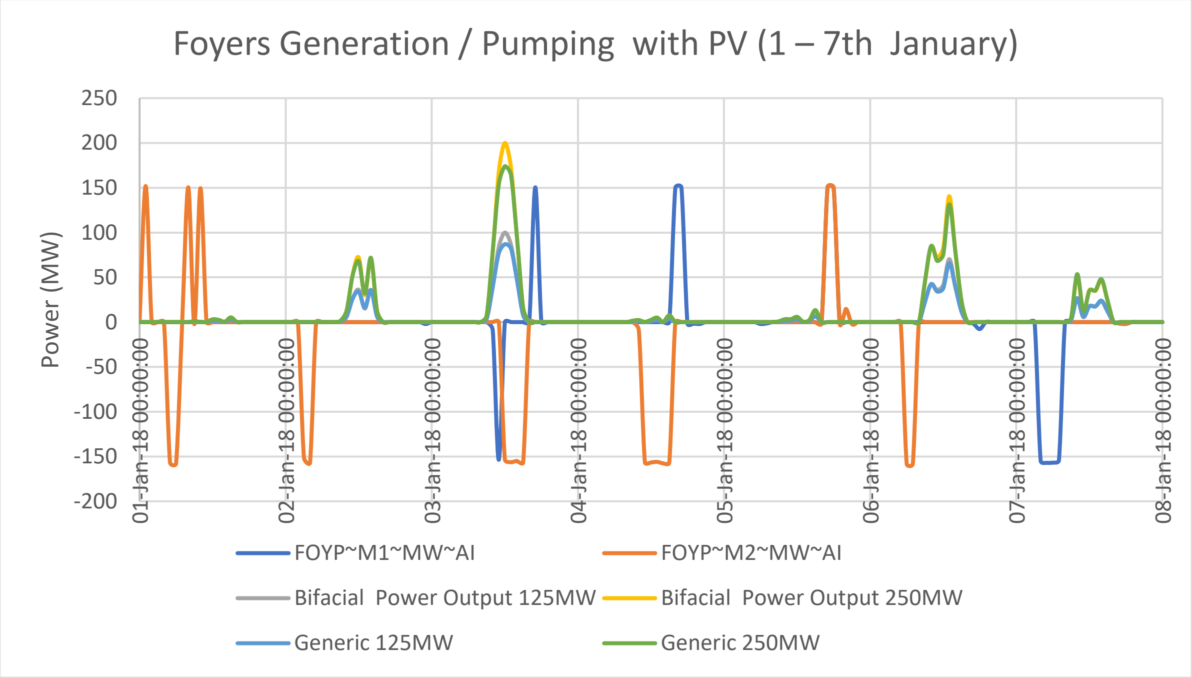


Figure 28 - Foyers Generation / Pumping with PV (1 – 7th January)

The more detailed generation pattern illustrated above highlights the higher efficiency of bifacial cells. On 3rd January 2018, Foyers motors 1 and 2 were active from 8am until 4pm. During that time, enough PV generated power is available to offset energy imported from the grid.

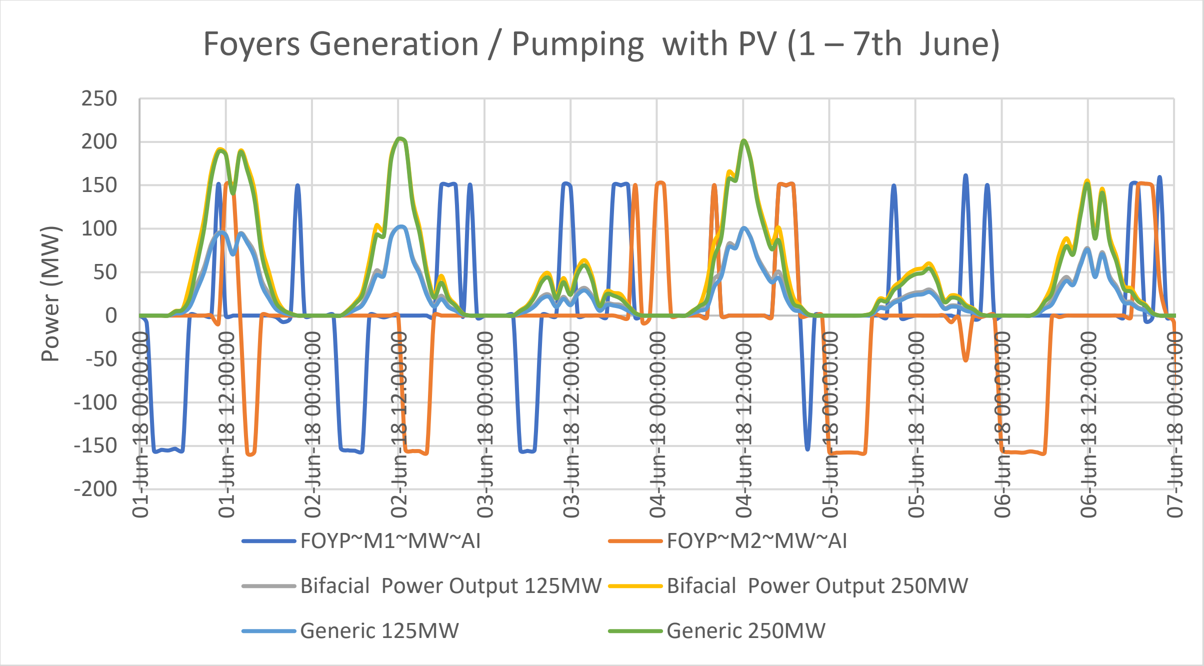


Figure 29 - Foyers Generation / Pumping with PV (1 – 7th June)

The benefit of cogeneration is evident over the first week of June 2018 as illustrated in Figure 29 above. PV generated energy at times compensates for energy imported from the grid and at other times provides an energy source for export to the grid.

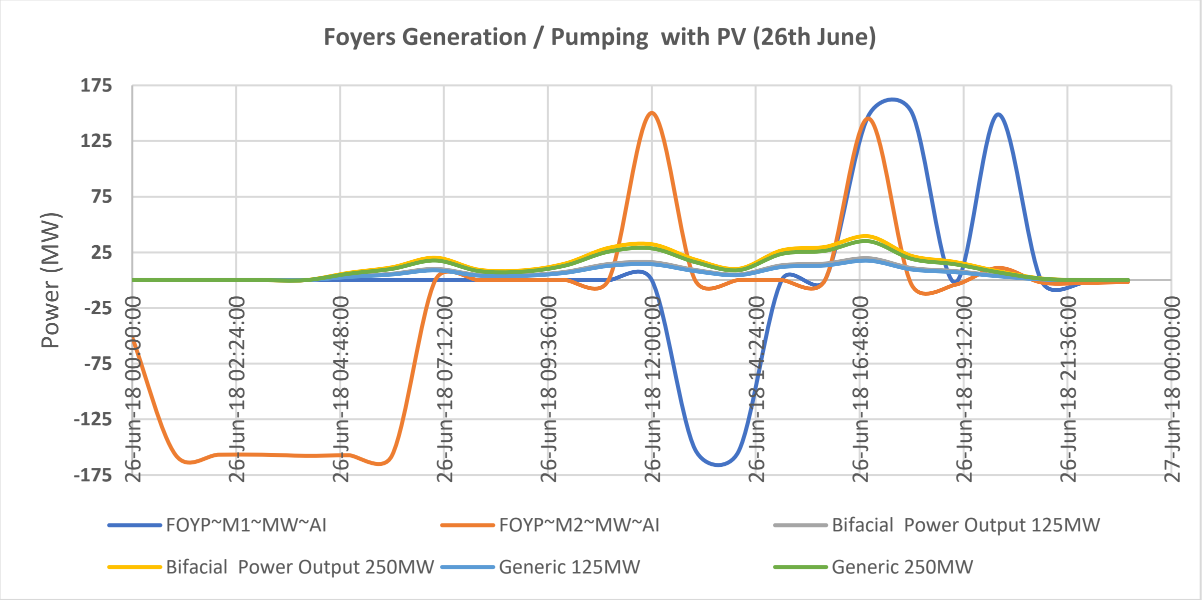


Figure 30 - Foyers Generation / Pumping with PV (26th June)

Figure 30 above illustrates the potential of FPV generation to partially compensate for electricity import from the grid along with power generation for export to the grid. In contrast to single sided cells, bifacial cells collect radiation on the front and rear side of the module, as they capture light reflected from the surface beneath the module and from its surroundings. The beneficial effect of bifaciality is highlighted by increased energy generation when compared with the standard panels as illustrated by comparison of the yellow and green lines of the graph.

4.3 250MW FPV plant

4.3.1 FPV Plant Sizing

The decision on size of FPV plant is based on the percentage of reservoir surface area deemed to minimise environmental impacts. From literature covered in the literature review of this study, recently deployed FPV plants' water surface coverage ranges from 1-60%. A further consideration for the model was the optimal tilt angle of the panels to facilitate maximum power generation from the arrays. Based on research conducted by Fordham (1999) who found the optimal tilt angle of PV at Eskdalemuir, Scotland was equal to the latitude of the site minus 20° ($\beta_{opt} = \varphi - 20^{o}$), the tilt angle used in this study was 38°.

Confirming the optimal tilt angle as 38° (see Table 8), the reservoir coverage ratio is calculated on that basis. The ratio of the module area to land area, is indicative of the percentage of reservoir covered by the modules along with spacing between panels. This is important to verify that the dimensions of the proposed FPV plant will adhere to the requirements of the site. Ideally, low reservoir coverage ratio is necessary to avoid shading and minimise environmental impacts. Simulations were performed, using PVsyst, to establish the annual output and specific yield at various tilt angles (Table 8 refers).

Table 8 - Energy yield (kWh) and global collector plane (kWh/m2) for different tilt angles

Tilt (°)	Annual energy (kWh)	Global collector plane (kWh/m^2)
0	171730	785
20	195590	913
25	198834	933
30	200963	949
34	201879	958
35	202005	959
36	202090	961
37	203128	962
38	**204934**	**963**
39	203084	964
40	202997	965
41	202870	965
42	201705	965

Since area is not a constraint in the reservoir, as the power is limited to 250MW, it is safe to say that the selected tilt angle should be the one that gives the highest specific yield (kWh/kW). Therefore, 38° seems the optimal angle when compared between the range from 0 to 42°, while also orientating the panels to the south. Finally, tracking was not considered for the plant, as it would increase the cost significantly.

A 250MW plant, utilising bifacial 440W panels (See Appendix 6) tilted at the optimised 38° angle, covers an area of 1,273,748m^2 or 127ha of the 29.7% of the surface area. Table 9 below provides an overview of the input data used to model the system. As the plant is in the Northern

Hemisphere, and modules will be south facing with tilted surface, the azimuth ($Z_s = 0°$) was set to zero (Kalogirou, 2014, p.63).

Table 9 - PVSYST 7.02 model: Foyer's Pumped Hydro Grid connected FPV system parameters

Main system parameters	**System Characteristics**		
PV field orientation	Tilt	38°	Azimuth 0°
PV modules	Model	Mono 440 Wp 72 cell bifacial	440 Wp
PV Array	No. of Modules	568178	Pnom total: 249998 kWp
Inverter	Model	Sinacon PV2180	Pnom: 2180 kW ac
Inverter pack	No. of units	89.0	Pnom total: 194020 kW ac
User's needs	Unlimited load (grid)		

The sun's path diagram may be used to find the position of the sun in the sky at any time of the year. The solar altitude angle and azimuth angle are functions of latitude, hour angle, and declination. The variations of hour angle and declinations over a period of one year for the coordinates of Foyers Hydro plant is depicted in Figure 31 below. Lines of constant declination are labelled by the value of the angles while hour angles are clearly labelled (Kalogirou, 2014, p.71).

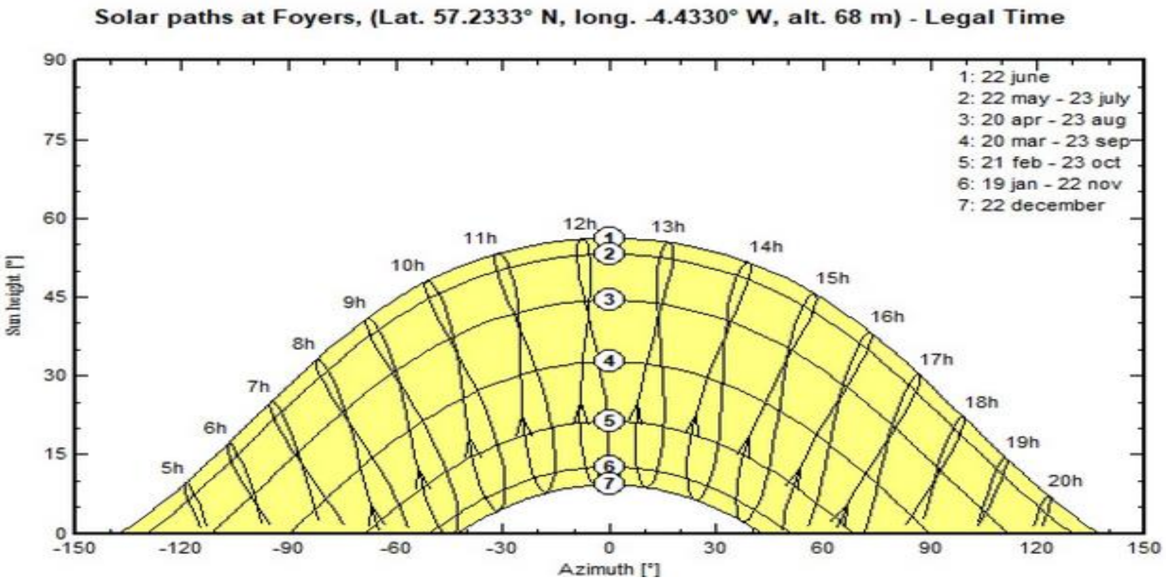


Figure 31 - Sun path diagrams

It is evident that significantly less solar irradiation is available from October through February (numbers 5-7) than is available during the rest of the year (numbers 1-4).

