공학석사 학위논문

Assessment of Feasible Sites for the Development of Floating Photovoltaic Systems in South Korea

수상 태양광 개발을 위한 한국 내 적합 지역 평가

2018년 5월

서울대학교 대학원

에너지시스템공학부

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이 논문을 공학석사 학위논문으로 제출함

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Guilherme Koch Schmitz의 공학석사 학위논문을 인준함

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Abstract

South Korea has experienced a considerable growth on the installation of photovoltaic modules in recent years. Nevertheless, the country still faces obstacles regarding the further expansion on the use of this technology. The main challenge is the lack of available land for the large-scale projects, which generally require great extent of area. Floating photovoltaic systems have been pointed as a solution due to their low requirement on land. In addition, recent studies have demonstrated higher efficiency of such technology compared to usual on-ground installations. Therefore, this study investigated the technical feasibility for the construction of floating photovoltaic across South Korea through a Geographic Information System (GIS) analysis. The study evaluated a total of 3178 lakes by analyzing technical factors such as irradiance, water body depth, and other features that have been proven to affect the performance of the floating systems. The assessment pointed to 45 lakes being suitable sites for the deployment of the designed systems. Furthermore, the potential capacity for electricity generation from photovoltaic floating units in the suitable lakes was estimated in approximately 126.4MWp. The economic assessment pointed to requirements of 21.9% reduction in initial costs in order for the designed systems to reach a break-even point. Moreover, a reduction of 43.9% would be essential for such systems to achieve the same economic standards as on-ground solar farms.

Keyword : floating photovoltaic systems, solar energy, GIS.
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1. Introduction

The production of energy from solar resources has increased significantly in recent years. In fact, studies point to a growth of approximately 40% in cumulative installed capacity at 2012 and 2013, and around 30% in 2014 and 2015 (IRENA,2016). These figures are much related to the high learning rates and rapid deployment of photovoltaic modules, whose price has experienced great reduction over the last years. According to IRENA (2016), the expected continuous growth on the deployment of solar PV could culminate on the global average total installation cost reaching USD 0.8/W in 2025, a 57% reduction compared to values in 2015.These values show an increase on the cost competitiveness of solar resources for utility-scale facilities, being the investment on the technology not only a matter of environmental and social awareness but also of economic profit.

Nevertheless, despite the recent phenomenal growth, solar energy technologies still pose several technological, financial and institutional challenges that restrain the development of large-scale projects. Measures established to overcome financial barriers, such as feed in tariffs (FIT) and renewable energy portfolio standards (RPS) have been successful on facilitating the market growth of solar PV in numerous countries (Reichelstein,2013). However, the technical limitations faced by solar PV modules have yet to be completely solved. Among these, the current low performance in conversion efficiency is the biggest step for widening the scale of solar energy projects.

Although efficiencies over 40% have been reached in laboratory, commercial efficiencies have yet to reach such numbers, ranging from 11% to 17% in current projects (Timilsina,2012). The main factor reducing the efficiency of solar modules is the working temperature, i.e. the temperature at the surface of the solar panel. Regions under high radiation condition, hence enabling higher output from the photovoltaic module, are also the ones who show higher ambient temperature. Thus, a dilemma may rise on the selection of solar energy facilities.

Furthermore, the considerable low efficiency of solar photovoltaic modules imposes the requirement of vast areas for the economic feasibility of large-scale projects. For instance, South Korea, which has experienced a considerable growth on the installation of photovoltaic modules, experiences challenges on increasing the number of utility-scale projects mainly due to the lack of terrain. Floating photovoltaic systems have been pointed as a solution for the country due to its low requirement on land and higher efficiency.

The conceptualization of reservoirs as potential areas for renewable energy production emerged in recent years. Initially, the main incentive on the integration of photovoltaic panels into lakes surface was the land premium and increase in the energy efficiency of the panels. Moreover, numerous studies pointed out a potential of decreasing evaporation rates of agricultural lakes by covering their surfaces with photovoltaic floating devices (Sahu,2016).

Efforts on the better understating of solar floating systems started in 2007, with the first research projects being developed in Japan. Since then, numerous developments have emerged mainly in China, Japan, South Korea and the United States (Trapani,2014). Despite no commercial projects being deployed until now, the installed capacity of solar floating systems was able to reach great figures. For instance, the world's largest floating solar farm, in the city of Huainan in China, is able to generate 40 MW of electricity according to the Sungrow Power Supply, the Chinese firm responsible for the project.

As mentioned above, South Korea has also been of great importance on the conceptualization of solar floating systems. The first project in the country was deployed in the Seoungmun Reservoir in 2009, with 2kW of generation capacity, being used exclusively for research purposes. In the same year, the Korea Water Resources Corporation (K-water) started to investigate the potential of developing floating photovoltaic systems in the country (Kim, 2016). These initial efforts were of great importance for the further growth of the technology, culminating on the construction of a 500kW systems in Hapcheon Dam in 2012 (Choi,2014a).

Nevertheless, despite several successful developments of solar floating devices, research on the methods for investigating feasible sites are limited. Lee et al. (2012) draws a first methodology on examining the feasibility of water reservoirs for the deployment of such systems. The study investigated the potential of three sites in the Hapcheon dam with basis on several parameters.

Despite the constrains already used on evaluating on-ground systems, Lee et al. (2012) introduced new factors, such as: water flow, water level variation, floating matter, ice formation, and maximum wind speed. Such factors were also pointed to have great impact on the efficiency of the photovoltaic floating systems by other studies. For instance, Choi (2014b) pointed to a significant decrease in conversion efficiency in relation to an increase on wind speed.

The assessment of suitable sites for the installation of floating photovoltaic system has been frequently conducted according to methodologies applied for other renewable energy system, mainly on-ground solar photovoltaics. For instance, Song and Choi (2016) examined the feasibility of an 1MW floating photovoltaic system to be installed on a pit-lake surface of the Ssangyon Limestone mine in the Gangwon Province in South Korea. This study was based on the use of Geographic Information System (GIS) and fish-eye lens camera to design the floating system in relation to the site characteristics.

Moreover, Lee (2016) also utilized GIS tools in order to assess possible sites for floating photovoltaic in South Korea. In fact, in this study terrain and climate factors, such as aspect, stream, average temperature and humidity were scored and utilized in an Analytic Hierarchy Process in order to find the most feasible site.

The use of GIS tools for floating photovoltaic project relies exclusively on the extensive contribution of such on the planning and development processes of renewable energy projects. In fact, GIS has been especially important of the assessment of suitable sites for wind and solar farms, as well as on the construction of renewable energy resources maps (Resch et.al.,2014).

Lucky (2011) also highlights the importance of GIS mapping on reducing social and environmental damages caused by the deployment of renewable projects. In other words, GIS tools enable decision makers to directly compare several variables affecting the efficiency of their projects, choosing most suitable sites while avoiding major project complications.

Nevertheless, the assessment of suitable sites for the deployment of floating photovoltaics based exclusively on parameters affecting on-ground facilities may culminate on misleading results. In floating photovoltaic projects, as a consequence of the solar modules being located on water surface, the supporting system of those differ greatly from on-shore systems (Cazzaniga et al.,2018). The exposition to wind and water loads and the requirements for the adequate construction assuring the buoyancy of the system, impose detailed research on aspects such as wind speed, water level change and others.

In light of this situation, this study investigates the technical feasibility of potential sites across South Korea for the construction of floating photovoltaic systems through a GIS analysis. The study evaluates the sites by analyzing technical factors such as irradiance, water body depth, and other features that have been proven to affect the performance of the floating systems. Furthermore, an economic analysis is performed on the feasible sites in order to identify the most economically viable project.

2. Literature Review

2.1. Floating Photovoltaic Systems

The continuous research and development of renewable energy technologies culminated on the significant rise on the supply of electricity from such sources. Still, large scale projects, especially solar and wind farms, are considerably few due to requirements of extensive lands. The wind energy industry has been able to solve this problem in some extent by redirecting their large projects to off-shore sites. In fact, according to the Global Wind Energy Council (GWEC,2016), a total of 2,219 MW of new offshore wind power was constructed through seven markets globally in 2016.

Likewise, the solar industry has been gradually focusing their developments on sites where the installation of photovoltaic panels will not interfere greatly. Amongst these, water bodies have been receiving great attention as result of the several benefits of such systems. The construction of solar farms in water reservoirs may occur in the four instances:

- Canal Top Solar Systems: in this type of construction, the solar panels are arranged over irrigational canals as shown in Figure 1. The first development of such projects occurred in India in 2014, with a 10MWp system being installed over 3.6km of the Narmada irrigation canal in the western part of the country. In addition, India also plans to further mature this resource by developing additional 50MWp grid-connected solar photovoltaic systems in canal banks (Kougias et al.,2016);

- Submerged Solar Systems: in these systems, the solar panels are installed on large floating frames, a few centimeters underwater and moored close to the shore. The literature on the performance of such systems is limited, with ongoing studies focusing mainly on the efficiency gain on deep and shallow waters (Cazzaniga et al.,2018);
- Off-shore Solar Farms: despite being the focus of numerous studies, the development of solar energy in the ocean still faces numerous challenges surrounding mainly structural stability. For instance, due to the possible structural damage caused by the kinetic wave energy, a robust platform had to be designed. The platform, developed by researchers at the Vienna University of Technology, incorporates a truss or pneumatic structure which is supported by floating cylinders that enable the system to float (Wang,2017);
- Reservoir/Lake Floating Solar System: these systems were primarily development as a mitigation for the high evaporations rates of irrigation reservoirs. That is, with the intention of reducing the evaporation effect from solar radiation, special floating covers were developed in order to shield the water surface (Santafe et al.,2014). As a result of the great declines in water evaporation volume and higher electricity production, further developments, aiming specifically on increment on power generation, took place.

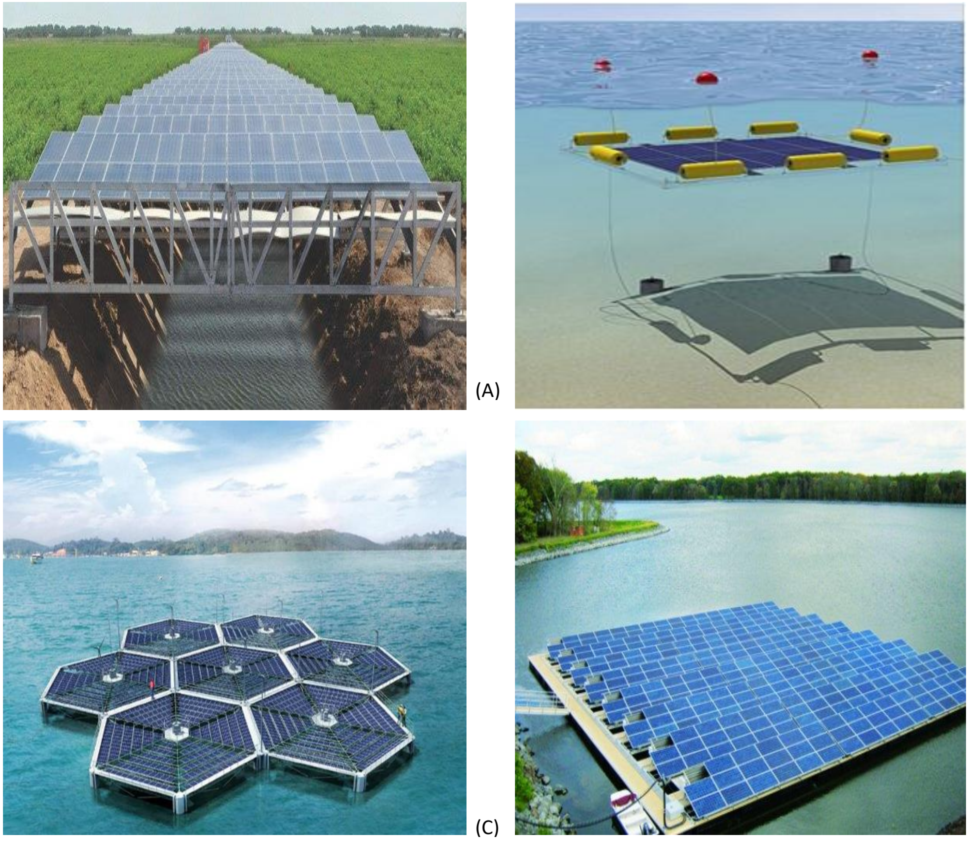

Figure 1 – Representation of: (A) Canal Top Solar System (PTI,2017); (B) Submerged Solar System; (C) Off-shore Floating Solar System; (D) Reservoir/Lake Floating Solar System (Trapani and Santafe,2015)

2.1.1. Reservoir/Lake Floating Solar System

The main purpose of floating photovoltaic systems is the improvement of water quality of the reservoirs and of the power efficiency of solar panels. The basic concept of such systems consists of a water surface covered by several conjoined floating devices (Ferrer-Gisbert et al.,2013). Figure 2 describes the general principal of floating photovoltaics. The solar modules are benefited by the cooling effect from the water body, while this suffer less from evaporation effects.

