# Feasibility of Photovoltaic Technology Integration in Cruise Ships

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The cruise industry is undergoing a transformative shift as environmental regulations tighten, fuel costs rise and public scrutiny over maritime intensifies. Among the emerging solutions, photovoltaics (PV) technology has gained increasing attention as a viable pathway towards cleaner and more energy-efficient ship operations. While PV systems are already well established in land-based applications, their integration into large, energy-intensive vessels such as cruise ships presents unique technical, operational and economic challenges that remain insufficiently explored. This thesis investigates the feasibility of incorporating PV technology into next-generation cruise fleets, providing a comprehensive assessment of how solar energy can meaningfully contribute to maritime decarbonization. The results indicate strong correlation between latitudinal coordinates where the cruise ship is operating and vertically integrated PV panels in the side of the cruise ship. In addition, from economic point of view, horizontally installed PV panels are proved to be noteworthy option in majority of the global cruise ship regions based on their installation costs combined with their annual energy production.

**Key words**: Photovoltaic, renewable energy, cruise ships, greenhouse gas, international maritime organization, direct normal irradiance, diffused horizontal irradiance, global horizontal irradiance

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Risteilyala on läpikäymässä murrosta ympäristösäännösten tiukentuessa, polttoainekustannusten noustessa ja merenkulkuun kohdistuvan julkisen valvonnan lisääntyessä. Uusista ratkaisuista aurinkosähköteknologia on saanut yhä enemmän huomiota toteuttamiskelpoisena polkuna kohti puhtaampaa ja energiatehokkaampaa laivojen toimintaa. Vaikka aurinkosähköjärjestelmät ovat jo vakiintuneita maalla sijaitsevissa sovelluksissa, niiden integrointi suuriin, energiaintensiivisiin aluksiin, kuten risteilyaluksiin, asettaa ainutlaatuisia teknisiä, toiminnallisia ja taloudellisia haasteita, joita ei ole vielä tutkittu riittävästi. Tässä opinnäytetyössä tutkitaan aurinkosähköteknologian sisällyttämisen toteutettavuutta seuraavan sukupolven risteilylaivastoihin ja tarjotaan kattava arvio siitä, miten aurinkoenergia voi merkityksellisesti edistää meriliikenteen hiilidioksidipäästöjen vähentämistä. Tulokset osoittavat vahvan korrelaation risteilyaluksen sijaintipaikan leveyskoordinaattien ja risteilyaluksen kylkeen vertikaalisesti integroitujen aurinkopaneelien välillä. Lisäksi taloudellisesta näkökulmasta vaakasuoraan asennetut aurinkopaneelit ovat osoittautuneet huomionarvoisiksi vaihtoehdoiksi useimmilla maailman risteilyalueilla niiden asennuskustannusten ja vuotuisen energiantuotannon perusteella.

**Avainsanat**: Aurinkosähkö, uusiutuva energia, risteilyalukset, kasvihuonekaasu, kansainvälinen merenkulkujärjestö, suora normaalisäteily, diffusoitunut normaalisäteily, globaali vaakasuorasäteily

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## Abbreviations

| | |
|---|---|
| AC | Alternating current |
| AOI | Angle of Incidence |
| a-Si | Amorphous silicon |
| AVATAR110 | AVATAR110, net-zero cruise ship concept |
| CAPEX | Capital Expenditure |
| CdTe | Cadmium Telluride solar cell solar cell |
| CIGS | Copper Indium Gallium Selenide solar cell |
| CLIA | Cruise Lines International Association |
| c-Si | Crystalline silicon |
| DC | Direct current |
| DHI | Diffused Horizontal Irradiance |
| DNI | Direct Normal Irradiance |
| DSSC | Dye sensitized solar cell |
| FPV | Floating photovoltaic |
| GHG | Greenhouse Gas |
| GHI | Global Horizontal Irradiance |
| Group III | Periodic table group 13 (B, Al, Ga, In, Tl, Nh) |
| Group IV | Periodic table group 14 (C, Si, Ge, Sn, Pb, Fl) |
| Group VI | Periodic table group 15 (O, Se, Te, Po, Lv) |
| GT | Gross Tonnage |
| GT-Lab | Green Transition-lab (Meyer Turku) |
| GW | Gigawatt |
| GWh | Gigawatt-hour |
| IEA | Internation Energy Association |
| IMO | International Maritime Organization |
| KPI | Key Performance Indicators |
| kW | Kilowatt |