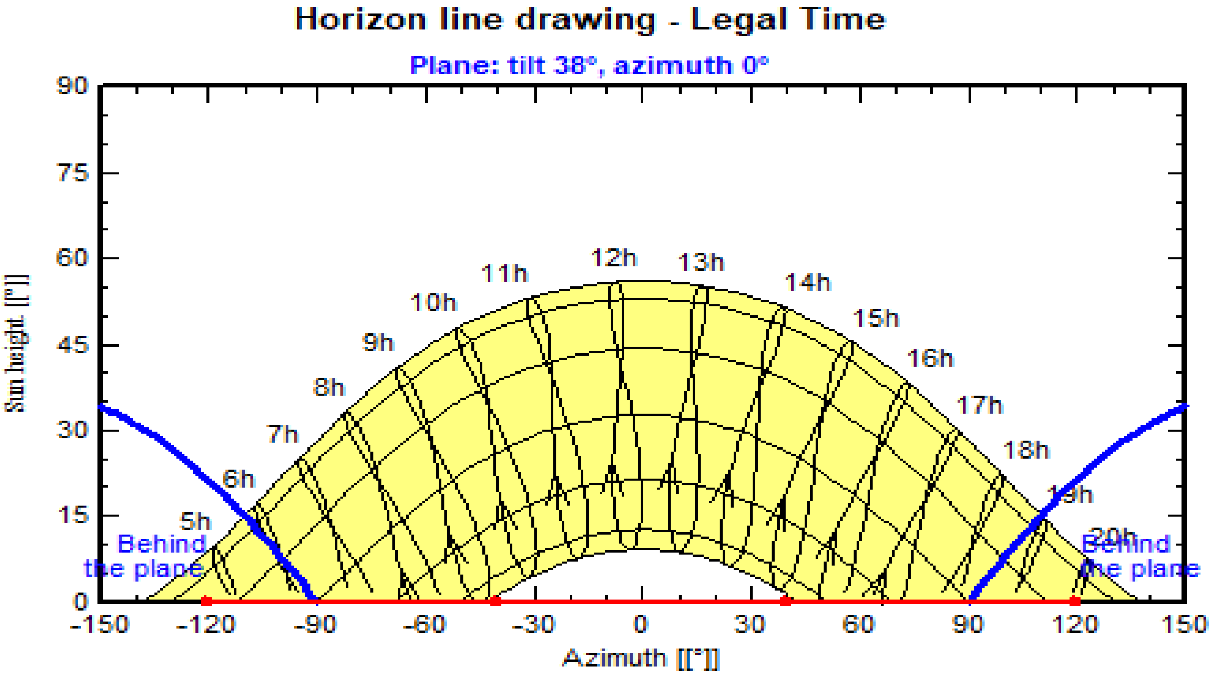
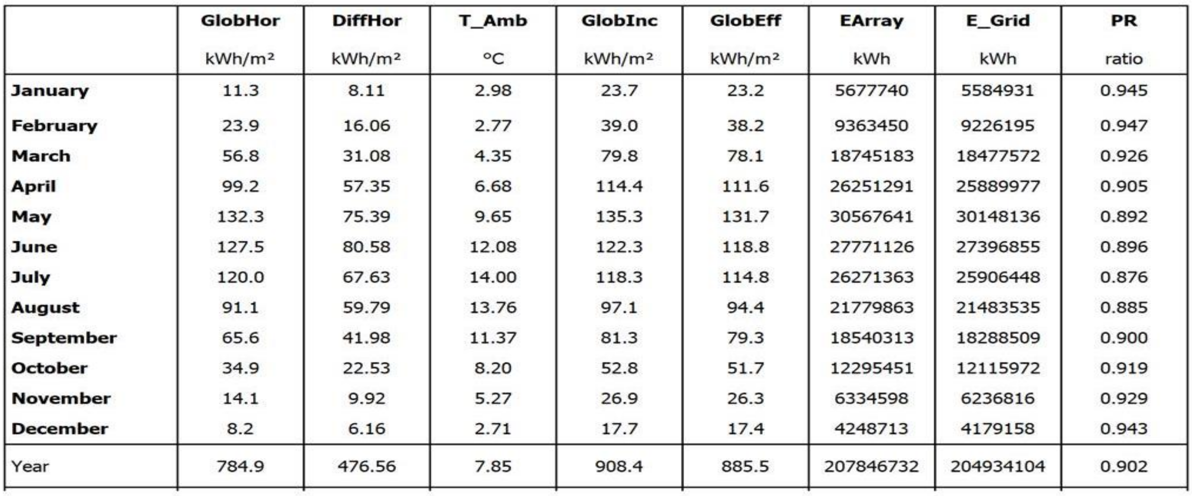


Figure 32 - Sun path diagrams

Panels tilted at 38° will be behind the horizon before 6am and after 7pm, the points at which the albedo effect would be expected. Given the low level of solar irradiance present in northern latitudes of almost 57°, negligible generation is expected as a result of the albedo effect.

Incoming daily averaged solar radiation on a horizontal surface inclined at 38°, and temperature for latitude 57.23° for each month of 2018, is presented in the table below (Table 10)

Table 10 - Foyer PV performance table



	GlobHor kWh/m²	**DiffHor** kWh/m²	**T_Amb** °C	**GlobInc** kWh/m²	**GlobEff** kWh/m²	**EArray** kWh	**E_Grid** kWh	**PR** ratio
January	11.3	8.11	2.98	23.7	23.2	5677740	5584931	0.945
February	23.9	16.06	2.77	39.0	38.2	9363450	9226195	0.947
March	56.8	31.08	4.35	79.8	78.1	18745183	18477572	0.926
April	99.2	57.35	6.68	114.4	111.6	26251291	25889977	0.905
May	132.3	75.39	9.65	135.3	131.7	30567641	30148136	0.892
June	127.5	80.58	12.08	122.3	118.8	27771126	27396855	0.896
July	120.0	67.63	14.00	118.3	114.8	26271363	25906448	0.876
August	91.1	59.79	13.76	97.1	94.4	21779863	21483535	0.885
September	65.6	41.98	11.37	81.3	79.3	18540313	18288509	0.900
October	34.9	22.53	8.20	52.8	51.7	12295451	12115972	0.919
November	14.1	9.92	5.27	26.9	26.3	6334598	6236816	0.929
December	8.2	6.16	2.71	17.7	17.4	4248713	4179158	0.943
Year	784.9	476.56	7.85	908.4	885.5	207846732	204934104	0.902

The annual performance ratio was recorded as 0.902 producing annual E_Grid generation of 204,934,104 kWh.

4.3.2 Normalised Production and Loss Factors

Normalised Production and Loss factors are illustrated in the bar chart below (see Figure 33). PV array Collection losses (Lc) of 8.5% are depicted by the purple section of the stacked bar chart. System loss of 1.3% attributed to Inverter related losses (Lr) are depicted by the green section of the stacked bar chart; while produced useful energy (Yf) of 90.2% is illustrated by the red section of the stacked bar chart.

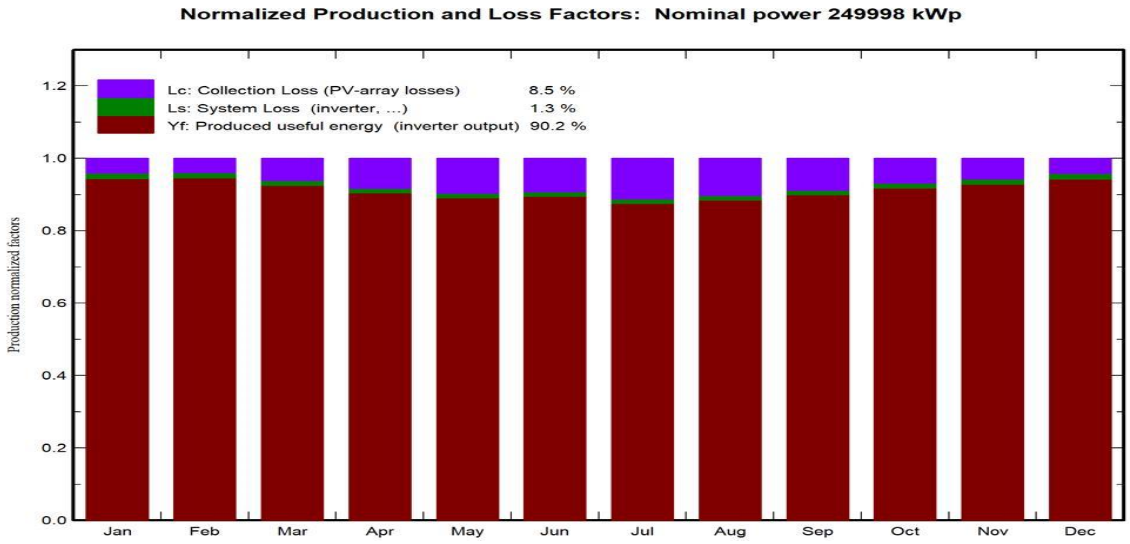


Figure 33 - Normalised production and loss factor

Daily, the Lc and Ls losses along with the produced useful energy (Yf) are recorded as 0.21 kWh/kWp/day; 0.03 kWh/kWp/day; and 2.25 kWh/kWp/day; respectively.

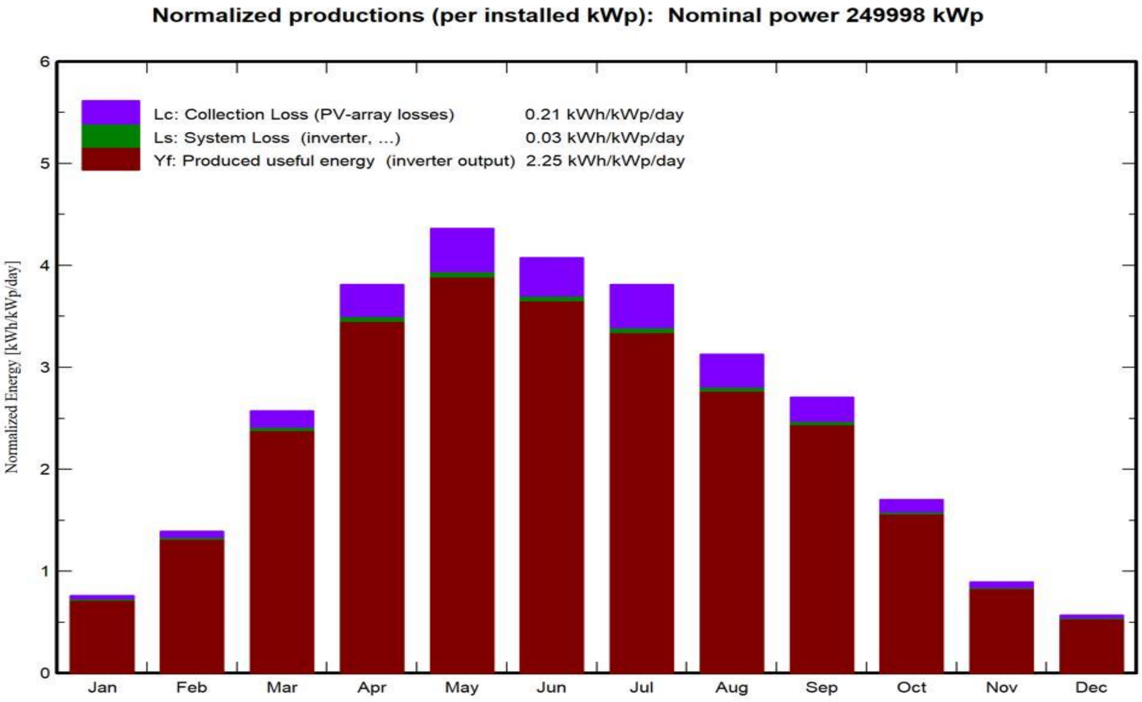


Figure 34 - Normalised production per kWp for the proposed FPV plant

Figure 34 above illustrates the normalised production per kWp for the proposed FPV plant with a nominal power of 2449998 kWp. Daily collection loss (PV-array losses) of 0.21 kWh/kWp; along with a system loss (inverter) of 0.03 kWh/kW; produces an inverter output of 2.25 kWh/kWp per day.