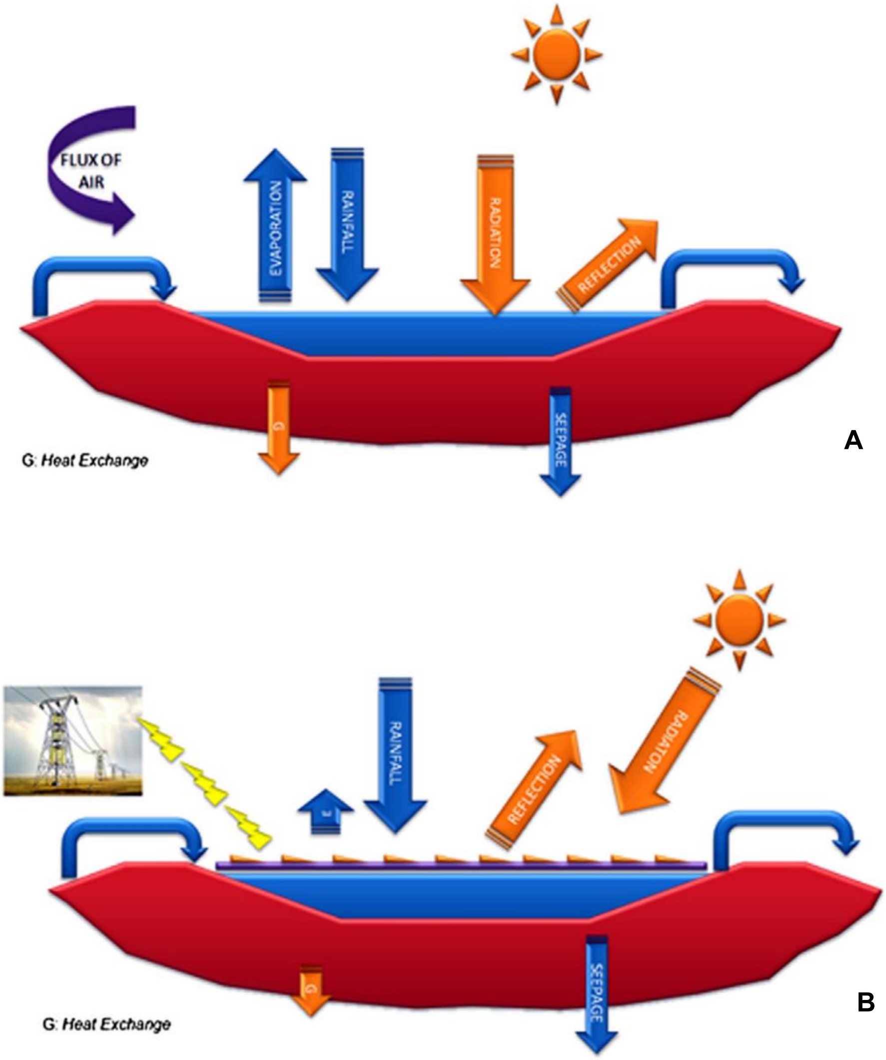

Figure 2 – Water and energy balance of uncovered reservoirs (A) and reservoirs covered by floating photovoltaic systems (B) (Ferrer-Gisbert et al.,2013).

Despite extensive research on the performance of floating systems, a standard construction design has yet to be stablished. From the first trial projects in 2007 to the current large power capacity systems, the structure of the system has varied greatly, yet studies on the most suitable assemblage are still being conducted.

Nevertheless, based on the structure of the constructed systems, Sahu et al. (2016) and Santafe (2014) listed the principal elements of the floating photovoltaic devices as:

- Pontoon: floating device characterized by a significant buoyancy level which allows its self-floatation as well as when heavily loaded. This platform is constructed in order to comport a significant number of solar modules in series/parallel combination as the available space permits;
- Floats: generally constructed of HPDE (high density poly-ethylene), this plastic hollow floats with effective buoyancy to self-weight ratio are combined forming large pontoons;
- Mooring System: permanent structure to which the floating platform is secured. The main goal of the mooring system is to assure that the panels stay in the same position, preventing them from turning or floating away;
- Solar Module Support Structure: consisted of metal frames, this structure must support the weight of the solar modules while transmitting wind forces across the floating platform to the mooring system;
- Flexible Couplings: rubber straps which enable the pontoons to move in relation to one another allowing the system to respond to variations in water level;
- Cables and Connectors: in order to feed the power produced in the solar array into the grid, cabling must be project according to the amount of electricity produced. Currently, most projects have not designed under water cabling systems, maintaining it above water.

Similarly, to on-ground systems, floating photovoltaic projects must also be designed in relation to the solar and power requirements, such as: inclination and orientation of the solar modules; inter-panel distance and arrangement operation and maintenance areas. However, in additional to those, parameters surrounding the characteristics of the waterbody as well as of the floating structure must also be considered.

Sahu et al. (2016) highlights that as a consequence of the geometric definition of water reservoirs (polygonal or irregular shapes fit into the local topography), the optimal alignment for maximum energy production cannot be secured. Therefore, according to the layout of the reservoir there may be numerous design options for the floating system to be installed. The author also argues that due to this variance of system construction, the geometry, types and materials of the devices must offer a considerable level of adaptability to different conditions of the waterbodies.

As a result of this, several research has been conducted on the effects of the reservoir's environment on the structure of the systems, aiming on encountering the best materials or designs for the devices. For instance, Choi (2014a) investigated, via mechanical load and corrosion test, the most suitable material for the construction of floating photovoltaic system structure. According to his results, a new high strength steel (POSH 690) would guarantee the mechanical requirements while decreasing the overall weight of the structure.

In addition, studies on the use of materials from the construction industry on the supporting of the floats (Seo et al.,2014); as well on the effects of grid connection of the floating system (Song and Jeon,2014) (Choi,2014b) and of wind forces on the system structure (Lee et al.,2013) (Choi and Lee,2015) have also been conducted.

Furthermore, the construction of the first tracking-type floating photovoltaic systems in 2011 increased significantly the number of studies on the performance of this type of construction. For instance, Choi and Lee (2015) performed an extensive research on the stability and durability of the structure of these systems.

In addition, Kim et al. (2014) argued that as a consequence of the nature of floating systems, flow characteristics of the water body should also be considered on the design of the tracking system. Therefore, via Matlab/Simulink, the author modelled a tracking-type system based on data on characteristic flows of current operating devices.

Similarly, to the on-ground systems, the use of tracking devices on floating systems aims to the increase on electricity generation by programming the solar module to track the sun via solar sensor. Nevertheless, compared to conventional solar projects, tracking systems on floating devices present better results due to the nature of the installation. In other words, while systems on the ground face limitation of 3kW on the number of modules that can operate in a single tracker, as a result of the external forces including self-weight being redirected to the water, the design of tracking devices on floating devices is more flexible (Choi et al.,2014). However, despite increases on efficiency, the utilization of tracking mechanisms on floating photovoltaic have been limited specially due to the high installation and maintenance costs (Cazzaniga et al.,2018).

2.1.2. Advantages and Disadvantages

As stated above, the first efforts on the construction of floating photovoltaic systems on water reservoirs occurred as a result of efforts on the reduction on evaporation rates. This reduction happens as a result of the decrease on the water temperature due to the shading produced by the floating structure, and due to the reductions of wind effect on the free surface of the water (Galdino and Olivieri,2017).

Santafe et al. (2014) argues that compared to other techniques available (e.g. chemical, biological), fixed or floating mechanical and structural systems have demonstrated significant results. The author highlights estimations conducted from lakes and dams in Turkey, in which potential water savings reached more than 20%.

In addition to reduction on water losses, the shading by the floating structure also reduces the growth of algae (phytoplankton) in the reservoir. This effect is significantly beneficial for lakes suffering from eutrophication which is directly related to the considerably growth of algae and other aquatic plants caused by an excess of dissolved nutrients. Furthermore, depending on the fraction covered by the floating photovoltaic structure, the system may be able to reduce the erosion of the banks in the reservoir as a result of the decrease on the formation of waves (Galdino and Olivieri,2017).

The transition of solar farms from on-ground installations to water bodies is also of great importance for numerous countries that do not possess great land area. For instance, Holm (2017) states that in regions where land is at a premium, installing solar panels on water shows to be a more economical alternative when the value of the land is accounted. The author further argues, when compared to other types of installation, cost related to grading and structural upgrades can be easily avoided.

The main advantage attributed to floating photovoltaic systems is the considerable efficiency increase of this when compared to on-ground installations. For example, Choi (2014a) through a study comparing the performance of a 100 kWp and 500kWp floating systems with a 1 MWp on-ground system, indicated efficiencies 11% greater for the systems installed on water. This occurs as a result of the cooling effect of the solar panels, which generally suffer thermal drift when installed on the ground. Azmi et al. (2013) and Yadav et al. (2016) also indicated a considerable increase on the efficiency and energy production of solar systems when installed in water bodies.

Galdino and Olivieri (2017) also claim that the increase on energy generation on floating photovoltaic systems may be the result of the rise on the incidence of radiation in the solar panel thanks to the reflectivity of the water. The authors argued that despite the reflectivity of a real liquid surface depending on factors such as ripple and suspended materials, the albedo of the water may play a significant role on rising the energy produced by the solar panels, especially in high latitudes regions.

Nevertheless, as a consequence of the early nature of the technology, factors such as economic viability, structural resistance and environmental impacts are yet being fully studied. For instance, there is uncertainty on the actual cost of the system compared to conventional designs. While some claim that a similar, if not lower, installations and maintenance costs may occur by avoiding the purchase and preparation of land as well as the costs related to cleaning (proximity to the water), others argue that the uncertainties surrounding the materials required for the system may lead to a decrease on the feasibility of such (Cazzaniga et al.,2018.).

Regarding environmental impacts brought by the technology, Galdino and Olivieri (2017) also discussed the possibility of impacts as result of low levels of oxygenation of the water body, which may lead to improper maintenance of the reservoir's fauna e flora. The authors suggested further studies on the gas exchange at the water surface, and highlighted that the coverage of a large portion of the water body may lead to significant environmental impacts.

2.1.3. Technology Development

The development of the first floating photovoltaic systems dates back to early 2000. At that stage, most of projects aimed on understanding the parameters surrounding the operation and maintenance of the system, as well as measuring the benefits offered by this type of construction. The Aichi project, initiated in 2007, is considered the first project integrating solar energy and water reservoirs (Trapani and Santafe,2015).

The project developed by the National Institute of Advanced Science and Technology in Japan focused on introducing the concept of floating photovoltaic systems while studying several configuration options. In fact, the group compared three photovoltaic system configurations and two floating assembly options (with and without cooling system), also comparing the results with a land based configuration (Ueda et al.,2008).

According to Ueda et al. (2008), the results of the Aichi project shown a great increase of performance of the floating cooled systems, with this reaching performance rater up to 9.6% greater than the other floating device in summer.