| | |
|---|---|
| kWh | Kilowatt-hour |
| LCOE | Levelized Cost of Electricity |
| LNG | Liquefied Natural Gas |
| mc-Si | Multi-crystalline silicon |
| MeOH | Methanol |
| mono-Si | monocrystalline silicon |
| MS7 | Mein Schiff 7 |
| MW | Megawatt |
| MWh | Megawatt-hour |
| NECoLEAP | Name of the Business Finland funded research program of Meyer Turku |
| OSC | Organic solar cell |
| POA | Plane-of-Array |
| PSC | Perovskite solar cell |
| PV | Photovoltaic |
| PVGIS | Photovoltaic Geographical Information System |
| RCG | Royal Caribbean Group |
| RCI | Royal Caribbean International |
| SFOC | Specific Fuel Oil Consumption |
| TW | Terawatt |
| TWh | Terawatt-hour |
| TW-yr | Terawatt-year |
| $V_{bi}$ | Built-in potential |
| VBPV | vertical bifacial photovoltaic |
| $\alpha_{AOI}$ | Angle of incidence |
| $\beta_{Tilt}$ | Solar panel tilt angle |
| $\theta_z$ | Zenith angle |

# 1 Introduction

The maritime industry is currently undergoing a significant transition toward more sustainable and energy-efficient operations. Increasing environmental awareness, tightening international regulations and global decarbonization targets are accelerating the development of alternative energy solutions within the shipping sector. One of the most important drivers behind this transition is the greenhouse gas (GHG) reduction strategy established by the International Maritime Organization (IMO), commonly referred to as the IMO 2050 framework [1]. The framework aims to achieve net-zero greenhouse gas emissions from international shipping by or around the year 2050 [2]. As a result, shipbuilders, operators and technology providers are increasingly required to develop solutions capable of reducing fuel consumption and emissions throughout the operational lifetime of the vessels.

Cruise ships represent one of the most energy-intensive vessel categories due to their large size and extensive on-board hotel functions. In addition to propulsion systems, cruise ships require continuous electrical power for accommodation services, entertainment systems, lighting, ventilation, restaurants and other passenger-related operations onboard the ship. Consequently, improving the environmental performance and energy efficiency of cruise ships has become an important area of development within the maritime industry. [3]

In response to tightening emission regulations and sustainability goals, the maritime industry is exploring a wide range of technologies including alternative fuels, energy-efficient systems, electrification, automation and renewable energy integration [4]. Among renewable energy technologies, photovoltaic (PV) systems have gained increasing interest due to continuous improvements in efficiency, durability and system integration possibilities [5].

The global energy landscape is defined by a striking imbalance between the energy humanity consumes and the vast solar resources available to us. World energy consumption in 2024 was approximately 18.77TW-yr (164 444 TWh) [6]. In contrast, the solar irradiation reaching Earth’s surface in one hour amounts to roughly 173 000 TWh [7]. In a year this accumulates to approximately 9220 times the total yearly energy demand of human civilization. This immense disparity highlights the extraordinary potential of solar energy as a primary global energy source.

PV technology offers a direct and scalable way to harness this abundant resource. By converting sunlight into electricity through semiconductor materials, PV systems can generate power without fuel consumption, emissions or moving parts. Even with the current efficiencies and practical limitations, such as geographic variability, intermittency and land use constraints, the theoretical potential remains enormous. Covering only a small fraction of the Earth’s surface with PV installations could meet global energy needs many times over [7].

The growing interest towards PV technology in cruise ships is also influenced by several market-driven factors. Environmental regulations and GHG emission pricing mechanisms increase the economic importance of reducing fuel consumption and emissions. By integrating emission-free PV energy into ship's energy system, part of the on-board energy demand can be covered and compensated using renewable energy, thereby reducing fuel usage and potentially lowering emission-related costs.

In addition to regulatory pressures, sustainability has become an increasingly important strategic and commercial factor for both shipbuilders and cruise operators [3]. Many cruise companies have announced long-term net-zero targets and sustainability strategies, requiring the implementation of renewable energy technologies and environmentally conscious solutions. Consequently, integrating PV technology into cruise ships can support both environmental objectives and corporate sustainability commitments.

Passenger expectations also influence the development of greener cruise solutions. Environmental awareness among consumers has increased significantly in recent years and sustainability-related values increasingly affect purchasing decisions and travel preferences among consumers. For some passengers, environmentally responsible operations and the use of renewable energy technologies may positively influence perceptions of a cruise company and its services.