A visual representation of the daily output energy from the system injected to the grid, is presented in the graphic below (see Figure 35), which again illustrates the low energy yield over the October through February period of the year.

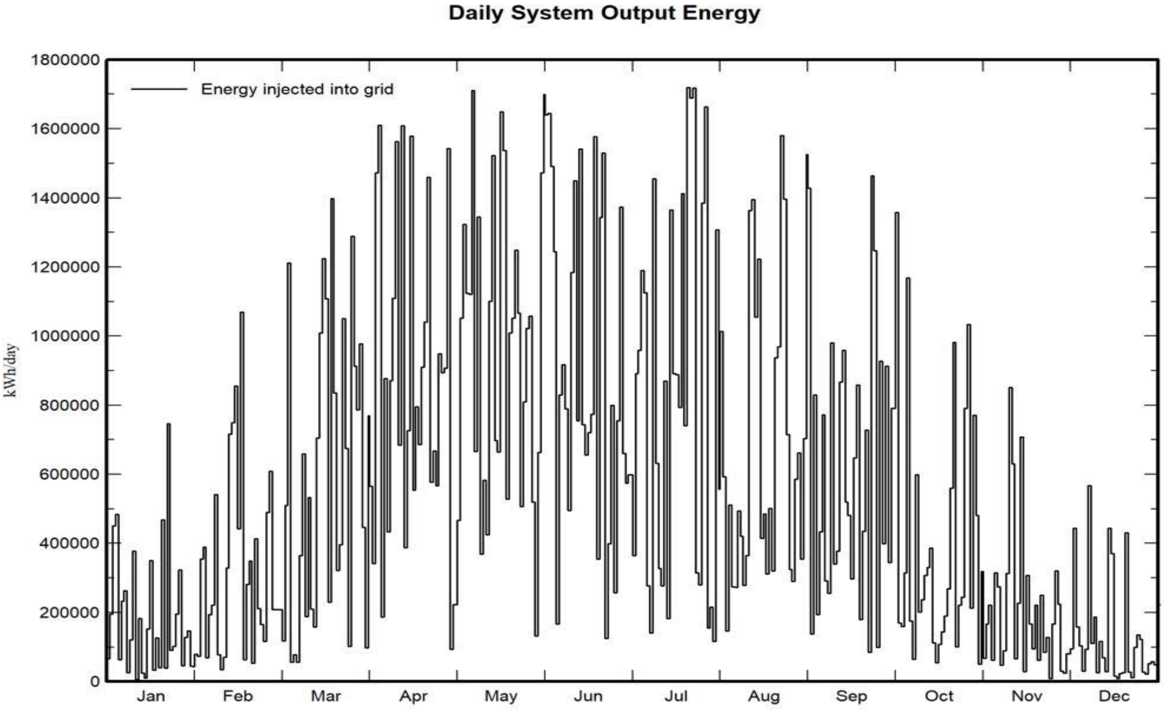
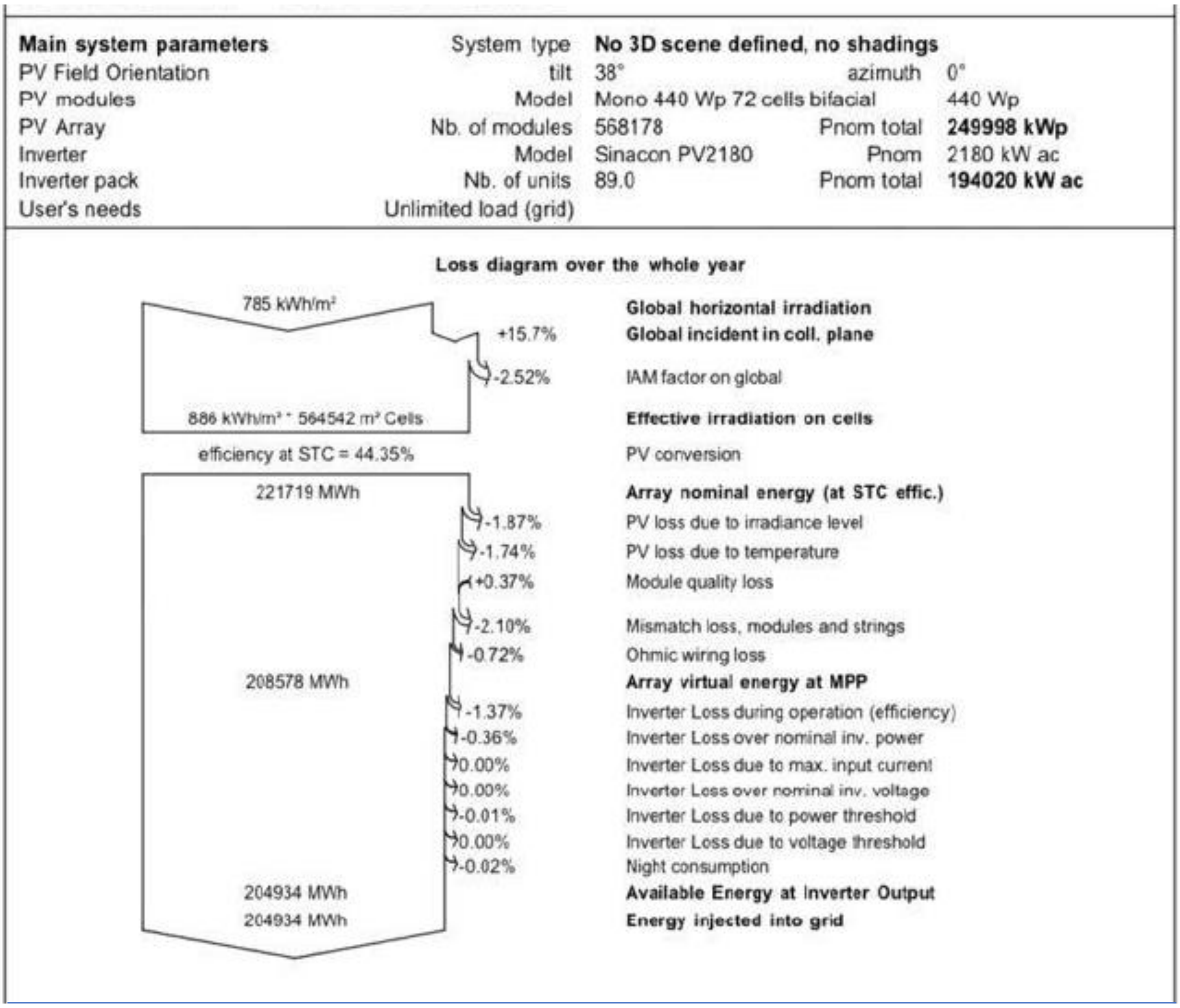


Figure 35 - Grid Connection output

The main FPV system comprises of arrays of 568,178 440W bifacial PV modules with a Pnom value of 249998 kWp, a field orientation of 38°, and utilising 89 inverter packs with a total Pnom of 194020 kW ac (see Figure 36 below). The PV conversion rate of 44.35% efficiency at standard temperature conditions (STC) was recorded. Array nominal energy at STC efficiency was 221,719 MWh. Excluding inverter losses, the loss calculation comprised losses from irradiance level and temperature, along with module quality loss, mismatch, and ohmic losses. The total array virtual energy at MPP was 208578 MWh. Losses attributed to inverter operation reduce available energy at the inverter output to be injected to the grid to 204934 MWh resulting in a capacity factor of 9.36%.



Main system parameters	System type	**No 3D scene defined, no shadings**		
PV Field Orientation	tilt	38°	azimuth	0°
PV modules	Model	Mono 440 Wp 72 cells bifacial		440 Wp
PV Array	Nb. of modules	568178	Pnom total	**249998 kWp**
Inverter	Model	Sinacon PV2180	Pnom	2180 kW ac
Inverter pack	Nb. of units	89.0	Pnom total	**194020 kW ac**
User's needs	Unlimited load (grid)			

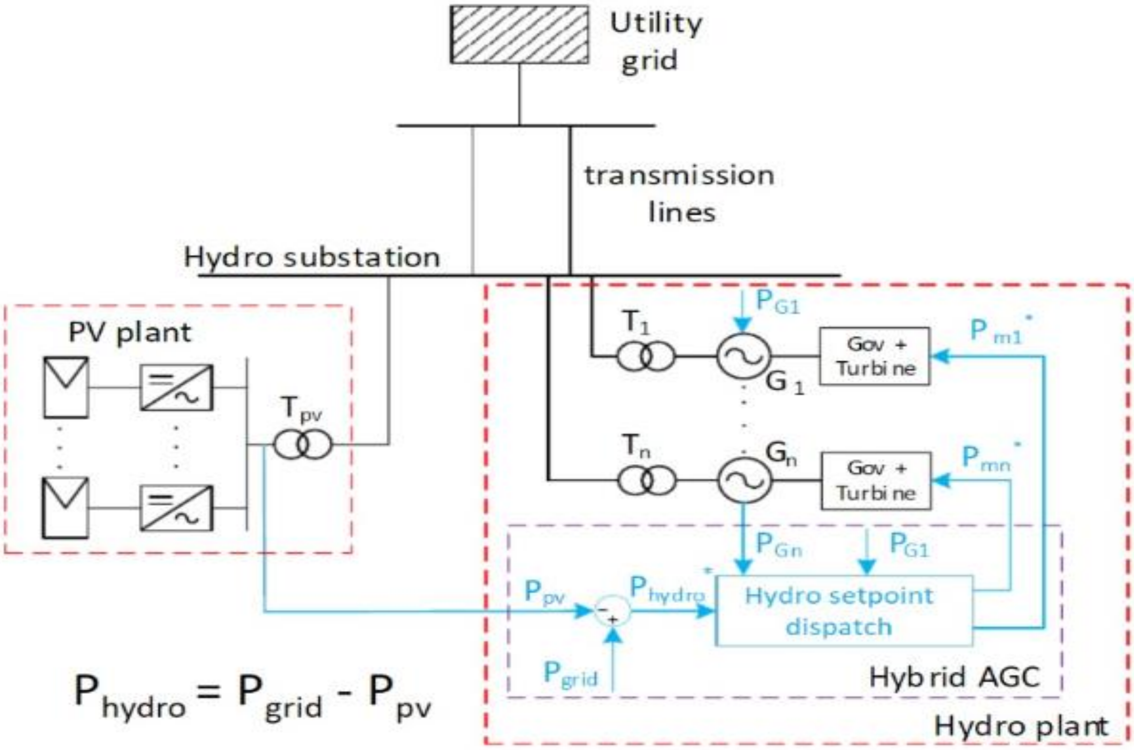
Loss diagram over the whole year

785 kWh/m²		**Global horizontal irradiation**
	+15.7%	**Global incident in coll. plane**
	-2.52%	IAM factor on global
886 kWh/m² * 564542 m² Cells		**Effective irradiation on cells**
efficiency at STC = 44.35%		PV conversion
221719 MWh		**Array nominal energy (at STC effic.)**
	-1.87%	PV loss due to irradiance level
	-1.74%	PV loss due to temperature
	+0.37%	Module quality loss
	-2.10%	Mismatch loss, modules and strings
	-0.72%	Ohmic wiring loss
208578 MWh		**Array virtual energy at MPP**
	-1.37%	Inverter Loss during operation (efficiency)
	-0.36%	Inverter Loss over nominal inv. power
	0.00%	Inverter Loss due to max. input current
	0.00%	Inverter Loss over nominal inv. voltage
	-0.01%	Inverter Loss due to power threshold
	0.00%	Inverter Loss due to voltage threshold
	-0.02%	Night consumption
204934 MWh		**Available Energy at Inverter Output**
204934 MWh		**Energy injected into grid**

Figure 36 - System Losses

4.4 Proposed integration

Integration of the proposed FPV site requires update of the control system settings at Foyers to facilitate prioritisation of FPV over hydro generation. This will ensure Foyers Hydro Power Station remains within the TEC limit agreed. A single line diagram of the proposed site with automatic generation control (AGC) set to $P_{HYDRO} = P_{GRID} - P_{PV}$ (See Figure 37 below).



AGC	Automatic Generation Control
P_{hydro}	Total hydropower setpoint
P_{grid}	Grid power setpoint given by grid dispatch center
P_{pv}	PV output power

Figure 37 - Integrated FPV SLD

For full Foyers SLD see Appendix 2.

4.5 Financial Analysis

Evaluating economic feasibility of this project is of critical importance as a loss-making venture would damage the standing of SSE Renewables' credibility within the marketplace. Decisions on whether to proceed with a project is dependent on potential benefits arising from such a venture, which must be informed by findings emanating from a feasibility study. It is one of the first activities undertaken at an early stage - the conceptualization phase of the project cycle.

A feasibility study assists in establishing project viability and facilitates decision-making of the best alternative from a range of potential options that may address the problem defined in the introduction to this study. Meticulous attention to detail is essential throughout this process to ensure appropriate and relevant information is generated.