In 2008, the first grid connected floating photovoltaic system was installed in the state of California in the United States of America. The project, developed in a winery, consisted of modular crystalline photovoltaic panels assembled on pontoons with inbuilt walkways in-between each row of panels (Trapani and Santafe,2015). The system supplies all the electricity needs of the winery also exporting the excess of production to the grid. According to the executives responsible for the construction and operation of the system, there was a decrease of 70% of water evaporation from the pond where the arrays where installed. In addition, a reduction on algae growth was also observed (Woody,2011).

The development of medium size projects started in 2009 with the construction of the 'Flotovaico', a 500kWp system installed in a lake in Imola, Italy. In this project, the solar panels were installed on an array connected by struts with polyethylene cubes arranged at the sides. According to the company running the system, increases on electricity output of approximately 25% were achieved by the new system. In the same year, a partnership between a Spanish company and the Polytechnic University of Valencia resulted on the development of 24kWp systems which expanded to 300kWp in 2010.

As the main objective of the project was the reduction of water evaporation levels in the irrigation lakes, the primary systems comprised two photovoltaic modules installed on a medium density polyethylene raft constructed for this applications. Despite the satisfactory performance results, the cost of the project was 30% higher than the conventional on-ground installations (Trapani and Santafe,2015).

The use of tracking mechanisms on floating photovoltaic systems initiated in 2010 on a winery pond in Suvereto, Italy. The project, supervised by a local research group titled SCINTEC (Scienza Industria Tecnologia), also comprised a reflector in front of the panel in order to maximize the solar radiation received (Trapani and Santafe,2015).

In addition, SCINTEC also constructed a floating photovoltaic system in a lake located in Pisa, Italy. In this project, the panels were arranged horizontally, with the reflectors placed on either edge forming a V-shape. As this configuration results on higher working temperatures, the panels were installed significantly close to the water in order to enhance the cooling effect. According to Tina et al. (2011). this configuration combined with the installed tracking mechanism resulted in rises of approximately 70% on the annual output compared to on-ground installations.

As the projects mentioned above shown successful results, the operators initiated plans to further increase the capacity of existing facilities as well as to install similar system on nearby areas. Consequently, France, Italy and the US experienced significant growth on the number of floating photovoltaic installations on following years. Amongst these projects, the system installed at a water treatment plant in New Jersey, US received great attention due to the introduction of a unique mooring structure that enabled the array to move up and down, following the water level of the reservoir (New Jersey American Water,2011)

Aside from the countries mentioned previously, South Korea also started to direct efforts to the development of floating systems. The Korea Water Resources Corporation (K-Water) is one of the main driving forces for this projects, since the entity aims to install 1.8GWp worth of floating photovoltaic systems in 31 dams by

2022 (K-WATER,2013). The first project of the corporation was a 100KWp systems installed in the Hapcheon dam, in the south of the country.

The system consists of 414 240W solar panels assembled on metal structural, tilted at 33° facing south. According to Choi (2014b), the selection of the materials was based on those able to resist high levels of moisture, hence reducing the risk of rupture by freezing. Following the satisfactory results of the first project, K-Water developed a structurally similar but larger project in the same dam. The 500kWp floating system consists of 2070 240W solar panels also tilted at angle of 33 ° on a metal structure.

The technological advances and the better understanding on installations and operation aspects of the systems installed, allowed the construction of the first large system in 2013. The project located in Okegawa, Japan, has an installed capacity of approximately 1,157kWp, consisting of 4530 photovoltaic panels. In addition, in 2014, a 2MWp floating system was installed in the Tengeh Reservoir in Singapore. The project, developed by the local economic development board and by the Solar Energy Institute of Singapore, aimed specifically on investigating the cost-effectiveness of floating photovoltaic systems (Trapani and Santafe,2015).

Although most of the technological growth occurred from 2007 until 2014, the number of floating photovoltaic solar projects increased most intensively from 2015. For instance, while only three large systems had ever been constructed in 2014, this number rose abruptly for 70 in the last two years (Minamino,2016).

In fact, as shown in Figure 3, most of the existing system started to operate between 2014 and 2016, with approximately 98% of the existing capacity being installed during this period. Furthermore, Figure 4 shows that above 94 MW of floating photovoltaic systems have been installed worldwide, with the majority of this capacity located in Japan. Actually, from the 70 projects recently developed, 45 were mounted in the country, which entails 60% (56.5MW) of the world's installed floating photovoltaic capacity being present in Japan.

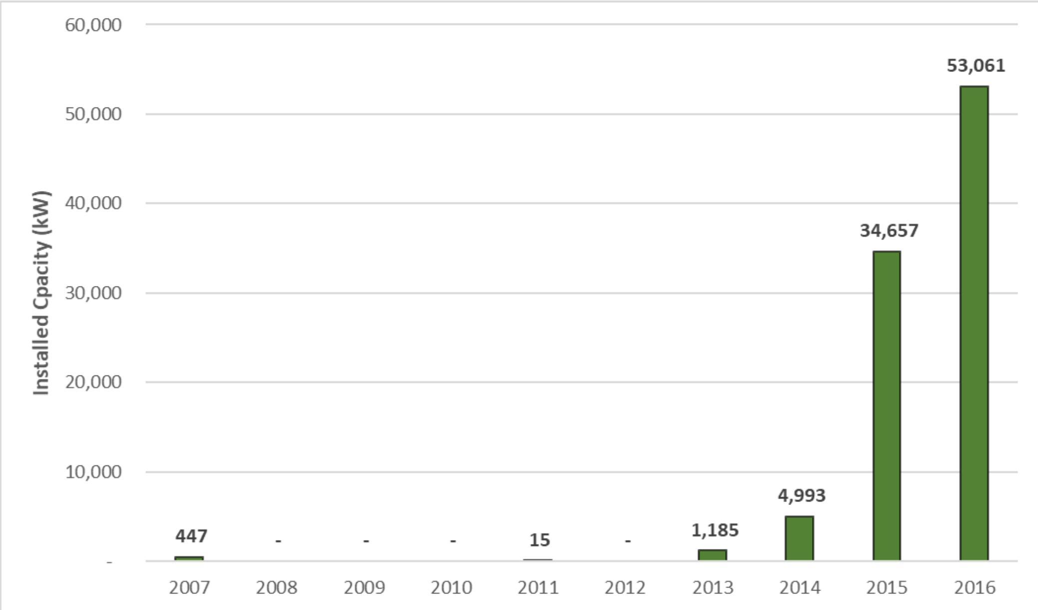

Figure 3– Global Floating Photovoltaic Capacity Installed by Year (Minamino,2016).

The main reason why Japan supplies the great majority of the electricity produced by floating systems is the size of the projects installed in Japanese water bodies. For instance, while 47% of the systems installed in the country range from 1000-1999kW, projects of this size represent only 30% of the installations across the world. In fact, 52% of the projects installed outside Japan have capacity ranging from 1-99kW.

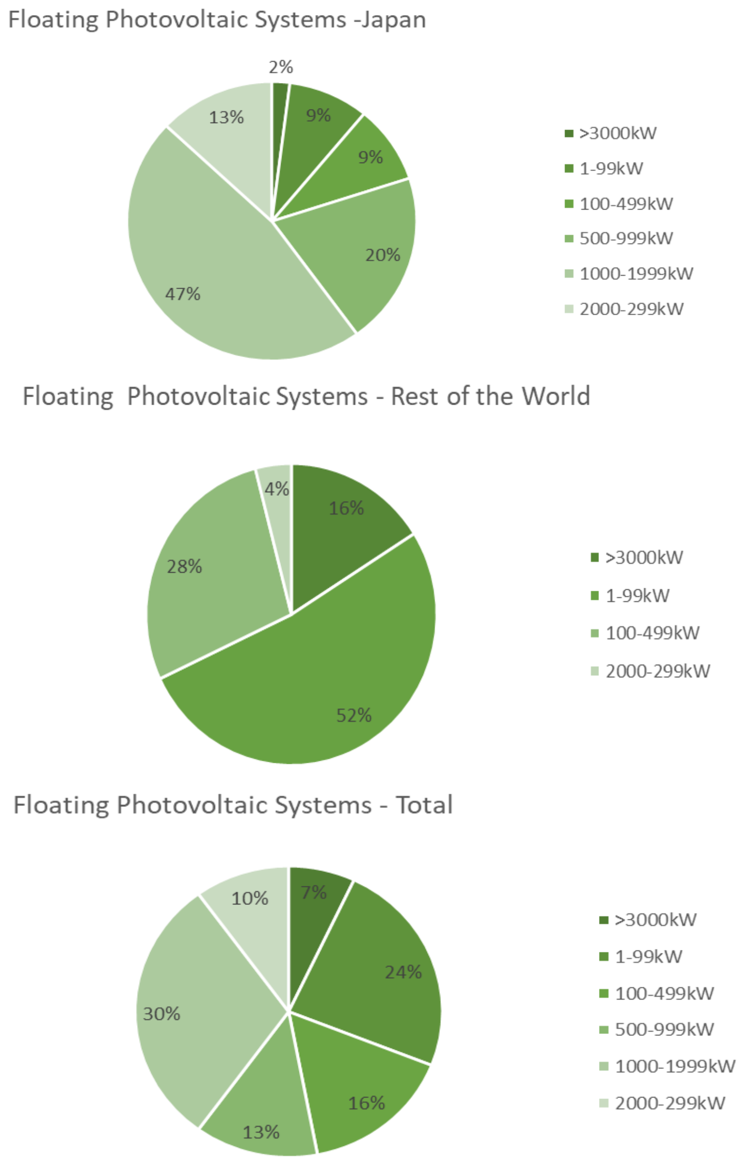

Figure 4− Statistics of Global Floating Photovoltaic (Minamino, 2016).

Nevertheless, as Table 1 shows, from the ten largest floating photovoltaic projects installed in world, only one was deployed in Japan. The largest project ever developed is located on a pit-lake in a former coal mine in Anhui province, China. The total installed capacity of the system reached 40MW in 2017, comprising 120 thousand solar panels, being able to supply the electricity needs of 15 thousand homes (Campbell,2017).

South Korea has also shown great increment on the its total installed capacity in recent years. Amongst the project developed, the 3MW systems installed on the Cheongpung Lake, and on Otae and Jipyeong reservoirs are the ones with larger capacity in the country. The last two systems were constructed by the same company, and together cover over 64,000 m^2, delivering electricity to 2,400 homes and reducing 3,600 tons of carbon dioxide per year (LG-CNS,2015).

The prospects on the technology are also considerably positive, being the renewable energy targets established by most countries the main driving force for the constant growth. For instance, India which plans to reach a 100 GW solar-power generation capacity by 2022, has redirected its efforts from on-ground to floating systems. The first results are two 10MW floating photovoltaic systems planned to be commissioned by 2018 (PTI,2017). Singapore, which had already launched a test system in 2016, has intentions to increase its capacity as a result of the satisfactory results. In fact, the statutory board of the Ministry of the Environment and Water Resources, has announced its intentions to build a 50MWp in one of the largest reservoirs in the country (Soh,2017). If the construction goes as planned, Singapore might surpass China and host the largest floating photovoltaic system in the world.

Table 1− Highest Installed Capacity Floating Photovoltaic Plants in the World (Minamino,2016).

RANK	SIZE (kW)	RESERVOIR/PLANT	COUNTRY	CITY/PROVINCE	OPERATING FROM
1	40,000	Coal mining subsidence area of Huainan City	China	Anhui province	April,2016
2	9,982	Pei County	China	Anhui	July,2017
3	7,550	Umenoki	Japan	Saitama	October,2015
4	6,776	Jining GCL	China	Shandong	December,2017
5	6,338	Queen Elizabeth II Reservoir	UK	London	March,2016
6	3,000	Cheongpung Lake	South Korea	Chungju	December,2017
7	3,000	Otae Province	South Korea	Sanju City	October, 2015
8	3,000	Jipyeong Province	South Korea	Sangju City	October,2015
9	2,991	Godley Reservoir Floating Solar PV	UK	Godley	January, 2016
10	2,870	Kato Shi (2 plants)	Japan	Hyogo	March,2015

2.2. GIS and Floating Photovoltaics

The literature regarding the assessment of floating photovoltaic sites is somewhat limited. As current researches focused on most part on the economic construction and maintenance of the device as well as on the safety issues regarding its installation. The few works combining GIS tools and floating photovoltaic technology are based on the parameters commonly utilized for on-ground systems.