Another important market driver is the cumulative long-term benefit achieved through even modest reductions in fuel consumption. Cruise ships typically operate for approximately 25–40 years [8], meaning that relatively small improvements in energy efficiency may accumulate into substantial fuel savings and emission reductions over the vessel's operational lifetime. From shipbuilder's perspective, the integration of renewable energy technologies may also provide strategic advantages. By developing expertise and offering vessels equipped with advanced sustainable technologies, shipyards can strengthen their competitive position in a market increasingly shaped by environmental regulations and sustainability expectations.

One of the companies actively contributing to the development of future sustainable cruise vessels is Meyer Turku, one of the world's leading cruise ship manufacturers. The company has also maintained a significant strategic partnership with Royal Caribbean Group (RCG), including an exclusive agreement extending until the year 2036 for the construction of certain next-generation cruise ships [9]. This collaboration has resulted in the development of some of the largest and most technologically advanced cruise vessels in the world, including the Icon-class ships.

This thesis investigates the feasibility of integrating PV technology into cruise ships, with particular emphasis on vessels comparable in size to those designed and constructed by Meyer Turku. The work has been conducted in collaboration with Meyer Turku and focuses on evaluating both technical and economic feasibility of ship-integrated PV systems in large passenger vessels. The making of this thesis took place between autumn 2025 and spring 2026.

The study utilizes the conceptual vessel AVATAR110 as a reference platform for analysis. The AVATAR110 concept represents a future-oriented cruise ship demonstrating Meyer Turku's capability to develop environmentally advanced and potentially net-zero emission vessels. AVATAR110 is the final product from Meyer Turku's NEcOLEAP project aimed to design a fully net-zero cruise ship [10]. Within this concept, PV systems are considered as a supplementary renewable energy source integrated directly into the ship's structures.

Two primary PV installations configurations are examined in this thesis. Horizontal PV installations located on sun deck and rooftop areas and vertical PV installations integrated into balcony railings and ship side structures. The performance of these configurations is analyzed across several major cruise operating regions, including Caribbean, Mediterranean and Baltic Sea. Emphasized attention is given to the effects of solar irradiation conditions, panel orientation, geographic locations and tilt angle on annual energy production.

In addition to technical feasibility, the thesis views economic aspects associated with PV integration. These include fuel savings, maintenance requirements, operational considerations and lifecycle aspects. The study also discusses practical implementation challenges related to marine environments, including partial shading caused by ship structures, corrosion risks and safety considerations such as electrical protection and fire safety. The primary objective of this thesis is to evaluate whether PV technology can provide meaningful technical, economic and environmental benefits for cruise ships. Furthermore, the work aims to identify which installation configurations and operational conditions are the most favorable for PV implementation onboard large passenger vessels.

In this thesis, generative artificial intelligence (AI) features have been used to assist with grammar and clarity of the writing. All interpretations, analyses and conclusions presented in the thesis are those of the author.

# 2 Solar Power Technology

This chapter explores the fundamental principles of photovoltaics and solar thermal system, the technological advancements that have improved efficiency, affordability and the growing volume of solar power in global energy transitions. By understanding and emphasizing the mechanisms and innovations driving solar technology, we can better understand its potential to shape a more sustainable and resilient energy-future. Solar power technology has rapidly evolved from niche scientific concept to one of the most transformative forces in modern energy system fields. In the core of solar power technology is the ideology to capture the abundant energy of the sun and convert it into usable energy. This process offers a clean and renewable alternative for fossil fuels that are still most used today.

Over the years the publicly available solar power technology for companies and consumers has evolved in terms of suitability and adaptability to different environments, efficiency in power production and variety of technologies used for power production. What is also remarkable, the price trajectory of solar panels has decreased by 20% each time the global cumulative capacity has doubled[11, 12]. This PV development arch is explained by Swanson's law which states that the price of solar PV panels tends to drop 20% for every doubling of cumulative shipped volume [12]. What is more, Swanson's law is more or less refined from Wrights law [13] which predicts that every cumulative doubling of units produced, costs decrease by a fixed percentage. This law states that increased experience and production volume drive efficiency in addition to costs falling by a consistent percentage for many technologies. The historical development of solar PV panel cost in relation to the installed global cumulative capacity has developed from 100 $ á 1 MW of power to less than 0.5 $ á 100 000 MW of power. In addition, the historical development of total renewable capacity additions by technology between the years 2015–2025 is shown in the Figure 1.