The remainder of this chapter will present important investment data analysis using the key financial metrics of:

4.5.1 Net Present Value (NPV)

Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows. Present value of an investment takes account of the value of these cashflows over time discounted to today's values (Lumby and Jones 2003, p.94). The discount factor selected during analysis is a critically important component of this model. NPV is used in capital budgeting to analyse the profitability of a projected investment or project.

4.5.2 Internal Rate of Return (IRR)

Internal rate of return is used to evaluate the attractiveness of a project or investment. It is the interest rate at which the NPV of all cash flows (both positive and negative) from the investment is equal to zero (ibid.).

4.5.3 Levelized Cost of Energy (LCOE)

Levelized Cost of Energy measures the lifetime costs of the project divided by the calculated energy production. It is a measure of the average net present cost of electricity generation for a generating plant over its lifetime. Its purpose is to make possible comparison of different methods of electricity generation.

4.5.4 Financial Analysis of the proposed Foyers Pumped Hydro 250MW FPV plant

There is no standardisation of cost for FPV plant across the globe and minimal data relating to actualised costs through auctions. Consequently, the approach taken in this analysis was to base the costs of the proposed large-scale FPV plant in the UK on (1) historic FPV plant costs of recent UK deployments; (2) Evaluation of cost data obtained from Wood McKenzie Energy Research and Consultancy 2019 Report; (3) Assess cost data obtained from a soon to be published report by the International Solar Energy Society in which the findings were presented in a webinar last month; and (4) A published article written by Emanuele Quaranta, a subject matter expert in the field of hybrid FPV-hydro installations.

All-in-cost of FPV systems are commonly expressed in $/Wp costs of each installed plant. A recent report published by Wood McKenzie Energy Research and Consultancy (2019) provide analysis of all-in-cost of FPV deployments during 2018 in the rapidly expanding Asian market (see Figure 38 below). Costs range from 1.01$/Wdc for deployments in India to 2.76 $/Wdc in Japan and highlight the various disparities between individual component costs across the region.

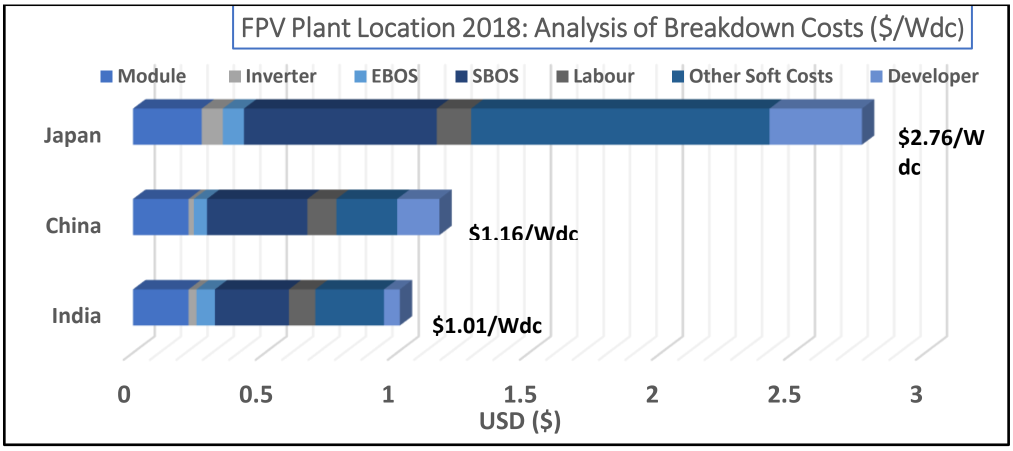


Figure 38 - Wood McKenzie 2019 - All-in-cost of FPV plant in Asia

Costs vary significantly across regions of the world. Important individual characteristics of a proposed site can result in significantly higher or lower costs.

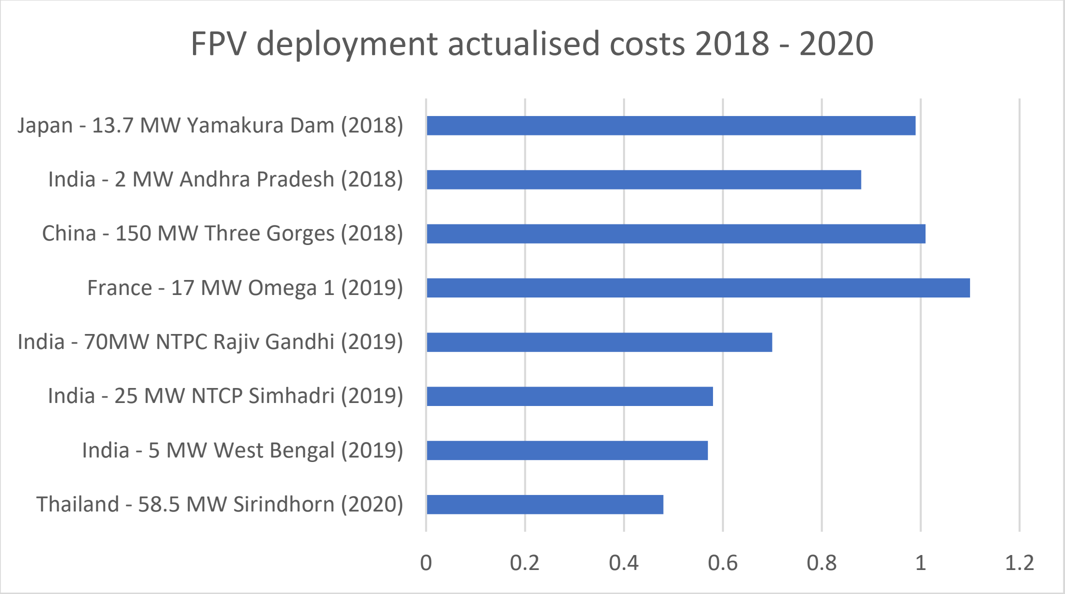


Figure 39 - ISES: FPV deployment costs (2020)

The chart above (see Figure 39) illustrates the disparity between FPV cost of plant in Europe when compared to the Asian market. An expectation of costs of between 0.48 $/Wp and 1.01 $/Wp in Asia is recorded as opposed to 1.10 $/Wp cost of the Omega I plant in France.

Conversion to £/Wp on 4 July 2020 report $/£ rate of 0.8 giving a £0.88 per watt peak price for the Omega I plant operational since 2019.

Consideration must be given to Economies of Scale, an important factor as far as all-in costs of floating solar applications is concerned, as larger installed capacity projects yield lower all-in costs on a dollar-per-watt basis (Cox, personal communication, 4 May 2020).

Today, a floating solar project costs 10% more than a solar plant on the ground, however this higher cost is overcome by the increased efficiency of FPV (Quaranta, 2020). Quaranta (2020) quotes an all-inclusive cost of ~ $763 per kWp for large FPV plant, or 0.763 $/Wp (0.61£/Wp). The estimation of all-in-cost does not however include labour costs which would add around from 0.1-0.13 $/Wp (approx. 0.1 £/Wp) to the cost making the total overall cost 0.71 £/Wp (Table 11 refers). As costs have fallen since the original UK FPV deployments, the actualised £/Wp price (Dobrotkova 2020) of Omega I - a 17MW installed capacity plant, located in Europe, which is 6.8% of the capacity of the planned Foyers FPV site –is used in the model. Averaging out Quaranta's costing with the actualised cost of the Omega I plant gives a cost of 0.795 £/Wp, which was rounded up to 0.8£/Wp, the figure used in the model of Foyers FPV plant.

Table 11 - FPV Installed

FPV plant/ date installed	Capacity (MW)	Cost (£/Wp)	Status
QEII (2016)	6.3	1.03	Actualised
Godley (2016)	3	1.17	Actualised
Omega 1 (2019)	17	0.88	Actualised
Large scale FPV Plant	**250**	**0.71**	**Proposed**

Analysis of Project Investment costs with a discount rate of 6% applied over the standard 25-year life of a solar photovoltaic plant was conducted. Annual Operation and Management cost of £100,000 was factored in along with annual depreciation of £1.66m. The depreciation figure was estimated on the basis that solar photovoltaic plant typically has a significantly longer lifespan than the 25-year investment period. The FPV base unit has an anticipated lifespan of 50 years or more. Furthermore, the plant would appear as a fixed asset on the balance sheet and attract capital allowances which would reduce the company's tax burden. The analysis assumes an energy price of £50/MWh. The investment has an NPV of -£48,941,049.13 and an IRR of 3.26%, significantly lower than the SSE hurdle rate of 7% (see Table 12).

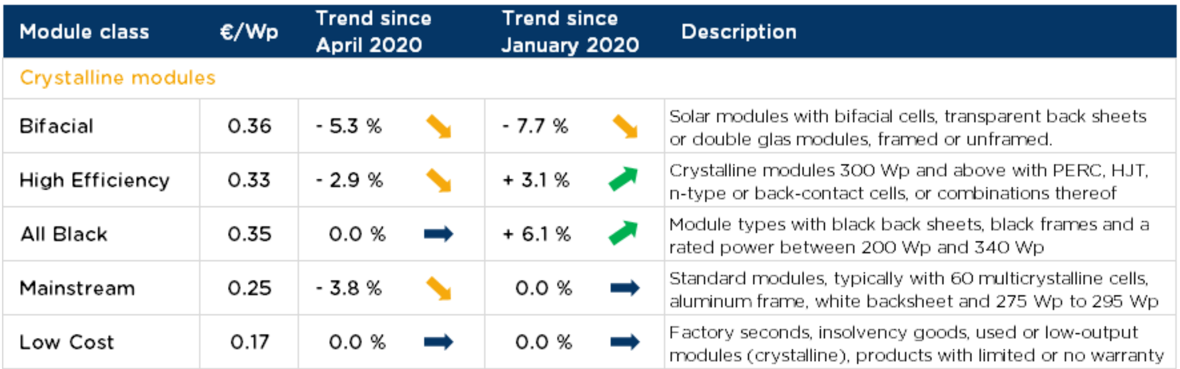
Table 12 - Project financials

Discount Factor	NPV	IRR	LCOE (£/MWh)
6%	-£48,941,049.13	3.26%	40

4.6 Sensitivity Analysis

Capex costs used in case 1 of this study relate to the latest auction prices recorded in 2019. The cost of solar photovoltaic modules has fallen dramatically since the end of 2019 and is expected to continue in this downward trend. Outlined in Table 13 below is the cost of a variety of crystalline module technologies and associated trend in price. Bifacial solar modules show a 7.7% drop since January 2020, though most of the price decline occurs between April and June this year.

Table 13 - Prices of PV modules on the European Spot Market in June 2020



Module class	€/Wp	Trend since April 2020		Trend since January 2020		Description
Crystalline modules						
Bifacial	0.36	- 5.3 %	↘	- 7.7 %	↘	Solar modules with bifacial cells, transparent back sheets or double glas modules, framed or unframed.
High Efficiency	0.33	- 2.9 %	↘	+ 3.1 %	↗	Crystalline modules 300 Wp and above with PERC, HJT, n-type or back-contact cells, or combinations thereof
All Black	0.35	0.0 %	➡	+ 6.1 %	↗	Module types with black back sheets, black frames and a rated power between 200 Wp and 340 Wp
Mainstream	0.25	- 3.8 %	↘	0.0 %	➡	Standard modules, typically with 60 multicrystalline cells, aluminum frame, white backsheet and 275 Wp to 295 Wp
Low Cost	0.17	0.0 %	➡	0.0 %	➡	Factory seconds, insolvency goods, used or low-output modules (crystalline), products with limited or no warranty

Prices reflect the average prices quoted on the European spot market (customs cleared). Source www.pxchange.com

The proposed FPV plant at Foyers is a large capacity plant which would attract a significant discount from suppliers. A proposed scenario in which PV module costs are updated to reflect June 2020 price for bifacial photovoltaic modules, along with an economy of scale negotiated discount of 15% from the supplier is modelled. The pie chart below illustrates the proportion of capex cost attributed to individual component parts of an FPV plant (see Figure 40) which shows that PV modules represent 34% of total Capex cost in 2018 (World Bank Group 2019).