For example, Lee and Lee (2016) investigated possible locations for the development of floating photovoltaic system in the two regions of South Korea. Based on terrain and climate factors, such as shaded relief, average temperate and precipitations days, the authors analyzed the data through Analytic Hierarchy Process, scoring the attributes based on existing literature for conventional solar photovoltaic projects. The research pointed to northern part of the Gyongsangbuk-do province as more feasible to comport the proposed system, highlighting a local lake and reservoir as optimal locations.

Furthermore, Song and Choi (2015) studied the technical and economic feasibility of installing a system on a pit-lake to be formed in one of the pits of a limestone mine located in the Gangwon Province in South Korea. Differently from the previous research, the authors evaluated exclusivity the solar radiation received the lake. The group created, via ArcGIS and a digital topographic map, a digital elevation model (DEM) with spatial resolution of 5m, which was then used to assess the effects of shadows on the reservoir. In addition, in order to assess shadow effects caused by small obstacles, the authors used a fish-eye lens camera that enabled the field analysis of the skyline at the site.

Based on the results from the solar assessment, the economic feasibility of a 1MW system was conducted via the System Advisor Model (SAM). The results indicated that the system, generating 971.57 MWh/year, would have a net-present value (NPV) of approximately $897.000 USD and a payback period of 12.3 years. Moreover, the system would also be able to reduce 471.21 tCO_2/year, double the value achieved by forest restoration of an abandoned mine.

Although the previous mentioned work shown the potential on the development of floating photovoltaic systems in South Korea, aspects surrounding the performance of floating devices was not thoroughly utilized. In contrast, Lee et al. (2012) highlighted the difference between assessing sites for floating photovoltaic systems and for conventional ones. Table 2 lists new parameters introduced by the authors as factors to be assessed when locating possible sites for floating devices.

Nevertheless, in this research the authors did not utilize GIS tools for the assessment of possible sites. Instead, they worked with predefined areas in the Hapcheon dam, evaluating their feasibility according to the parameters introduced. According to the results, just one of the areas demonstrated technical potential for the project, and via an economic analysis in RetScreen the group also indicated the Internal Return Rate (IRR) of such projects varying from 5.3 to 7.1 according to the size of the system.

Table 2− Parameters to be evaluated when assessing sites for floating photovoltaic systems (Lee et al.,2012).

CLASSIFICATION	FACTOR	INDICATOR
Factors affecting the efficiency	Solar Irradiance	Selection of relatively high annual solar irradiance
	Fog	Avoid regions with high incidence of foggy days (10 days or less)
	Shadowing	Avoid regions surrounded by obstacles that may bring shadow or decrease the amount of sun hours.
Factors affecting the installation or operation of the system	Water Level	Due to possible difficulties on installing the mooring gear, avoid reservoirs whose water levels may reach values under 5m.
	Wind Speed	In order to avoid increase of cost on the structure of the system and to assure more stability, select regions with wind speeds under 30m/s
	Water Flow	Select regions characterized by water flows under 0.5m/s
	Ice Formation	In order to avoid changes on structure select regions with lower rates of ice formation (low water levels).
	Floating Matter	High quantities of floating matter may affect the stability of the structure holding the panels.
	Accessibility	Prioritize sites with easy accessibility
	Neighboring Areas	Avoid sites with high intake of water from neighboring areas
	Reservoir use	Avoid reservoir specifically used for leisure or commercial activities
Power System Interconnection Factor	Transmission Lines Availability	Consider the availability of sufficient capacity in the transmission lines and the future plans of those
	Distance to Transmission Lines	Select regions which system interconnection may assure voltage drops under 5% with no great cost
	Distance to Load	Select areas closer to load zones
Legal and Institutional Factors	Legislation	Avoid areas restricted for the construction of the system
	Compensation	Select areas that do not require great values of compensation

3. Methodology

Based on the parameters introduced by Lee et al. (2012), and on the available data, the following thresholds were applied for the selection of areas suitable for floating photovoltaic installations:

- Factors affecting the efficiency of the system:
    - Foggy days: exclusion of regions with incidence of foggy days exceeding 10 days per year;
- Factors affecting the installation or operation of the system:
    - Wind Speed: selection of regions which have not registered wind speeds exceeding 30m/s in order to avoid increases on the structure cost and to assure more stability,
    - Water Level: due to possible difficulties on installing the mooring gear, selection of reservoirs whose water levels have not registered values under 5m;
    - Accessibility: prioritize sites easily accessible;
- Legal and Institutional Factors: exclusion of areas restricted for the construction of the system.

3.1. Data Source

Table 3 presents the data used throughout the stages of the study, as well as the sources of collection. With the intention of properly observe the climate characteristics of the regions, data on maximum instant wind speed and water level were collected within a timeframe of 20 years. In addition, data on the incident global horizontal insolation consists of measurements conducted from 1982 to 2012.

Table 3– List of Data Sources

DATA	SOURCE
ROADS SHAPE FILE	Korean National Special Infrastructure (NSIP)
LAKES SHAPE FILE	
RESTRICTED AREAS SHAPE FILE	
MAXIMUM INSTANT WIND SPEED (1997-2016)	Korean Meteorological Administration (KMA)
AVERAGE NUMBER OF FOGGY DAYS	
LAKES WATER LEVEL (1997-2016)	Korean Rural Community Corporation (KRC)
GLOBAL HORIZONTAL INSOLATION (1982-2012)	Koran Institute of Energy Research (KIER)

3.2. Methodology stages

Figure 5 describes the overall methodology adopted in this study. The assessment of the technical feasible sites, that is the identification of sites with characteristics in agreement to the thresholds selected, was conducted through ArcMap 10.1.

Following the identification of the constrains and collection of the required records, the manipulation of data was conducted. The maximum instant wind speed registered in the twenty-year time was averaged. Due to this data as well as the average yearly number of foggy days being registered just on local meteorological stations, a spatial interpolation was conducted. The choice of Kriging Interpolation for this procedure was based on this being the most appropriate when spatially correlated distance is present in the data. Finally, similarly to the above mentioned data, the global horizontal insolation measures were also interpolated. Nevertheless, in this case, the Inverse Distance Weighting (IDW) was chosen as previous maps developed by KIER were constructed by applying the same method.

After the manipulation of data, the values were associated to each lake according to their position. Based on established threshold, the feasible lakes were selected and the economic viability of the comported projects was performed in the software RETScreen. This software is described as a clean energy management software by the developer, being able to conduct project feasibility and energy performance analyses (NRCAN,2018).

The size of the projects to be installed in each reservoir was measured according to their area. The area required by megawatt was seized according to the methodology introduced by Song and Choi (2015).

In addition, the possible impacts brought by extensive coverage of the lake were also taken into consideration. Hein (2010) argued that in order to avoid impacts on the ecosystem of the water bodies as well as on the activities performed on such, developments must not cover over 25% of the surface of the reservoir, value then considered as a threshold for this study. The classification of suitable lakes was conducted according to the results obtained in the economic analysis.

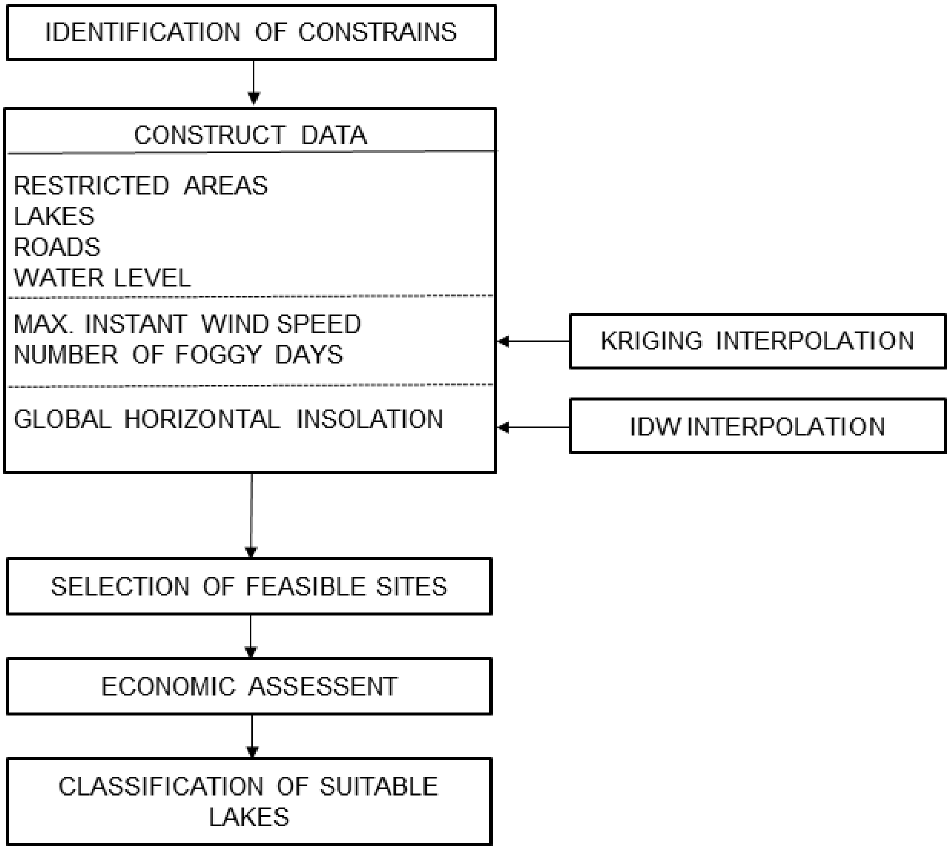

Figure 5– Flow chart of the Analysis

3.3. Photovoltaic System Design

With the intention of measuring the installing capacity of each lake, the required area for a 1MW system was first estimated according to methodology presented by Song et. al. (2016).

$$\mathrm{M_s} = \left(\frac{V_{mx} - mppt + V_{mn} - mppt}{2}\right) \Big/ V_{module} \qquad \textit{(Equation 1)}$$

First, the number of modules was estimated based on the Maximum Power Point Tracking (MPPT) voltage in the inverter and on the open circuit voltage in the module, as follow:

$$S_p = \left[(C.\,1000W/kW\ \ )/I_p\right] \Big/ M_s \qquad \textit{(Equation 2)}$$

Where: Ms and Sp stand for module per string and strings in parallel respectively; Vmx-mppt is the maximum MPPT voltage in the inverter; Vmn-mppt is the minimum MPPT voltage in the inverter; Vmodule is the maximum power voltage of the module, and Ip is the module maximum power.

Second, the number of inverters required (IEA) for the system was measured as stated on Equation (3).

$$IEA = \left(M_s\ .S_p\ .P_{module}\right) \Big/ ((RDC - AC\ \ .P_{inv}) \qquad \textit{(Equation 3)}$$

Where: P_{module} is the module maximum power; RDC-AC is the DC-to-AC ratio (1.0), and P_{inv} is the maximum AC power of the inverter.

Further, the spacing between arrays was estimated as described on Equation (4).

$$X_1 = L\ .[\cos\theta + \sin\theta\,.\tan(lat + 23.5)] \qquad \textit{(Equation 4)}$$

Where: θ is the tilt angle of the installed array , L is the length of the module and lat is the latitude of the solar site.

Finally, the require area for the solar site was calculated as stated on Equation (5).

$$A = M_s\ .MW.X_1.S_p \qquad \textit{(Equation 5)}$$

Where: M_w denotes the width of the module.

Table 4 shows the characteristics of the photovoltaic module and inverter applied in the equations.

Table 4– Technical characteristic of the solar (a) panel and inverter (b)

a)

PHOTOVOLTAIC MODULE	
Model	BLK-210
Maximum Power	215.25 W
Module Width	1 m
Maximum Power	41V
Maximum Power	4.3 A_{dc}
Open Circuit Voltage	47.7 V
Short Circuit Current	5.8 A_{dc}

b)

INVERTER	
Model	SB4000US
Maximum AC Power	4000 W_{ac}
Maximum DC Power	4186 W_{dc}
Maximum DC current	18 A_{dc}
Maximum DC voltage	600 V_{dc}
Minimum MPPT	250 V
Maximum MPPT	480 V

3.4. Economic Assessment

The economic analysis of the feasible lakes was conducted through the RETScreen software, commonly used for the feasibility analysis of energy efficiency, renewable energy and cogeneration projects. The global horizontal radiation obtained via ArcMap was inputted in the software as well as the parameters described on Table 5.

The addition of 30% on the cost of the system was based on the cost measurements of ongoing projects, which commonly reported this surplus compared to conventional on-ground installations. In addition, the operation and maintenance estimation (1% of the total installation cost) was based on Kang et al. (2017) and other studies.

Moreover, the efficiency of the solar panels was set at 18% based on findings of Choi (2014b), according to which improvements of 11% were experienced on floating panels compared to conventional on-shore installations.

Table 5− Economic assessment parameters

PARAMETER	UNIT	VALUE	REFERENCE
MODULE EFFICIENCY	%	18	Choi (2014b)
DISCOUNT RATE	%	5.5	Korean Development Institute (KDI)
INFLATION RATE	%	3	Korean Development Institute (KDI)
INSTALLATION COST	KRW	1,800,00.00/kW +30%	Korean Energy Agency
O&M COST	KRW	1% of Installation Cost	Kang et al. (2017)
REC VALUE	KRW	113/kWh	Korean Energy Agency
SYSTEM MARGINAL PRICE	KRW	76/kWh	Korean Energy Agency
REC MULTIPLIER	-	1.5	Korean Energy Agency

4. Results

4.1. Construct Data

Figure 6 consists of figures presenting the data collected as well as the results achieved via spatial interpolation. Figure 6a presents all the 3178 South Korean lakes registered in the KNIP. The majority of the lakes is evenly spread across the country, with a slightly high concentration on the south-west region.

Figure 6b presents the location of the restricted areas, where the construction of the floating photovoltaic system wouldn't be possible or would result on higher cost. Through spatial selection tool, 400 lakes were found to be located in such areas, thus not being suitable for the construction of the system.

As mentioned previously, due to the structural nature of floating photovoltaic systems, lakes characterized by wind speeds over 30m/s are not suitable for the development of such systems. Based on the average maximum instant wind speed over a twenty-year period registered in local meteorological stations, the map shown in Figure 7a demonstrates the results achieved by Kriging interpolation.

From the raster layer produced, the average maximum instant wind speed of each lake was retrieved. According to these measurements, all 2778 lakes positioned on non-restricted areas do not present wind speeds over 30m/s. The lakes presenting higher wind velocities (over 28 m/s) are positioned in coastal regions, with reservoirs located in the Jeju Island characterized by maximum instant wind speed over 29.5 m/s. In contrast, lakes located in the central and north regions of the country were found to have their maximum instant wind speed lower than 18m/s, showing higher feasibility in terms of structural safety.

As previously stated, photovoltaic systems, if installed in regions with high incidence of foggy days, present a considerable decrease on its overall efficiency. Therefore, lakes presenting rates higher than 10 foggy days per year were considered not feasible in this study. Figure 7b presents the result achieved via Kriging interpolation of the average yearly foggy days registered in several locations across South Korea.

As the figure shows, South Korea has a high incidence of foggy days. In fact, through extracting the values for each reservoir, it was found that the vast majority have numerous days with fog within a year. From the 2278 lakes located in non-restricted areas and with average maximum instant wind speed lower than 30m/s only 120 lakes have incidence of foggy days lower than 10 days per year. Most of the lakes with higher incidence rates were found to be located in the north-east and south region of the country, while lakes positioned in the south-west were presented the lowest rates.

The investigation on the changes of water levels in the 120 lakes relied heavily on the availability of such data. Amongst these only 53 lakes had their water levels registered on KRCC, being their majority reservoirs with greater superficial area. In fact, none of the lakes with superficial area lower than 20,000 m^2 have their level measured by the corporation. Therefore, due to the lower superficial area for the installation of the systems and the uncertainties on the minimum water level of these lakes, they were considered not feasible.

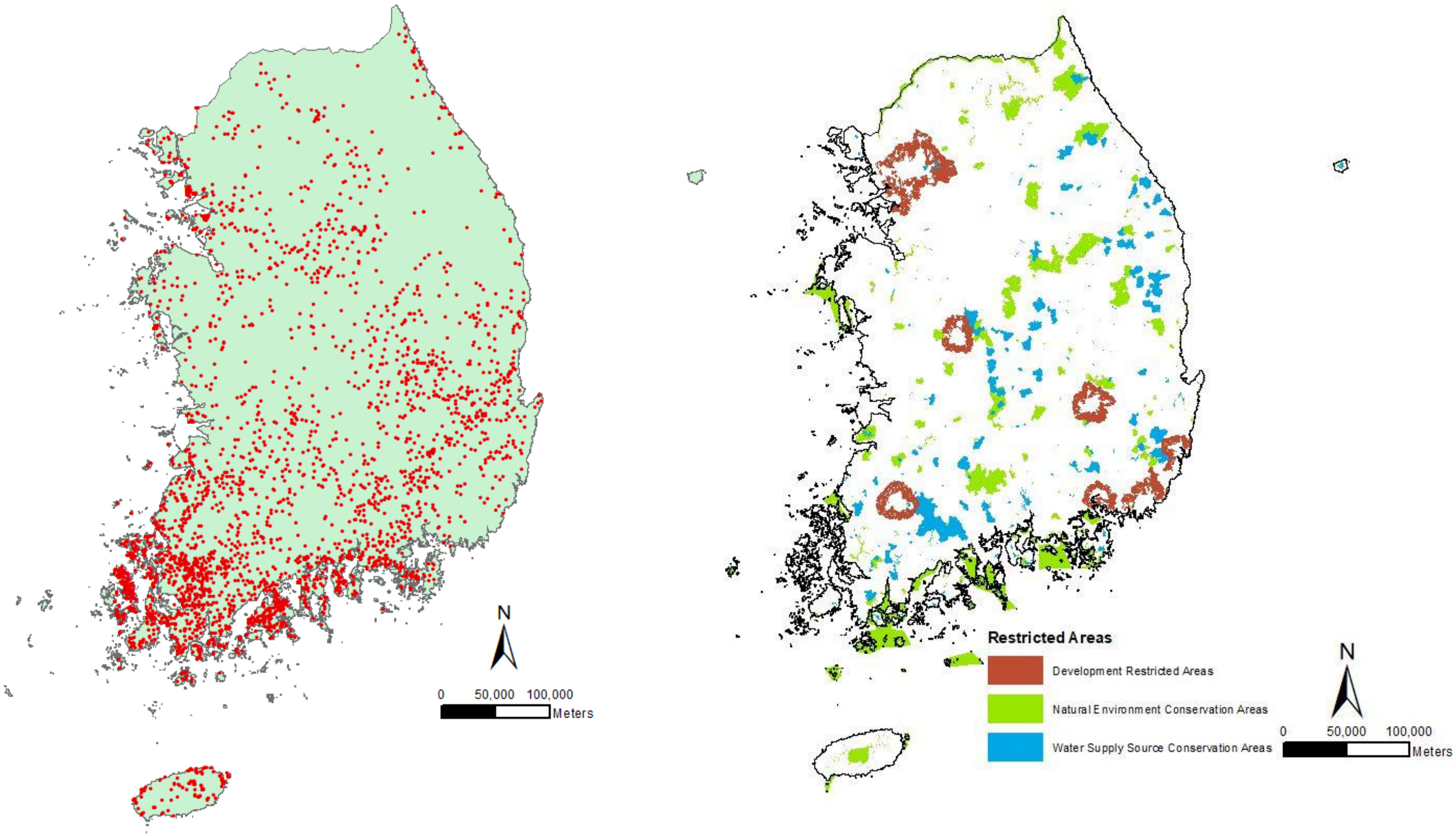

Figure 6– (A) Location of Lakes in South Korea – red dots; (B) Restricted Areas in South Korea (Based on data from NSDI).

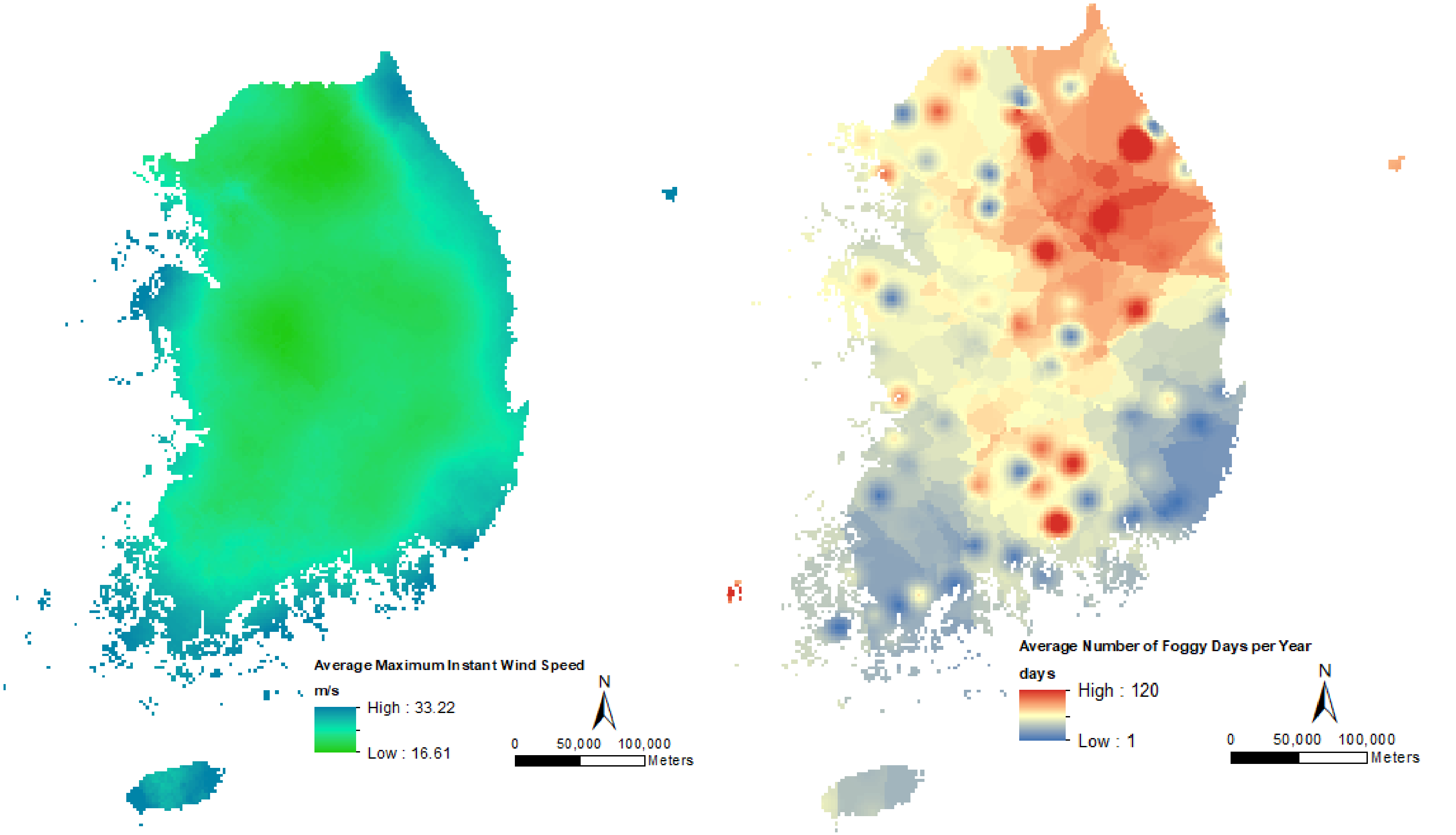

Figure 7– (A) Result on the technically feasible lakes for the construction of floating photovoltaic systems in South Korea (blue dots). (B) Average Global Horizontal Irradiance Map (Based on data from KIER)

From the 53 remaining lakes, an investigation on the lowest record of water level over a twenty-year period was conducted. Lakes with records of water levels lower than 5m were considered not viable for the construction of the systems, as difficulties on the installation of the mooring gear may arise on such conditions. As a result, 45 lakes did not register such levels, thus being technically feasible. Figure 8A show the location of such lakes, and Table 6 presents the main characteristics those.