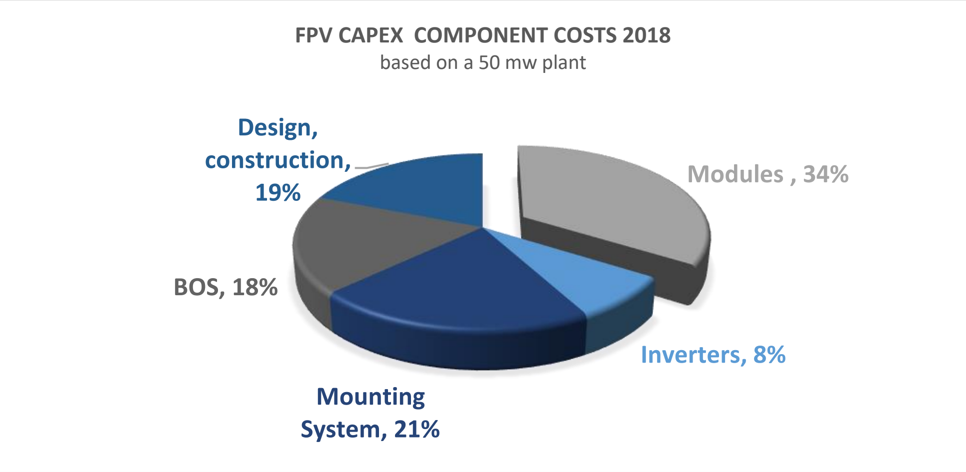


Figure 40 - FPV CAPEX 2018: Component Costs (%) (World Bank Group 2019)

Table 14 - CAPEX Calculation

Capex as of June 2020: including Economies of Scale negotiated discount of 10%		
Cost of Plant less PV modules	**Cost of PV Modules (34%)**	**Current CAPEX**
	£68,000,000	£200,000,000
	PV module cost in June 2020 (7.7% discount) = 68,000,000-5,236,000 = £62,764,000	**New CAPEX** **£194,764,000**
	Negotiate 15% discount (EoS)	£29,214,600
	CAPEX with discount	**£165,549,400**

4.6.1 Based on a CfD of £60

Table 15 - FPV cost reflecting lower cost modules and an economies of scale discount

Discount Factor	Capex	Net Present Value	IRR
6%	£165,549,400	£11,707,202	6.73%

A discount factor of 6% applied to Capex of £165,549,400 over the 25-year lifespan of this project, with a CfD of £60, an IRR of 6.73% and an NPV of £11,707,202 are achievable. The

IRR returned is slightly lower than SSE's hurdle rate of 7%, therefore based solely on hurdle rate the investment would be rejected. Many other factors contribute to investment decisions related to such a project. Given the prestige associated with such a venture, serious consideration would be given to all added-value elements during the appraisal process. Another option would be to negotiate a slightly higher economies of scale discount which is a distinct possibility given the negotiating power of a company like SSE.

4.7 Regulation and Policy

4.7.1 Contracts for Difference (CfD)

The Contracts for Difference (CfD) scheme is the government's main mechanism for supporting low-carbon electricity generation. The scheme is designed to incentivise investments in new low-carbon electricity generation in the UK by providing stability and predictability to future revenue streams.

CfD is a long-term contract between an electricity generator and Low Carbon Contracts Company (LCCC). The contract enables the generator to stabilise its revenues at a pre-agreed level (the Strike Price) for the duration of the contract. Under the CFD, payments can flow from LCCC to the generator, and vice versa as the price of energy fluctuates. This provides developers of projects with high upfront costs and long lifetimes with direct protection from volatile wholesale prices, and they protect consumers from paying increased support costs when electricity prices are high.

Under the CfDs, when the market price for electricity generated by a CFD Generator (the reference price) is below the Strike Price set out in the contract, payments are made by LCCC (see below) to the CFD Generator to make up the difference. However, when the reference price is above the Strike Price, the CFD Generator pays LCCC the difference. This is shown in Figure 41 below.

Renewable generators located in the UK that meet the eligibility requirements can apply for a CfD by submitting what is a form of 'sealed bid'. There have been 3 auctions, or allocation rounds, to date, which have seen a range of different renewable technologies competing directly against each other for a contract.

Successful developers of renewable projects enter into a private law contract with the Low Carbon Contracts Company (LCCC), a government-owned company. Developers are paid a flat (indexed) rate for the electricity they produce over a 15-year period; the difference between the ‘strike price’ (a price for electricity reflecting the cost of investing in a particular low carbon technology) and the ‘reference price’ (a measure of the average market price for electricity in the GB market).

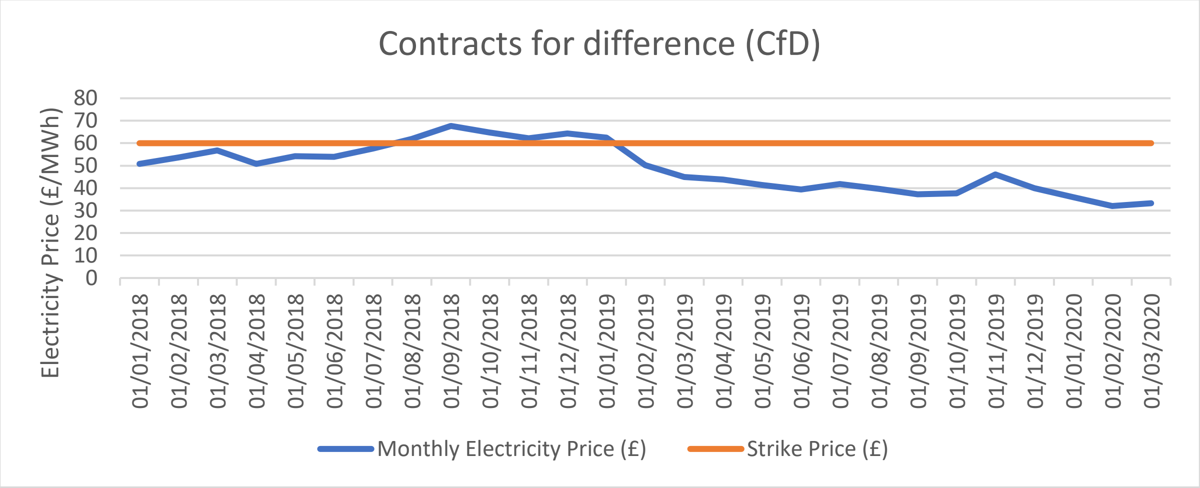


Figure 41 - Contracts for difference

In Figure 41 under the CfD scheme, the energy strike price of £60 (represented by the yellow line) has been used for illustrative purposes, to demonstrate its impact through example. In 2018, the year began with an energy price of £50, by March 2020 this price had dropped to around £33. Illustrated by the blue line in the graph above. Significant price variations are evident over the 26-month period captured. The price of energy fluctuated from a high of £67.69 at the beginning of September 2019 to a low of £32.04 in January 2020. A model of generation of the proposed Foyers FPV plant over this duration would indicate an average cost of £3.91 per MWh to be repaid for the period of August 2018 – January 2019 under the CfD scheme. Moreover, the company is protected from falls in energy price over this period as the strike price is guaranteed.

Table 16 - £60 Strike Price

Month/Year	Energy price (£)	Strike Price	Excess	Average over 6mth
Aug 2018	61.94	£60	£1.94	£3.91
Sep 2018	67.69		£7.69	
Oct 2018	64.76		£4.76	
Nov 2018	62.19		£2.19	
Dec 2018	64.32		£4.32	
Jan 2019	62.55		£2.55	

The recent announcement from the UK government informing that PV projects will be included into the fourth CfD allocation round (AR4) is a welcome development for PV developers.

5 Conclusion and Recommendation

This study set out to provide an overview of a recent new application of solar photovoltaic technology, floating solar photovoltaics (FPV) also known as floatovoltaics. FPV technology sites solar arrays on bodies of water as opposed to traditional ground-mounted arrays using structures adapted to this new environment. Over recent years FPV deployments have increased dramatically, in their geographical spread, number of annual deployments, and the installed capacity of plant installations. Asia hosts the greatest number of FPV plants accounting for around 86% of installations at the end of April 2018. The climatic conditions experienced in the region makes many locations in Asia ideal settings which can benefit from the positive attributes of FPV such as: a reduction of water evaporation; no land usage; the high level of solar irradiation present in the area; greater cell efficiency due to the cooling effect of water; and higher power output of 10-15% more than an alternative ground-mounted PV system.

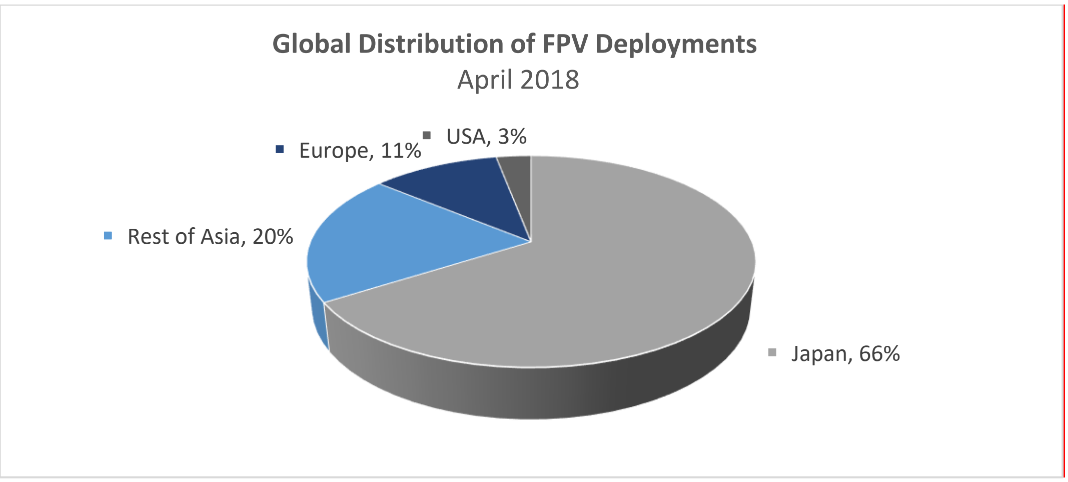


Figure 42 Global Distribution of FPV Deployment by April 2018

Many locations in the northern hemisphere, may experience the same benefits but to a lesser extent due to lower levels of solar irradiation and reduced rate of water evaporation. Nevertheless, UK FPV plants have benefited from this technology since 2014, when the first FPV deployment at Sheeplands Farm was installed. Currently in the UK, the two largest FPV farms at Godley Dam and the Queen Elizabeth II reservoir near Heathrow, generate electricity to power local water treatment plants.

Recent focus on co-location of FPV with hydro plant would appear to offer significant advantages due to its ability to share infrastructure, and thereby reduce the cost of deployment.

Moreover, electricity generation from solar power has the potential to fill dead time at Foyers when the plant is not generating from its traditional hydro resource. Additionally, FPV-hydro has the potential to smooth the intermittency and variability associated with solar via the hydro resource which would essentially function as a large storage medium.

This study employed a case study approach to investigating feasibility of optimisation of power generation through a hybrid FPV-Hydro farm located at Foyers Pumped Hydro Plant in inverness, Scotland. Feasibility was evaluated on three key variables: (1) technical feasibility; (2) financial feasibility; and(3) environmental impacts.

5.1 Key Findings

The technical model was developed to estimate the energy yield of FPV plants of 125MW capacity and 250MW capacity, using generic 440W monocrystalline panels and 440W bifacial panels, to establish the optimal size and best fit for the Loch Mhor reservoir. Homer Pro software was used to model the systems. Comparison of output from the Homer Pro model with the same system modelled using solar calculator and PVSYST 7.02 was found to be inconsistent with output obtained from the latter two software applications. The full final proposed FPV plant was modelled with PVSYST 7.02.

5.2 Technical feasibility

Analysis of the technical feasibility of optimising electricity generation from FPV plant at Foyers demonstrated that FPV would provide additional energy to partially fill dead time at Foyers. The 250 MW plant, using bifacial cell technology, has the capacity to yield 204934MWh of electricity annually to the grid. As there are occasional periods of overlap of FPV and hydro generation, minor adjustment to the control settings would be required to prioritise energy generated from solar over hydro generation during daylight hours. Additionally, solar PV has the potential to provide for electricity imported from the grid for periods where generators operate in reverse to refill the reservoir. The proposed FPV plant capacity was calculated to be 9.36%, a reflection of the low levels of incoming solar radiation present throughout the year in the Scottish Highlands.

5.3 Financial feasibility

Data obtained from credible sources provided for a costing of the proposed FPV plant and the investment sum was calculated. Analysis of potential revenue streams provided cashflows for the model which was then discounted to present values by application of a discount factor of 6%. The NPV of -£48,941,049 was produced and an IRR of 3.26% recorded. As the IRR represents the discount rate which would be required to produce a zero profit/loss over the lifetime of the project which was calculated using a 25-year operational lifetime, a profit would only arise if a discount rate of less than 3.26% had been applied. This falls well short of the hurdle rate of 7% applied to all SSE potential investments. Further discount rates of 8%, 10%, and 12% were modelled to illustrate the impact of incremental 2% discounts. An assumed price of energy of £50/MWh was used for initial analysis.

Table 17 - £50/MWh Strike Price Analysis

Discount Factors	NPV	IRR
12%	-£107,320,151.36	3.26%
10%	-£92,742,059.28	3.26%
8%	-£73,861,315.21	3.26%
6%	-£48,941,049.13	3.26%

Levelized Cost of Energy was calculated as £0.040/kWh.

5.3.1 Alternative Scenario: Energy cost of £60

The price of solar photovoltaics has fallen significantly throughout 2020. A recalculation of the Capex of the project was conducted to reflect this change. Assuming an economies of scale discount of 15% could be negotiated, the cost of the investment falls to £165,549,400. Assuming an electricity strike price of £60 is factored into the calculation, while using the discount factor from case 1, the project would achieve an IRR of 6.73%, and an NPV of £11.7m.