With the purpose of conducting the economic assessment of the technically feasible lakes, the solar potential of those was also measured. This was performed based on the global horizontal insolation data supplied by KIER. Figure 8B presents the IDW spatial interpolation based on the available data. As observed in the map produced by KIER and in other studies, the south-west region of South Korea receives a higher level of solar irradiance, while the northern part receives the lowest. Consequently, lakes located on those regions presented higher and lower values, respectively.

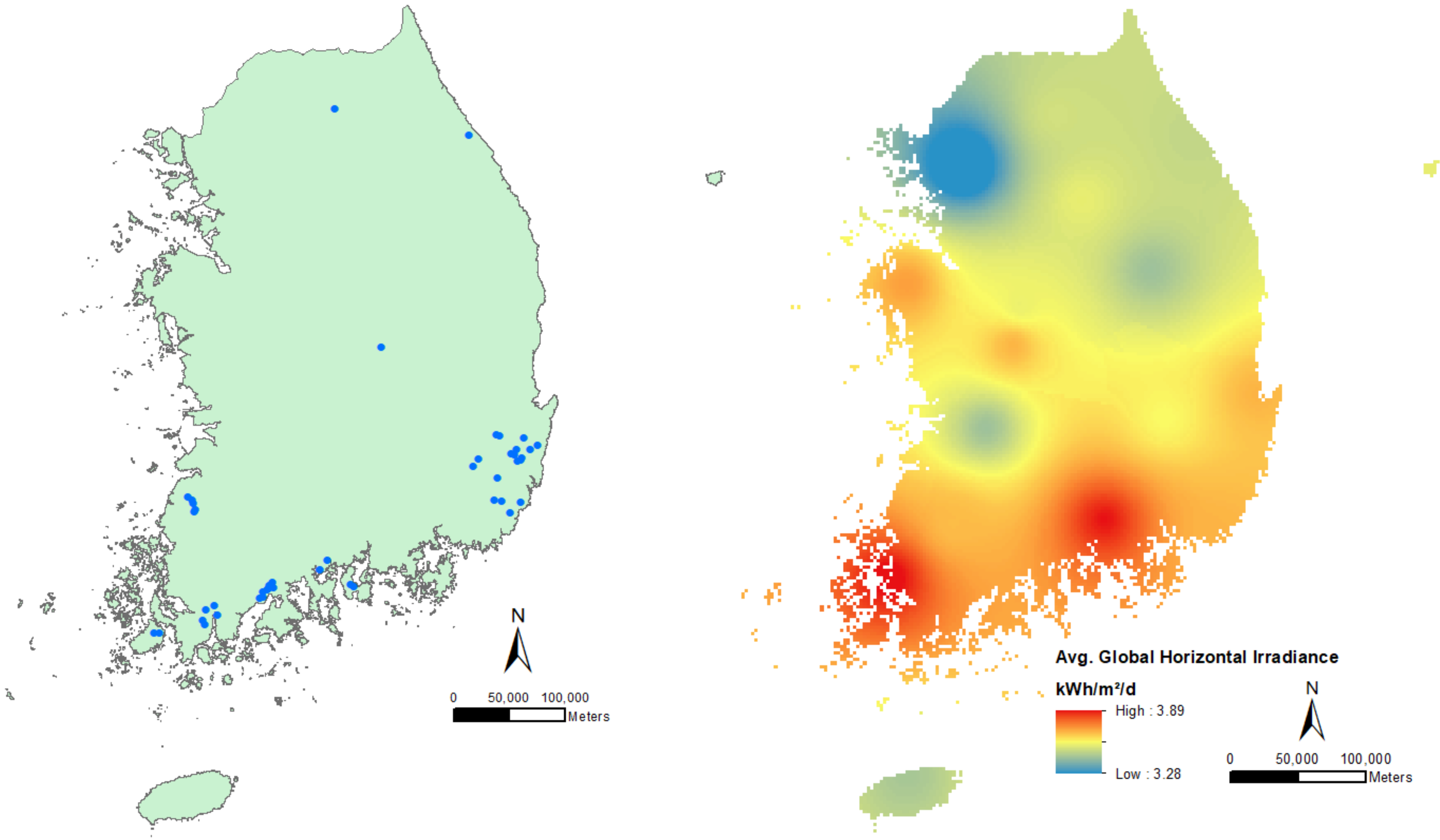

Figure 8 − (A) Result on the technically feasible lakes for the construction of floating photovoltaic systems in South Korea (blue dots). (B) Average Global Horizontal Irradiance Map (Based on data from KIER)

Table 6– Result on the technically feasible lakes for the construction of floating photovoltaic systems in South Korea.

NAME	LOCATION	AREA (m^2)	AVERAGE MAX INSTANT WIND SPEED (m/s)	FOGGY DAYS/YEAR	MINIMUM WATER LEVEL (m)
BANG-NAE	GYEONGSANGBUK-DO	42,916	21.6	7	170.7
CHEOG-GWA	ULSAN	49,285	22.9	8	128.1
CHIL-DONG	JEOLLANAM-DO	139,788	22.7	10	111.5
DAE-AN	JEOLLANAM-DO	30,476	20.9	8	65.6
DAE-BI	GYEONGSANGBUK-DO	157,140	22.2	8	170.2
DAE-GOG	JEOLLANAM-DO	190,993	22.9	7	58.9
DAE-SEOG	GYEONGSANGNAM-DO	34,766	23.8	7	112.8
DA-JEONG	GYEONGSANGNAM-DO	37,901	24.3	8	120.3
DEOG-CHON-2	JEOLLANAM-DO	30,902	23.3	9	31.3
DEOG-LIM	JEOLLABUK-DO	203,355	21.1	8	105.7
DEOG-SAN	JEOLLANAM-DO	266,347	22.9	4	43.8
DO-CHON	JEOLLANAM-DO	267,246	23.5	7	49.5
DU-DOL	ULSAN	94,909	22.5	10	98.7
DU-SAN	ULSAN	72,644	22.9	8	142.3
GAE-UN	GYEONGSANGBUK-DO	180,280	19.7	8	78.3
GA-IN (BONG-UI)	GYEONGSANGBUK-DO	108,383	22.5	8	181.3
GAM-DONG	JEOLLANAM-DO	89,046	22.9	4	30.0
GANG-JEONG	JEOLLANAM-DO	205,274	25.1	9	39.8
GEUM-SA	JEOLLANAM-DO	182,731	24.6	5	100.0
GO-LA	JEOLLABUK-DO	63,559	21.5	10	47.8
GONG-AM	ULSAN	65,249	23.4	8	153.0

Table 6 (continued).

NAME	LOCATION	AREA (m^2)	AVG. MAX INST. WIND SPEED (m/s)	FOGGY DAYS/YEAR	MIN.WATER LEVEL (m)
GYEONG-PO	GANGWON-DO	180,701	24.5	9	29.0
HA-DONG	GYEONGSANGBUK-DO	111,479	21.8	8	146.3
HAE-PYEONG-LI	JEOLLANAM-DO	228,696	23.6	5	49.8
HOM-GOG	GYEONGSANGBUKGO	33,854	21.4	9	182.2
HWANG-GIL	JEOLLANAM-DO	30,532	22.6	9	60.9
HWA-SAN	ULSAN	109,352	24.6	8	90.2
IB-SIL	GYEONGSANGBUK-DO	49,400	22.3	9	256.9
JAG-CHEON	JEOLLANAM-DO	66,717	24.0	7	102.5
JANG-HEUNG	GYEONGSANGNAM-DO	53,890	23.9	7	104.0
JO-YEON	GANGWON-DO	129,447	16.9	5	109.1
MI-DONG	JEOLLABUK-DO	47,711	21.0	5	100.4
MYEONG-GYE	GYEONGSANGBUK-DO	190,028	22.2	7	123.0
NAE-GEUM	GYEONGSANGNAM-DO	29,888	24.2	10	45.6
O-SAN	JEOLLANAM-DO	100,002	26.2	5	44.6
PYEONG-GEUM	JEOLLANAM-DO	23,244	20.8	8	28.7
SEOG-GYE	GYEONGSANGBUK-DO	83,383	22.6	9	113.0
SEOG-MUN	JEOLLANAM-DO	444,067	25.2	10	78.3
SEO-SAN	JEOLLANAM-DO	327,516	24.8	5	79.2
SIN-BANG	JEOLLANAM-DO	68,550	22.9	4	100.0
SIN-GEUM	JEOLLANAM-DO	67,004	22.0	9	8.7
SONG-JEON	GYEONGSANGBUT-DO	95,150	22.2	9	112.2
WOL-GA	JEOLLANAM-DO	121,363	26.3	3	15.3
WOL-PYEONG	ULSAN	53,146	22.7	8	162.3
YONG-CHEON	BUSAN	27,779	24.7	8	93.6

4.2. Photovoltaic Systems

Table 7 describes the results obtained by dimensioning a 1MW photovoltaic systems according to the methodology described above. The area required by systems depended heavily on the tilt angle in which the panels are installed, since the space between the panels has to be increase in order to avoid any shadowing on the panels.

Table 7– Dimensions of photovoltaic systems

<table>
<tr><th colspan="2">DESIGN PARAMETER</th><th>VALUE</th></tr>
<tr><td colspan="2">Modules per String</td><td>8</td></tr>
<tr><td colspan="2">Strings in Parallel</td><td>1452</td></tr>
<tr><td colspan="2">Total Number of Inverters</td><td>625</td></tr>
<tr><td rowspan="4">Total Area Required</td><td>0^{O}</td><td>5,772.2 m^2</td></tr>
<tr><td>30^{O}</td><td>10,259.5 m^2</td></tr>
<tr><td>35^{O}</td><td>10,763.1 m^2</td></tr>
<tr><td>40^{O}</td><td>11,184.7 m^2</td></tr>
</table>

The floating photovoltaic systems of each reservoir was dimensioned based on these results as well as on the area available on those. That is, the power capacity of each lake was established as a proportion of the total area available on site and the area required for an 1MW system. Table 8 shows the great variance of potential install capacity in result of changes on tilt angle, with the increase of this resulting on systems with smaller capacity. Furthermore, the lakes with largest available area, hence large capacity, were found to be located in Wando Island and Gwangju, in the south-west part of South Korea.

Table 8− Installation capacity of the feasible sites in relation to tilt-angle.

NAME	AVAILABLE AREA (m^2)	POTENTIAL INSTALL CAPACITY (MW)			
		0°	30°	35°	40°
BANG-NAE	10,729.0	1.8	1.0	1.0	1.0
CHEOG-GWA	12,321.3	2.1	1.2	1.1	1.1
CHIL-DONG	34,947.0	5.8	3.4	3.2	3.1
DAE-AN	7,619.0	1.3	0.7	0.7	0.7
DAE-BI	39,285.0	6.5	3.8	3.6	3.5
DAE-GOG	47,748.3	8.0	4.7	4.4	4.3
DAE-SEOG	8,691.5	1.4	0.8	0.8	0.8
DA-JEONG	9,475.3	1.6	0.9	0.9	0.8
DEOG-CHON-2	7,725.5	1.3	0.8	0.7	0.7
DEOG-LIM	50,838.8	8.5	5.0	4.7	4.5
DEOG-SAN	66,586.8	11.1	6.5	6.2	6.0
DO-CHON	66,811.5	11.1	6.5	6.2	6.0
DU-DOL	23,727.3	4.0	2.3	2.2	2.1
DU-SAN	18,161.0	3.0	1.8	1.7	1.6
GAE-UN	45,070.0	7.5	4.4	4.2	4.0
GA-IN (BONG-UI)	27,095.8	4.5	2.6	2.5	2.4
GAM-DONG	22,261.5	3.7	2.2	2.1	2.0
GANG-JEONG	51,318.5	8.6	5.0	4.8	4.6
GEUM-SA	45,682.8	7.6	4.5	4.2	4.1
GO-LA	15,889.8	2.6	1.5	1.5	1.4

Table 8 (continued).

NAME	AVAILABLE AREA (m^2)	POTENTIAL INSTALL CAPACITY (MW)			
		0^o	30^o	35^o	40^o
GONG-AM	16,312.3	2.7	1.6	1.5	1.5
GYEONG-PO	45,175.3	7.5	4.4	4.2	4.0
HA-DONG	27,869.8	4.6	2.7	2.6	2.5
HAE-PYEONG-LI	57,174.0	9.5	5.6	5.3	5.1
HOM-GOG	8,463.5	1.4	0.8	0.8	0.8
HWANG-GIL	7,633.0	1.3	0.7	0.7	0.7
HWA-SAN	27,338.0	4.6	2.7	2.5	2.4
IB-SIL	12,350.0	2.1	1.2	1.1	1.1
JAG-CHEON	16,679.3	2.8	1.6	1.5	1.5
JANG-HEUNG	13,472.5	2.2	1.3	1.3	1.2
JO-YEON	32,361.8	5.4	3.2	3.0	2.9
MI-DONG	11,927.8	2.0	1.2	1.1	1.1
MYEONG-GYE	47,507.0	7.9	4.6	4.4	4.2
NAE-GEUM	7,472.0	1.2	0.7	0.7	0.7
O-SAN	25,000.5	4.2	2.4	2.3	2.2
PYEONG-GEUM	5,811.0	1.0	0.6	0.5	0.5
SEOG-GYE	20,845.8	3.5	2.0	1.9	1.9
SEOG-MUN	111,016.8	18.5	10.8	10.3	9.9
SEO-SAN	81,879.0	13.6	8.0	7.6	7.3
SIN-BANG	17,137.5	2.9	1.7	1.6	1.5
SIN-GEUM	16,751.0	2.8	1.6	1.6	1.5
SONG-JEON	23,787.5	4.0	2.3	2.2	2.1
WOL-GA	30,340.8	5.1	3.0	2.8	2.7
WOL-PYEONG	13,286.5	2.2	1.3	1.2	1.2
YONG-CHEON	6,944.8	1.2	0.7	0.6	0.6

Table 9 comprises the main results obtained though the economic viability of each lake conducted via RETScreen. These results are in agreement with outcomes achieved in other studies as described previously. For instance, all systems show low levels of profitability if compared with on-ground designs. Moreover, a significant variation on the economic performance of the systems occurs as the tilt angle of the photovoltaic panels changes.

In fact, as shown by the average values of payback time and IRR on Table 9, the designs with tilt angle of 0^{O} (flat panels) show the least feasibility, while systems comprising panels installed in a tilt angle of 30^{O} demonstrated to be the most profitable design. This is in line with the current installations in South Korean, which are in their majority designed in such angles.

Table 9 - Economic analysis according to tilt angle.

TILT ANGLE	AVERAGE PAYBACK TIME	AVERAGE IRR
0^{O}	16.89	1.67%
30^{O}	15.34	2.66%
35^{O}	15.37	2.65%
40^{O}	15.47	2.57%

Figure 9 presents the install capacity of the 45 technically feasible reservoirs in South Korea for systems with tilt angle of 30°. The largest projects (over 6.5 MW) are positioned in the south-west region together with the majority of the medium size systems (4 up to 6.5MW), which can also be seen in the northern part of the country. In contrast, the smallest systems (up to 4MW) are mainly conglomerated in the south-east region.

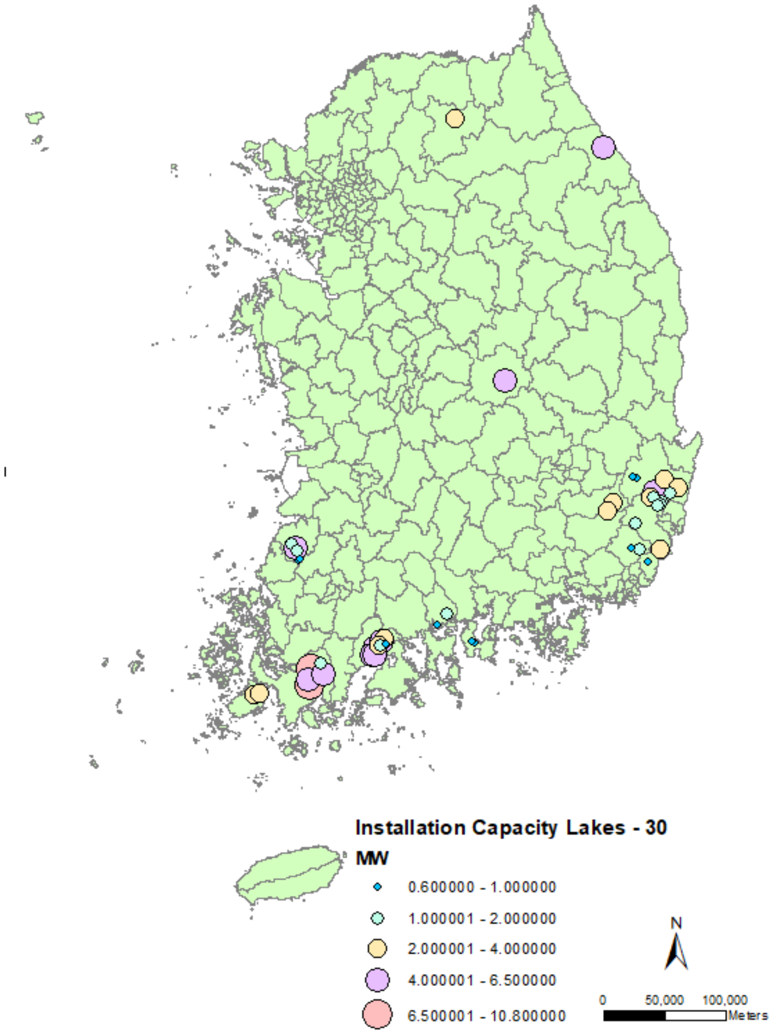

Figure 9 - Install capacity technically feasible reservoirs (Tilt Angle of 30^0)

The projects residing on the south-west region of the country have shown higher economic feasibility than others, which is also in line with the solar energy map developed for South Korea. In fact, projects siting on lakes Wol-ga, Nae-geum and Dae-jeong, located in Jeollanam-do and Gyeongsangnam-do, have demonstrated the highest economic feasibility, with the shortest payback time and highest IRR. In contrast, projects residing on lakes Gae-un and Jo-yeon, Gyeong-po and Dae-go, are the least economic feasible amongst the projects investigated. Nevertheless, in an economic perspective, all projects are not considered a profitable investment, which is a directly connected to their high initial cost.

Table 10– Results of the economic assessment in relation to tilt-angle

NAME	PAYBACK TIME (YEARS)				IRR (%)			
	0º	30º	35º	40º	0º	30º	35º	40º
BANG-NAE	17.01	15.31	15.31	15.39	1.59%	2.69%	2.69%	2.63%
CHEOG-GWA	16.99	15.35	15.36	15.45	1.60%	2.66%	2.65%	2.59%
CHIL-DONG	16.97	15.52	15.57	15.69	1.61%	2.54%	2.50%	2.42%
DAE-AN	16.88	15.40	15.44	15.55	1.67%	2.62%	2.60%	2.52%
DAE-BI	17.04	15.34	15.34	15.42	1.57%	2.67%	2.67%	2.61%
DAE-GOG	16.96	15.52	15.57	15.69	1.62%	2.54%	2.51%	2.42%
DAE-SEOG	16.92	15.31	15.32	15.42	1.64%	2.69%	2.68%	2.61%
DA-JEONG	16.64	15.11	15.14	15.24	1.82%	2.83%	2.81%	2.74%
DEOG-CHON-2	16.96	15.52	15.56	15.69	1.62%	2.54%	2.51%	2.42%
DEOG-LIM	16.95	15.46	15.49	15.61	1.63%	2.59%	2.56%	2.48%
DEOG-SAN	16.82	15.31	15.35	15.46	1.70%	2.69%	2.66%	2.59%
DO-CHON	16.78	15.30	15.34	15.45	1.73%	2.69%	2.67%	2.59%
DU-DOL	17.00	15.37	15.38	15.47	1.59%	2.65%	2.64%	2.57%
DU-SAN	16.98	15.34	15.36	15.45	1.61%	2.66%	2.65%	2.59%
GAE-UN	17.29	15.64	15.65	15.74	1.43%	2.46%	2.45%	2.39%
GA-IN (BONG-	17.02	15.31	15.32	15.40	1.59%	2.69%	2.68%	2.63%
GAM-DONG	16.96	15.52	15.57	15.69	1.62%	2.54%	2.51%	2.42%
GANG-JEONG	16.52	15.22	15.28	15.41	1.89%	2.75%	2.71%	2.62%
GEUM-SA	16.61	15.29	15.35	15.48	1.84%	2.70%	2.66%	2.57%
GO-LA	16.95	15.48	15.52	15.63	1.63%	2.57%	2.54%	2.46%
GONG-AM	16.98	15.33	15.34	15.43	1.61%	2.67%	2.66%	2.60%

Table 10 (continued).

NAME	PAYBACK TIME (YEARS)				IRR (%)			
	0°	30°	35°	40°	0°	30°	35°	40°
GYEONG-PO	17.52	15.53	15.50	15.55	1.29%	2.53%	2.55%	2.52%
HA-DONG	16.94	15.23	15.23	15.31	1.63%	2.75%	2.74%	2.69%
HAE-PYEONG-LI	16.94	15.52	15.56	15.69	1.63%	2.54%	2.51%	2.43%
HOM-GOG	17.02	15.32	15.33	15.41	1.58%	2.68%	2.68%	2.62%
HWANG-GIL	16.73	15.23	15.27	15.37	1.76%	2.74%	2.72%	2.64%
HWA-SAN	16.93	15.26	15.27	15.36	1.64%	2.72%	2.72%	2.66%
IB-SIL	16.98	15.34	15.36	15.45	1.61%	2.66%	2.65%	2.59%
JAG-CHEON	16.58	15.26	15.32	15.45	1.85%	2.72%	2.68%	2.59%
JANG-HEUNG	16.92	15.25	15.25	15.34	1.64%	2.73%	2.73%	2.67%
JO-YEON	17.39	15.64	15.63	15.70	1.37%	2.46%	2.47%	2.42%
MI-DONG	16.92	15.45	15.48	15.60	1.65%	2.59%	2.57%	2.49%
MYEONG-GYE	16.99	15.36	15.37	15.46	1.60%	2.65%	2.64%	2.58%
NAE-GEUM	16.63	15.10	15.12	15.22	1.82%	2.84%	2.82%	2.75%
O-SAN	16.45	15.16	15.21	15.35	1.94%	2.79%	2.75%	2.66%
PYEONG-GEUM	16.89	15.42	15.45	15.57	1.66%	2.61%	2.59%	2.51%
SEOG-GYE	16.99	15.35	15.37	15.46	1.60%	2.66%	2.65%	2.59%
SEOG-MUN	16.55	15.25	15.31	15.44	1.87%	2.73%	2.69%	2.60%
SEO-SAN	16.51	15.20	15.25	15.39	1.90%	2.77%	2.73%	2.63%
SIN-BANG	16.79	15.36	15.41	15.52	1.72%	2.65%	2.62%	2.54%
SIN-GEUM	16.67	15.15	15.18	15.28	1.80%	2.80%	2.78%	2.71%
SONG-JEON	16.97	15.33	15.34	15.43	1.62%	2.67%	2.66%	2.60%
WOL-GA	16.44	15.08	15.13	15.26	1.94%	2.85%	2.81%	2.72%
WOL-PYEONG	17.00	15.36	15.37	15.47	1.60%	2.65%	2.64%	2.58%
YONG-CHEON	16.93	15.32	15.34	15.44	1.64%	2.68%	2.67%	2.60%

In fact, the risk analysis feature on RETScreen highlighted the high impact of the initial cost of the systems on its profitability. Figure 8 shows the impact factor of the initial cost, O&M cost, electricity export rate and ROC credit rate for the projects on lake Wol-ga.