Table 18 - £60/MWh Strike Price Analysis

Discount Factor	Capex	NPV	IRR
6%	£165,549,400	£11,707,202	6.73%

The IRR returned is lower than SSE’s hurdle rate of 7%, however IRR is not the only measure on which investment appraisal relies. Many other factors contribute to investment decisions related to such a project. Given the prestige associated with such a venture, serious consideration would be given to all added-value elements during the appraisal process. Moreover, the negotiating power of SSE is significant, therefore it is probable that a higher economies of scale discount would be negotiated.

The use of metrics such as NPV and IRR, while useful during the investment decision-making process, do not capture other important financial considerations such as capital allowances and the ability to off-set the asset against company taxes. LCOE is a useful tool for evaluating projects and making business decisions but fails to take account of costs associated with environmental damage, factors relating to climate change, or reputational impacts.

The investment must take account of the opportunity cost of capital during the investment appraisal process. The proposed investment in FPV technology would currently fail this test as energy generated by wind farms have a lower LCOE than FPV at this point in time.

5.4 Environmental Impacts

5.4.1 Emissions

A potential annual CO_2(eq.) savings of 57,749 tonnes is achieved as a result of electricity generated by a 250MW FPV plant operating from Foyers Pumped Hydro site.

5.4.2 Water preservation

A reduction in water evaporation was predicted to yield annual savings of 206,641,830kg, which equates to an additional annual revenue of £1.47m.

5.4.3 Visual impact

The visual impact of an FPV farm at Foyers Hydro Plant would be negligible.

5.4.4 Land Usage

Land usage will be preserved for forestry and farming. Only minimal disruption to land will occur during site preparation as current infrastructure will be shared. Construction and deployment of FPV is simpler and faster as modular floats or pontoons can be assembled onshore, before being launched into position.

5.4.5 Ecosystem

Shading caused by floats or pontoons has the potential to inhibit algae growth and negatively impact aquatic ecosystems. A mitigating strategy may be to position floats at a distance from shore beyond the area where sunlight reaches the bottom of the reservoir. Additionally, arrays could be divided into clusters of floats separated by a stretch of water, thereby minimising impact on organisms residing in that habitat.

5.5 Operations and Management

5.5.1 Increased need for cleaning services

FPV is considered to require less cleaning and maintenance than a ground-mounted system due to less dust accumulating on the surface of modules sited on water. In fact, there is a greater need for regular cleaning due to the problem bird soiling presents. UK FPV plants have been shown to experience significantly more in the way of bird soiling than FPV plants elsewhere in the world. Additionally, nesting and damage from bird activity contributes to energy losses and reduced power output. Soiling also creates hotspots within solar panels resulting in accelerated material degradation in the areas affected by the high temperature. Component break-down and eventual failure is sometimes experienced. Between 10% and 20% loss of efficiency is attributed to bird activity.

Bird mortality is a common occurrence on FPV plants due to electrocution resulting from contact with damaged wiring. The risk of fire is high when animal corpses are not removed quickly following death or when birds peck at wiring and components causing the DC part of the system to arc and nesting material to ignite. Mitigating the problem requires installation of bird deterrent technologies such as ultrasonic or sonic repellers, or visual scare devices, along with regular cleaning which must be reflected in a higher O&M budget.

5.6 Risk

FPV is currently in the nascent stage of development. Little in the way of research of real-life operation of floating solar installations is available to inform investment decision-making. While solar photovoltaic plant is a proven technology, application of solar arrays on bodies of water have not yet been adequately tested and proven to last over the typical lifespan of a solar plant. Base structures along with their moorings and anchorage systems experience continual stress due to constant movement of the water below. This element of FPV plant should be fully considered during the design phase of the project.

5.7 Design

A critical element of design for FPV operating on a hydro reservoir is the anchorage and mooring system which must withstand large water level variations. Cable routing and design elements are vitally important to efficacy of FPV plant. Appropriate cable routing matching module and float dimensions will minimise potential challenges which result in downtime. The degree of slack to cables is critical to efficient functioning of the plant; excess slack will result in cables contacting the water or being submerged in water, which generally results in degradation of cables and leakage or low insulation resistance which impacts inverter function and raises the issue of electrical safety. Other considerations of FPV operating on a hydro facility is the fetch, or wind build-up, which causes vibration of the floating structures. This may result in snapped cables, mechanical stress at the joints of rigid structures, and damaged cable sheaths. Moreover, excessively high winds have the potential to dislodge modules which could be hurled into an area that blocks turbine blades, resulting in a lengthy period of downtime for repairs to be implemented.

5.8 Cooling Effect

Water has a cooling effect on solar panels, which suppress the rise of the surface temperature of the module. The cooling effect results in 5-15% increased energy yield due to the higher performance ratio of FPV. Although the cooling effect is highest when FPV is operating in tropical climates, in cooler climates the cooling effect has also been confirmed though it was found to be less extreme.

5.9 Health and Safety

The design of FPV must incorporate appropriate spacing of modules and suitably placed walkways to ensure that maintenance costs associated with replacing modules, cleaning, and inspections are conducted with minimal risk to personnel. Combiner boxes and other components of plant must be positioned appropriately and not partially block aisles forcing personnel to climb over them to access arrays.

5.10 Discussion

The conclusions drawn, and outlined above, confirm the technical feasibility of the proposed 250MW floating solar plant at Foyers. However, the economic case suggests that the impact of climatic conditions in Scotland, limits power generation from solar photovoltaic modules severely, and revenues generated fail to reach the hurdle rate. With a negative NPV and low IRR recorded for case 1 of this study, such an investment would not produce profits over the 25-year lifespan of the plant. Nevertheless, the rate at which cell technologies are advancing coupled with downward pressure on cost of PV modules, would suggest FPV has the potential to yield profits within the coming years. Furthermore, a higher strike price on the contract for difference (CfD) has the potential to raise the IRR to nearer the hurdle level. The additional benefit of impact of capital allowances on this investment would also require consideration.

Both tangible and intangible benefits should be evaluated. The prestige of becoming the first energy company to deploy large-scale FPV in the UK holds appeal. The option to partner with a company specialising in FPV, such as Lightsource BP, should be considered as risk could be shared. Also, solar photovoltaic farms often have a lifespan that greatly exceeds the 25-year lifespan used in the model. Improvement to design of the system could reduce collection losses (8.5%) and system losses (1.3%) which would improve efficiency and increase profitability.

A compounding factor of costs is the exchange rate used when converting USD to GBP. Variability of rate due to political uncertainty will diminish once there is a degree of certainty on where the UK is headed in terms of international trade.

Additional limitations impacted accuracy of the FPV plant modelled. Research cites the cost of the base structures and their attachments as costing up to 20% more than a GMPV system. The cost of these structures has not been incorporated into the numerous software applications available for modelling systems. As a compensatory measure, a significantly lower increase to the Wp efficiency gain expected from the cooling effect, was used in the model. Furthermore, a model is only as good as the data input and at best will provide an idealised generation output.

This study provides a guide to the current size of the global FPV market; the trend towards larger installed capacity deployments; analysis of water body coverage of major FPV deployments; data pertaining to actualised auction prices; and inclusion of periods of up to 10 years of O&M covered by supplier of large-scale plant, confirmed through reference to tender documents. Furthermore, this is the first study to highlight the risk of fire resulting from stacking of PV modules as happened following typhoon Faxai's impact on Yamakura Dam in Japan, in September of last year. Also, the first study to highlight the variety of serious challenges arising from bird activity on FPV plants in the UK along with the need for higher O&M budgets.

An FPV plant at Foyers would require an in-depth Environmental Impact Assessment to establish the full extent of possible damage to the environment and ecology of the area, to ensure all possible measures are taken to minimise or mitigate impacts.

5.10.1 Security

A cost for securing the area with fencing the affected area should be considered during project appraisal.

5.10.2 Recommendations for future research

There is a lack of real-life FPV operational output data for analysis. The following areas of research are proposed: (1) Measurements of water temperatures and energy yield of floating installations across a wide range of geographical locations would provide a foundation on which projections could be made; (2) research into the performance of base structures, joints, and their attachments with respect to material fatigue due to conditions where water level variation is a regular occurrence; (3) the impact on PV modules and arrays of wind drag and lift forces (4) Modelling of hybrid FPV-Hydro plant to quantify potential short-term and long-term operational co-benefits and its value to the grid; (5) impact of FPV on aquatic life and ecosystems.

In conclusion, following years of advancements in photovoltaic technologies and cost reductions resulting from downward pressure produced by increased competition, the time for expansion is now.

With regards to renewable energy technology and greenhouse gas reduction, the UK has committed to various legally binding targets. The electrical power generation from non-polluting and sustainable sources, such as solar technologies, will contribute to the partial fulfilment of targets and help meet the UK’s climate change obligations.

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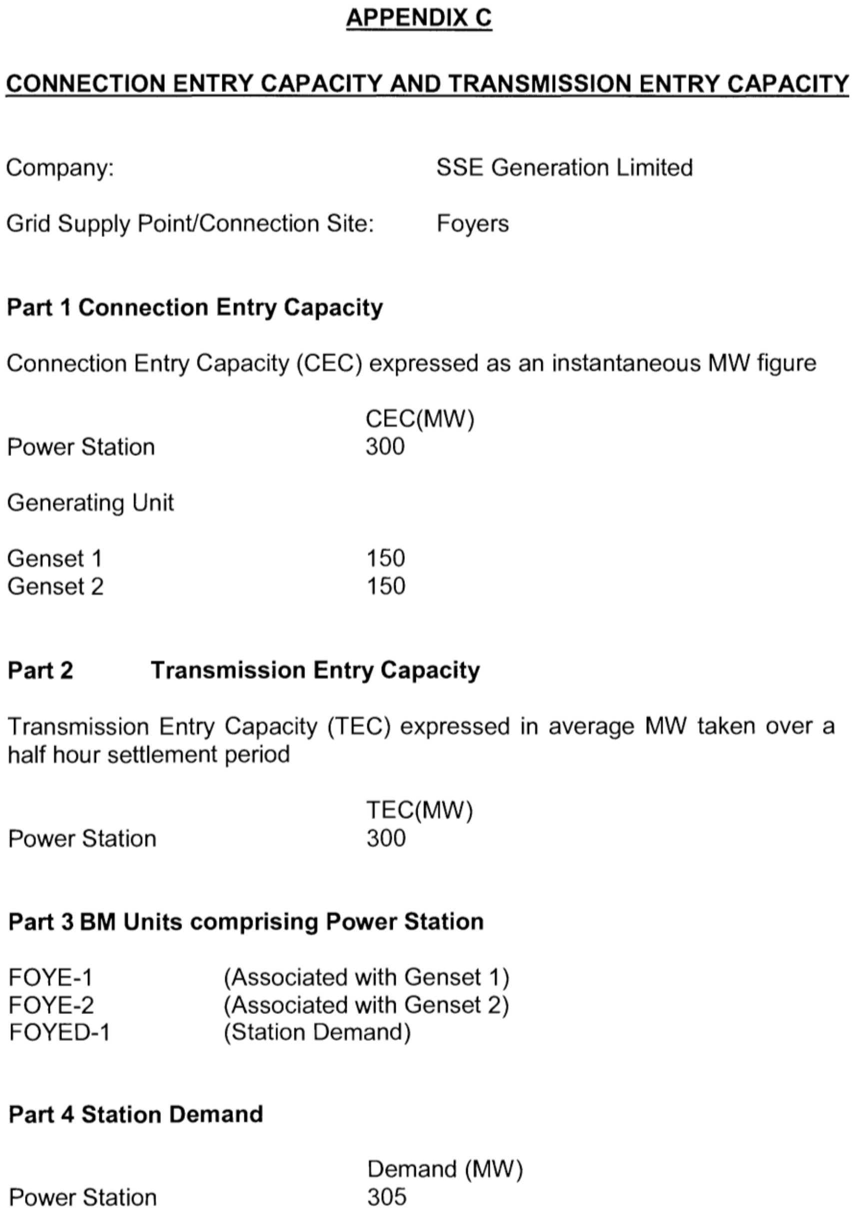
7 Appendices

7.1 Appendix 1 – Grid connection



APPENDIX C

CONNECTION ENTRY CAPACITY AND TRANSMISSION ENTRY CAPACITY

Company: SSE Generation Limited

Grid Supply Point/Connection Site: Foyers

Part 1 Connection Entry Capacity

Connection Entry Capacity (CEC) expressed as an instantaneous MW figure

	CEC(MW)
Power Station	300
Generating Unit	
Genset 1	150
Genset 2	150

Part 2 Transmission Entry Capacity

Transmission Entry Capacity (TEC) expressed in average MW taken over a half hour settlement period