The negative impact of the initial costs demonstrates the profitability of the project is affected significantly by variations on this value. In contrast, the ROC credit rate and the electricity export rate applied on the project has demonstrated a considerable effect on increasing the viability of such. Changes on the O&M cost have demonstrated to not disturb greatly the viability of the project.

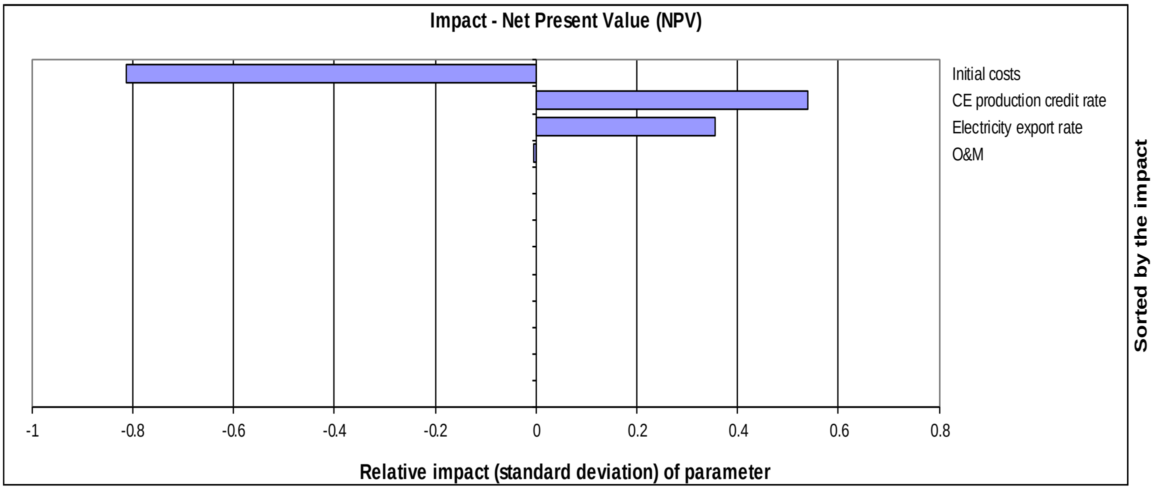

Figure 10 − Risk analysis from the economic assessment of Lake Wol-ga.

5. Discussion

The assessment conducted in this study have pointed to 45 lakes, out of the 3178 residing in South Korea, as feasible sites for the construction of floating photovoltaic systems. The main aspects that led to this result was the high rate on incidence of foggy days in South Korea as well as the small surface area and low water level of the examined lakes.

Although fog does not cause any structural impact, it may lead to significant drops on power output (up to 50%), which decreases significantly the economic viability of the project. The threshold of 10days per year pointed by Lee et al. (2012) aims to identify optimal regions in which the capacity factor of the system would not be greatly affected.

As a consequence of the high incidence of foggy days in South Korea, optimal regions were significantly limited. The extension of the threshold for 15 days per year would result on 26.5% of the total lakes being potentially feasible for the construction of the system prior to water level assessment. Therefore, as the uncertainties surrounding the features of the technology are resolved, hence the economic risk decreases, non-optimal areas may be further investigated and possibly commissioned for the construction of the system.

Although the number or lakes registering water levels lower than 5m was limited, data on the change on water level of the reservoirs did not cover the majority of the lakes, thus resulting on the exclusion of those in this study. As mentioned previously, great part of these reservoirs are characterized by small surface area, which might point to low water levels. However, this may only be assured with proper measurements.

The total area available for the construction on feasible lakes limits considerably the size of the developments. As the further extension may lead to increases on energy production, this may also lead to rises on environmental and social impacts. Therefore, further investigations on the ecology and social activities present in each reservoir are crucial to the extension of their capacity.

As described above, factors such as water flow, floating matter and surrounding areas may limit the position of the device on the surface of the lake. Thus, an on-site study might also be beneficial for identifying the area where the floating photovoltaic systems will operate more efficiently.

The design of the floating photovoltaic systems has also shown to be expressively dependent on the tilt angle in which the solar panels are installed. In fact, the total installation capacity of the lakes in South Korea decreases considerably as the tilt angle increases. While, a design considering a 0^{o} tilt angle would result on national capacity reaching approximately 216.1 MW, this figure drops to 126.4 MW on designs considering an angle of 30^{o}.

Nevertheless, projects using tilt angle of 30^{o} have demonstrated higher economic feasibility as a result of higher efficiency of the systems. For instance, the largest feasible reservoir, lake Seog-mun, is able to comport an 18.5 MW system designed with tilt angle of 0^{o}, and a 10.8 MW systems when the angle is increased to 30^{o}. According to the results from RETScreen, the first system would generate up to

20.1GWh annually with a capacity factor of 12.4% while the second 12.7GWh with a capacity factor of 13.5%.

This difference of 1.1% points on the capacity factor, though small, leads to great changes on the economic viability of the reservoir. Based on the same costs and economic parameters, the first system would reach its equity payback at the half of the 16th year of the project while the second reaches this during 15th year. In addition, the IRR of 2.73% of the second design is considerably higher than the 1.87% reached by the second one. Nevertheless, the results achieved in the economic simulations are far from satisfactory if compared to other renewable resources especially to conventional on-ground installations.

The most feasible water reservoirs among the ones investigated, lakes Wol-ga, Nae-geum and Dae-jeong, resulted on an IRR of 2.85%, 2.84% and 2.83% respectively; and an equity payback time of 15 years. Estimation on the average IRR of solar energy projects ranges from 9 to 11%. In addition, all these lakes resulted in a negative value of NPV, which demonstrates an overall net loss.

Nevertheless, the results from this study diverge from those found in the literature. For instance, the northern part of Gyeongsangbuk-do province, pointed as a feasible site for the construction of floating photovoltaic system by Lee and Lee (2016), does not comport any of the reservoirs with highest economic viability found in this study, which are predominantly located at the Jeollanam-do province.

Furthermore, the results of the economic assessment deviate greatly from those found in other studies. For instance, Song and Choi (2015) measured a payback time of approximately 12 years and an IRR of 9.87% for their 1MW floating photovoltaic system. In addition, Lee et al. (2012) found payback periods and IRR ranging from 12 to 10.5 years and 5.3 to 7.1%, respectively, as the size of their floating systems increased from 100kW to 2MW.

The deviations on the results may be explained by the methodology applied on the assessment of sites as well as by the parameters considered at the economic analysis. The assessment of the system designed to installed in a pit lake by the first authors, did not consider any of the factors utilized in this study. The uncertainties regarding the variations on the water level of the reservoir as well on other parameters not accounted by the authors may affect the system performance thus decreasing its economic profitability.

The economic assessment performed by Lee et al. (2012) despite being significantly similar to the one conducted in this study, it considers values that increased considerably the feasibility of the systems. As the study has its basis on values of 2011, both the REC value (KRW 220/kW) and system margin price (KRW 180/kW) are much higher to the ones applied.

If those values area computed on the economic assessment of the sites selected in this study, we are able to observe a great increase on their feasibility. In the case of the lake Wol-ga, the payback time of the project would decrease to 8.2 years while the IRR would surge to 10.5%, figures which would put floating photovoltaic systems competing with on-ground installations.

These results demonstrate how policies regarding measures to increase the use of renewables have indeed a great impact on their feasibility. Nevertheless, in the case of floating photovoltaic systems the initial cost of the technology seems to have the greatest effect on the economic viability of these projects. In fact, the risk analysis of the systems designed have showed this, with great changes rising from slight variations on this value.

The nature of the technology, which still faces uncertainties on proper materials and design, is the main factor leading to the higher initial investments. Nevertheless, as several other renewable energy technology and practices, the learning curve of these systems may culminate to a rapid decrease of the initial cost as the results of the ongoing projects are assessed.

In fact, based on the economic assessment of all 45 feasible lakes, in order to the floating photovoltaic projects to break-even (zero-NPV), a reduction of approximately 21.9% is required. Furthermore, for these system to reach at IRR of 10%, a reduction of about 43.9% on the initial investment must occur. Although these requirements are significantly high, solar energy technologies, as described previously, have faced great reductions in recent years, with predictions for further decreases.

The construction of the floating photovoltaic systems in the feasible lakes identified in this paper would symbolize the introduction of approximately 126.4MWp of renewable sources in the South Korean electricity mix. Currently, the supply of electricity in the country derives greatly from coal and nuclear reactors, resources surrounded by controversy due to their potential for severe environmental impact.

According to recent plan published by the South Korean's Ministry of Trade, Industry and Energy, the local electricity demand is predicted to reach 100.5 GW in 2030. As a response to this increase and as a consequence of growing concerns surrounding air quality and nuclear safety, renewables are predicted to account for 20% of the electricity supply by that period (Chung,2017).

The rise from the current 7% to 20% by 2030 indicates the construction of 48.7GW of renewable energy projects. According to the plan, the expansion of solar panels for personal use, in rural areas and at small business is predicted to account for 19.9GW, while the remaining 28.8GW is projected to be supply by large-scale projects, especially wind farms. Furthermore, the plan also describes the reinstallation of the feed-in tariffs in the country, which increases the economic viability of renewables.

This prediction may also affect greatly the development of floating photovoltaic resources in South Korea. The introduction of a feed-in tariff scheme combined with possible reductions on cost, increases significantly the economic feasibility of these projects. For instance, analyzing a scenario in which a feed-in tariff of 100 KRW/kWh for the systems designed for lake Wol-ga, a considerable increase of the IRR from 2.85% to 9.97% is observed.

Although the introduction of floating photovoltaic systems has not been mentioned in the plan, it is reasonable to argue that based on the estimations achieved in this study, South Korea may gain numerous benefits by investing in those systems. The construction of all projects proposed in this study would imply on the provision of approximately 126.4 MW of electricity from renewables on the national energy mix. The development of this optimal sites may lead to the further improvement of the technology, which may result on the construction of systems able to perform on non-optimal areas. Finally, the environmental aids of this technology are not only limited to the reductions on green-house gases emissions, but also expand to the improvement of quality of the reservoirs as well as the reductions on land use.

6. Conclusion

The supply of electricity from solar energy farms has increased considerably in recent years. This is a directly consequence of the sharp decline of the solar panels and operation and maintenance cost. Nevertheless, due to the challenges faced by the technology (e.g. low efficiency, land requirements), the development of large scale projects has been somewhat slow.

Based on the results of initial projects and on the successful transition of wind farms to offshore, floating photovoltaic systems have been considered a possible solution for the construction of high power systems. In light of this, this study assessed 3178 lakes in South Korea in order to identify possible sites for the construction of floating photovoltaic systems within the country.

The results pointed to 45 lakes being technically feasible for the deployment of floating photovoltaic systems, which consist a total installation capacity of 126.4MW. The somewhat low number of viable lakes is mainly due to the high incidence of fog in South Korea, with 2658 reservoirs being excluded due to high incidence of this phenomenon. Furthermore, the lack of data on the water level variance also culminated on some reservoirs being excluded for further investigation. Nevertheless, the majority of these reservoirs had small superficial area, hence having high probability of low water level and ice formation.

The economic assessment of the projects designed for the feasible lakes suggested that none of those would be profitable based on current cost estimations for the system. The reservoirs showing higher economic viability were located in the Jeollanam-do and Gyeongsangbuk-do provinces, in the south-west and east part of

South Korea. The systems designed for these lakes had equity payback around the 15^{th} year of the twenty-year period project, and a IRR of approximately 2.85%.

The further assessment of the reservoirs pointed as feasible in this study relies on on-site assessment where the most adequate position of the system within the water body can be observed. This would require research on aspects such water flow, floating material and vegetation which were not covered in this study. Furthermore, as data on the ongoing projects are available, validation on the methodology here proposed must also be conducted.

With basis on the result of this study, integration of the potential floating photovoltaic systems into the South Korean's national grid entails an input of 126.4MW of electricity from renewable resources. As the country energy consumptions increases and the concerns on air quality grow, the need on the development of large renewable energy projects becomes more evident. Therefore, the introduction of floating photovoltaic systems alongside with other renewable energy technologies must be fomented in order to secure the diversification and sustainability of the local energy mix.

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