	TEC(MW)
Power Station	300

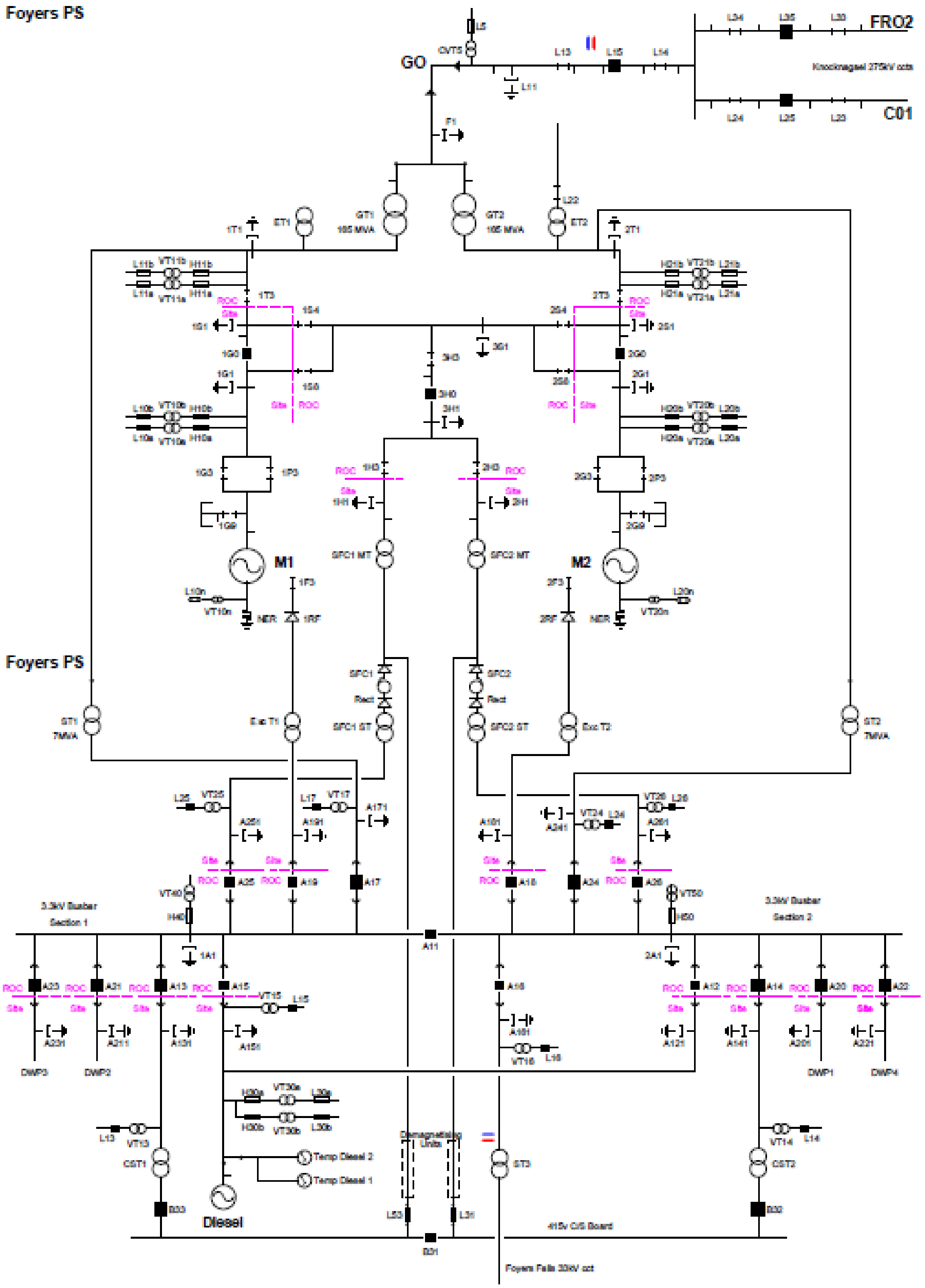
Part 3 BM Units comprising Power Station

FOYE-1	(Associated with Genset 1)
FOYE-2	(Associated with Genset 2)
FOYED-1	(Station Demand)

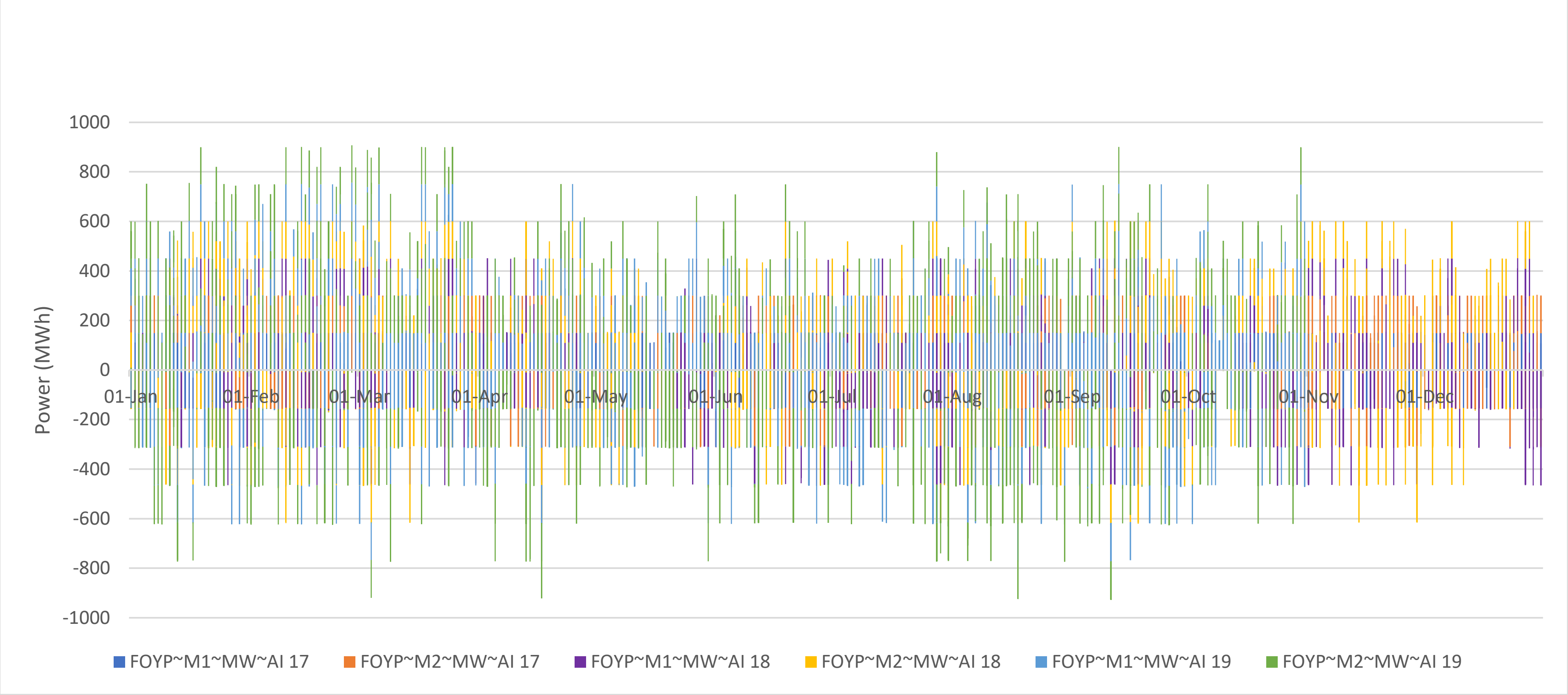
Part 4 Station Demand

	Demand (MW)
Power Station	305

7.2 Appendix 2 – Foyers SLD



7.3 Appendix 3 - Foyers Daily Generation (MWh) data for 2017



7.4 Appendix 4 – List of SSE Hydro

Name	Operator	Scheme	Location (UK grid reference)	Council area	Gross head (m)	Capacity (MW)	Commissioned
Achanalt	SSE	Conon	NH308619	Highland	20	3	1956
Aigas	SSE	Affric-Beauly	NH474436	Highland	18	20	1962
Allt-na-Lairige	SSE	Sloy-Awe	NN231136	Argyll and Bute	249	6	1956
Cashlie	SSE	Breadalbane	NN507419	Perth and Kinross	142	11	1959
Cassley	SSE	Shin	NC396232	Highland	113	10	1959
Ceannacroc	SSE	Great Glen	NH223108	Highland	90	20	1959
Chliostair	SSE	-	NB059091	Western Isles	125	1	1960
Clachan	SSE	Sloy-Awe	NN191133	Argyll and Bute	294	40	1955
Clunie	SSE	Tummel	NN912597	Perth and Kinross	53	61	1955
Cuaich	SSE	Tummel	NN674876	Highland	27	2.5	1959
Cuileig	SSE	-	NH179767	Highland	-	3.2	2002

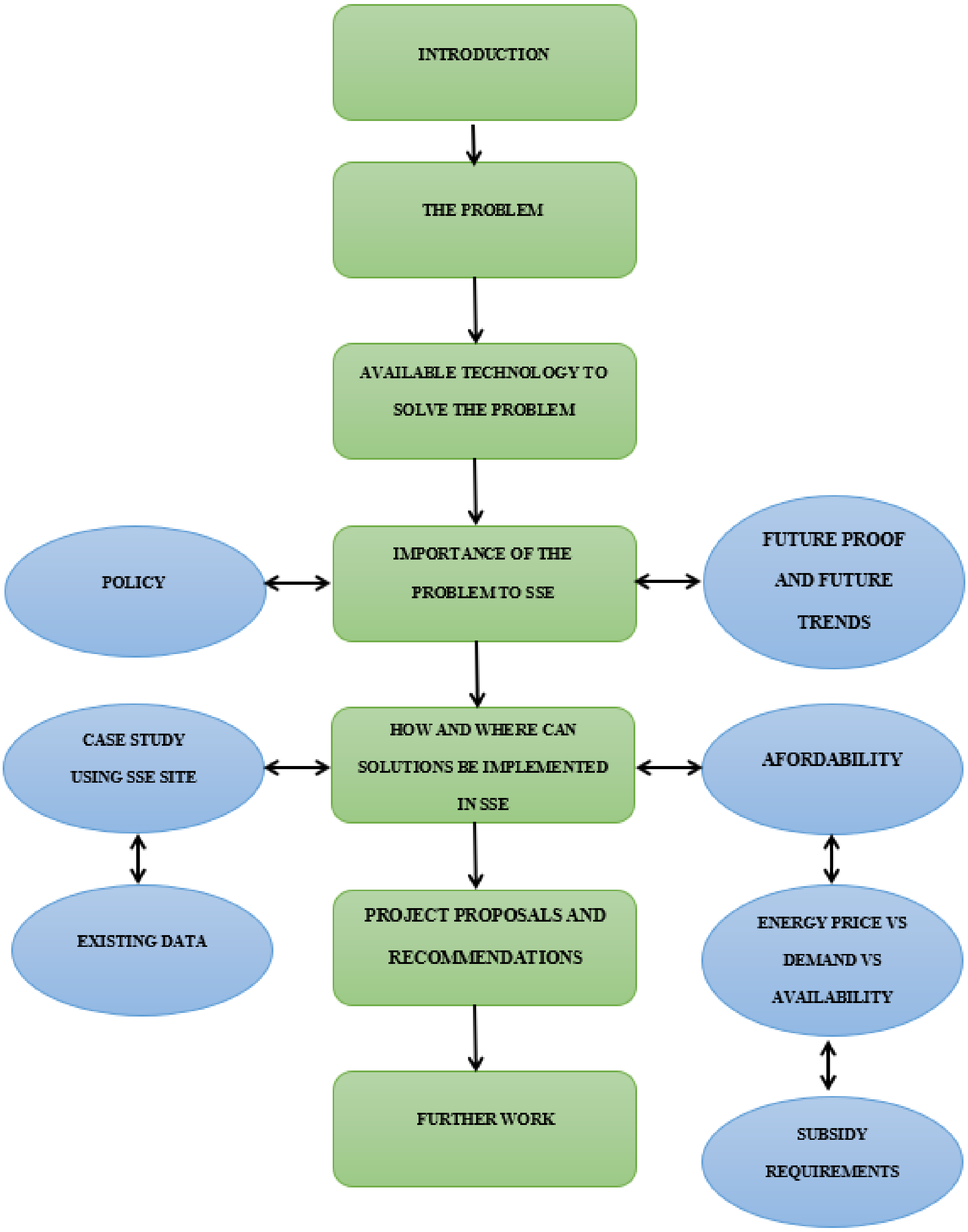
Culligran	SSE	Affric-Beauly	NH377404	Highland	60	19	1962
Dalchonzie	SSE	Breadalbane	NN740219	Perth and Kinross	29	4	1958
Deanie	SSE	Affric-Beauly	NH291387	Highland	113	38	1963
Errochty	SSE	Tummel	NN772593	Perth and Kinross	186	75	1955
Fasnakyle	SSE	Affric-Beauly	NH318295	Highland	159	69	1951
Finlarig	SSE	Breadalbane	NN585345	Perth and Kinross	415	16.5	1955
Foyers	SSE		NH503217	Highland	179	300	1974
Foyers Falls	SSE	Foyers	NH503217	Highland	108	5	1974
Gaur	SSE	Tummel	NN464569	Perth and Kinross	30	7.5	1953
Gisla	SSE	-	NB128257	Western Isles	47	0.7	1960
Glendoe	SSE	Glendoe	NH451031	Highland	600	100	2009
Glenmoriston	SSE	Great Glen	NH364156	Highland	93	37	1957

Grudie Bridge	SSE	Conon	NH320623	Highland	168	18.7	1950
Inverawe	SSE	Sloy-Awe	NN016321	Argyll and Bute	36	25	1963
Invergarry	SSE	Great Glen	NH319013	Highland	53	20	1956
Kerry Falls	SSE	-	NG829719	Highland	56	1	1952
Kilmelfort	SSE	Sloy-Awe	NM832141	Argyll and Bute	111	2	1956
Kilmorack	SSE	Affric-Beauly	NH494442	Highland	17	20	1962
Kingairloch	SSE	-	NM836532	Highland	-	3.5	2005
Lairg	SSE	Shin	NC575069	Highland	10	3.5	1959
Lednock	SSE	Breadalbane	NN698303	Perth and Kinross	91	3	1961
Livishie	SSE	Great Glen	NH353159	Highland	259	15	1962
Loch Ericht	SSE	Tummel	NN553727	Perth and Kinross	55	2.2	1962
Loch Gair	SSE	Sloy-Awe	NR924908	Argyll and Bute	109	6	1961

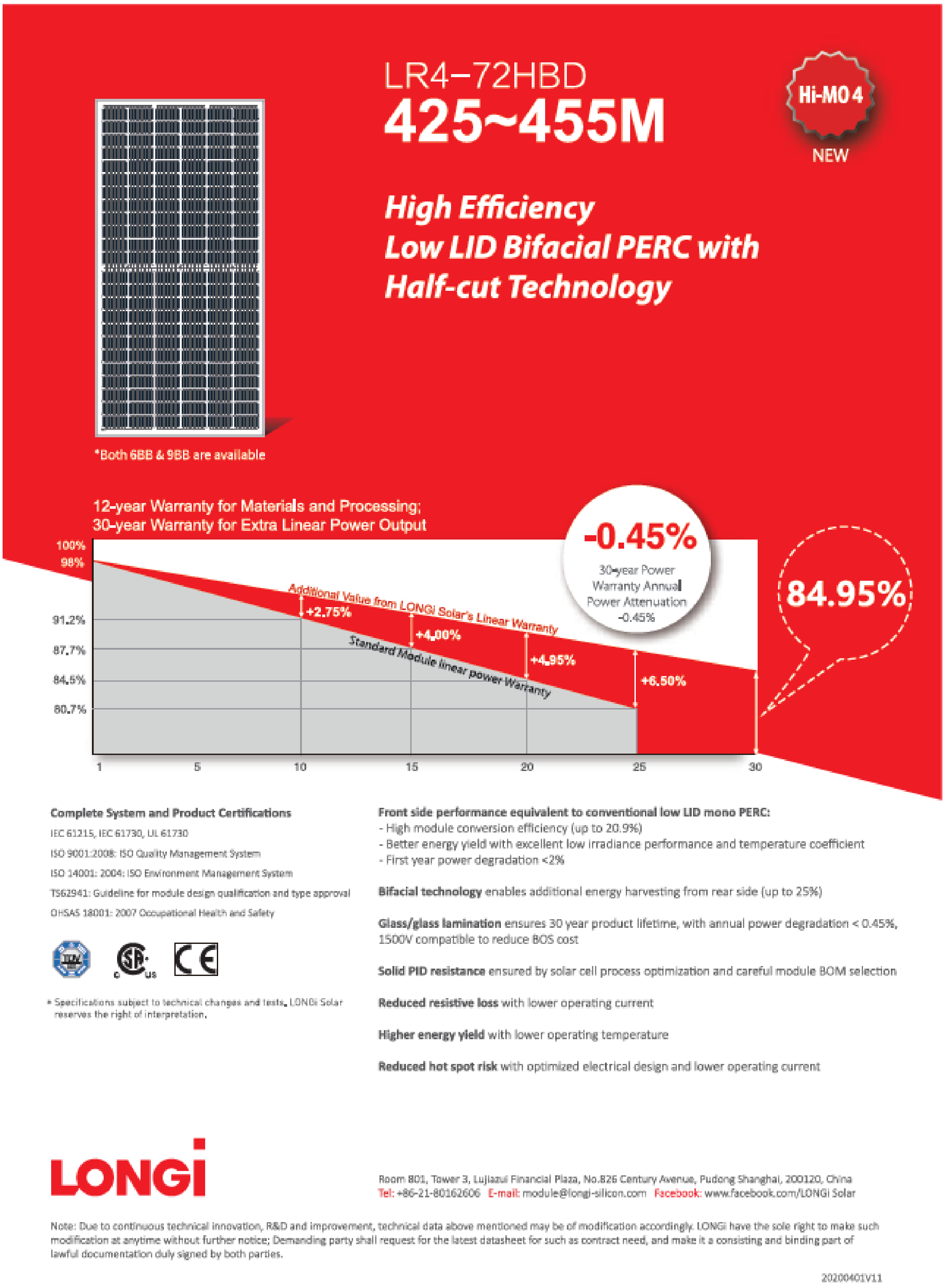
Lochay	SSE	Breadalbane	NN545349	Perth and Kinross	180	45	1958
Lubreoch	SSE	Breadalbane	NN453417	Perth and Kinross	30	4	1958
Luichart	SSE	Conon	NH394570	Highland	56	34	1954
Lussa	SSE	Sloy-Awe	NR735260	Argyll and Bute	116	2.4	1952
Mossford	SSE	Conon	NH330633	Highland	161	18.6	1957
Mullardoch	SSE	Affric-Beauly	NH222309	Highland	27	2.4	1955
Nant	SSE	Sloy-Awe	NN015208	Argyll and Bute	172	15	1963
Nostie Bridge	SSE	-	NG852272	Highland	149	1	1948
Orrin	SSE	Conon	NH436545	Highland	222	18	1959
Pitlochry	SSE	Tummel	NN935577	Perth and Kinross	15	15	1950
Quoich	SSE	Great Glen	NH107011	Highland	101	18	1955
Rannoch	SSE	Tummel	NN529582	Perth and Kinross	156	44	1930

Shin	SSE	Shin	NH573974	Highland	81	18.6	1958
Sloy	SSE	Sloy-Awe	NN320098	Argyll and Bute	277	152.5	1950
Sron Mor	SSE	Sloy-Awe	NN161200	Argyll and Bute	46	5	1957
St Fillans	SSE	Breadalbane	NN690246	Perth and Kinross	253	16.8	1957
Storr Lochs	SSE	-	NG500506	Highland	136	2.4	1952
Striven	SSE	Sloy-Awe	NS056839	Argyll and Bute	123	8	1951
Torr Achilty	SSE	Conon	NH446545	Highland	16	15	1954
Trinafour	SSE	Tummel	NN724647	Perth and Kinross	91	0.5	1959
Tummel Bridge	SSE	Tummel	NN763590	Perth and Kinross	53	34	1935

7.5 Appendix 5 – Overview of the work undertaken in this project.



7.6 Appendix 6 – PV Specification



High Efficiency
Low LID Bifacial PERC with
Half-cut Technology

*Both 6BB & 9BB are available

12-year Warranty for Materials and Processing;
30-year Warranty for Extra Linear Power Output

Complete System and Product Certifications

IEC 61215, IEC 61730, UL 61730

ISO 9001:2008: ISO Quality Management System

ISO 14001: 2004: ISO Environment Management System

TS62941: Guideline for module design qualification and type approval

OHSAS 18001: 2007 Occupational Health and Safety

* Specifications subject to technical changes and tests. LONGi Solar reserves the right of interpretation.

Front side performance equivalent to conventional low LID mono PERC:
- High module conversion efficiency (up to 20.9%)
- Better energy yield with excellent low irradiance performance and temperature coefficient
- First year power degradation <2%

Bifacial technology enables additional energy harvesting from rear side (up to 25%)

Glass/glass lamination ensures 30 year product lifetime, with annual power degradation < 0.45%, 1500V compatible to reduce BOS cost

Solid PID resistance ensured by solar cell process optimization and careful module BOM selection

Reduced resistive loss with lower operating current

Higher energy yield with lower operating temperature

Reduced hot spot risk with optimized electrical design and lower operating current

LONGi

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Note: Due to continuous technical innovation, R&D and improvement, technical data above mentioned may be of modification accordingly. LONGi have the sole right to make such modification at anytime without further notice; Demanding party shall request for the latest datasheet for such as contract need, and make it a consisting and binding part of lawful documentation duly signed by both parties.

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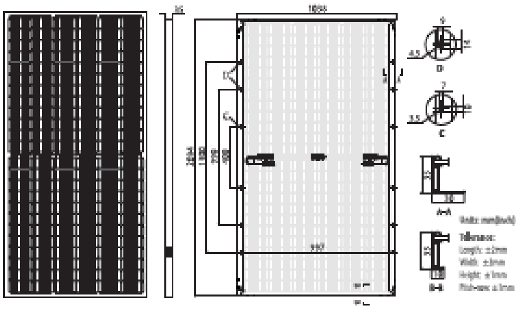
LR4-72HBD **425~455M**

Design (mm)



Mechanical Parameters

Cell Orientation: 144 （6×24）
Junction Box: IP68, three diodes
Output Cable: 4mm², 300mm in length,
length can be customized
Glass: Dual glass
2.0mm coated tempered glass
Frame: Anodized aluminum alloy frame
Weight: 27.5kg
Dimension: 2094×1038×35mm
Packaging: 30pcs per pallet
150pcs per 20'GP
660pcs per 40'HC

Operating Parameters

Operational Temperature: -40℃ ~ +85℃
Power Output Tolerance: 0 ~ +5 W
Voc and Isc Tolerance: ±3%
Maximum System Voltage: DC1500V (IEC/UL)
Maximum Series Fuse Rating: 25A
Nominal Operating Cell Temperature: 45±2℃
Safety Class: Class Ⅱ
Fire Rating: UL type 3
Bifaciality: Glazing 70±5%

Electrical Characteristics

Test uncertainty for Pmax: ±3%

Model Number	LR4-72HBD-425M		LR4-72HBD-430M		LR4-72HBD-435M		LR4-72HBD-440M		LR4-72HBD-445M		LR4-72HBD-450M		LR4-72HBD-455M	
Testing Condition	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax/W)	425	317.4	430	321.1	435	324.9	440	328.6	445	332.3	450	336.1	455	339.8
Open Circuit Voltage (Voc/V)	48.7	45.6	48.9	45.8	49.1	45.9	49.2	46.0	49.4	46.2	49.6	46.4	49.8	46.6
Short Circuit Current (Isc/A)	11.22	9.06	11.30	9.13	11.36	9.18	11.45	9.25	11.52	9.30	11.58	9.36	11.65	9.41
Voltage at Maximum Power (Vmp/V)	40.4	37.7	40.6	37.9	40.8	38.0	41.0	38.2	41.2	38.4	41.4	38.6	41.6	38.8
Current at Maximum Power (Imp/A)	10.52	8.42	10.60	8.49	10.66	8.54	10.73	8.60	10.80	8.65	10.87	8.70	10.93	8.76
Module Efficiency(%)	19.6		19.8		20.0		20.2		20.5		20.7		20.9	

STC (Standard Testing Conditions): Irradiance 1000W/m², Cell Temperature 25℃, Spectra at AM1.5

NOCT (Nominal Operating Cell Temperature): Irradiance 800W/m², Ambient Temperature 20℃, Spectra at AM1.5, Wind at 1m/S

Electrical characteristics with different rear side power gain (reference to 445W front)

Pmax /W	Voc/V	Isc /A	Vmp/V	Imp /A	Pmax gain
467	49.4	12.09	41.2	11.34	5%
490	49.4	12.67	41.2	11.88	10%
512	49.5	13.24	41.3	12.42	15%
534	49.5	13.82	41.3	12.96	20%
556	49.5	14.40	41.3	13.50	25%

Temperature Ratings (STC)

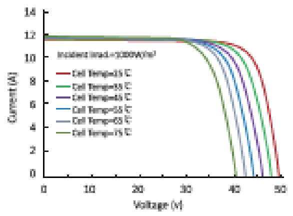
Temperature Coefficient of Isc	+0.050%/℃
Temperature Coefficient of Voc	-0.284%/℃
Temperature Coefficient of Pmax	-0.350%/℃

Mechanical Loading

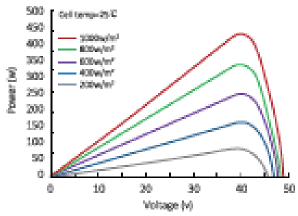
Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Hailstone Test	25mm Hailstone at the speed of 23m/s

I-V Curve

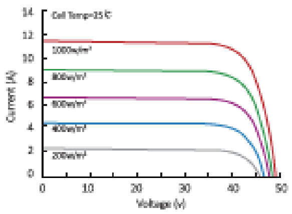
Current-Voltage Curve (LR4-72HBD-440M)



Power-Voltage Curve (LR4-72HBD-440M)



Current-Voltage Curve (LR4-72HBD-440M)



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