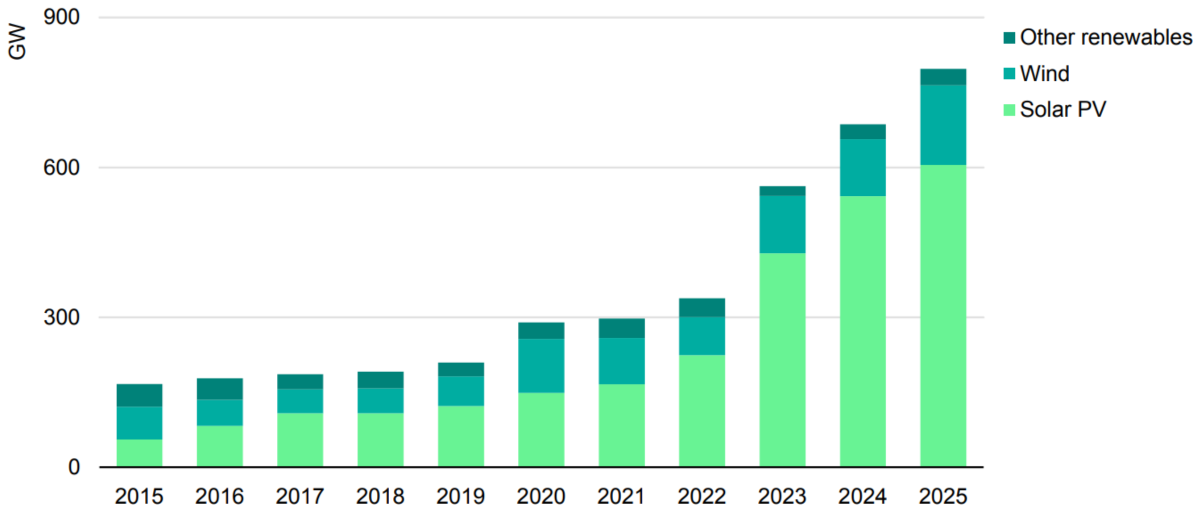

Figure 1 Total renewable capacity additions by technology, 2015-2025. The cumulative addition of solar PV rose by 12% in 2025, surpassing 600GW for the first time. This picture is reproduced from Global Energy Review report 2026 given by International Energy Agency (IEA) [14] with license CC BY 4.0. [14]

When speaking of solar cell, the focus is on the “lowest” level of PV energy hierarchy. A PV cell is an individual photoelectric cell capable of producing electric current when exposed to photons. These cells can be thought of as monomers or building blocks and when linked together they create a polymer, a single solar panel. Solar panel consists of multiple solar cells connected series and encapsulated together in a protective package. In the commercial field, solar panels are the standard unit manufactured and sold by solar energy companies. At the top of the hierarchy is PV system. PV system is a complete setup capable of producing solar electricity for the consumer. PV system includes one or more solar panels linked together electrically as well as other important additional components that support the complete setup. Other important components in PV system are inverters, mounting structures and possible battery storage and charge controllers. The electrical current produced from the PV system is direct current (DC). Inverters are key components responsible for transforming the produced DC into alternating current (AC), that is usable for consumers. [4]

## 2.1 Solar Radiation

To understand the transformation of solar radiation to electricity, some specified terms are introduced regarding the radiation. The incident radiation can be divided into three separate components: Direct Normal Irradiance (DNI), Diffused Horizontal Irradiance (DHI) and Global Horizontal Irradiance (GHI). The total irradiance hitting the solar panel’s surface perpendicularly is also known as plane of array (POA) irradiance. DNI equals the amount of solar radiation a solar panel receives perpendicular to the sun’s rays. To put it simply, DNI accounts for the direct sunlight coming to the solar panel’s surface. DNI is measured in watts per square meter [W/m$^2$]. DHI arriving at the solar panel’s surface consists of scattered irradiance. It represents all the rest of sun’s rays that are bounced off and scattered by atmospheric molecules (water vapor, gases, dust). Therefore, DHI equals the sun's radiation reaching a solar panel any other direction except directly perpendicular to the panel. DHI is measured in watts per square meter [$W/m^2$]. GHI consists of both DNI and DNI. To calculate GHI, a Global horizontal irradiance equation (1) is presented:

$$GHI = DHI + DNI\cos\theta_z \tag{1}$$

where angle $\theta_z$ represents the solar zenith angle, an angle between the sun's rays and vertically perpendicular direction from the ground [15]. Zenith angle is illustrated in the Figure 2 below.

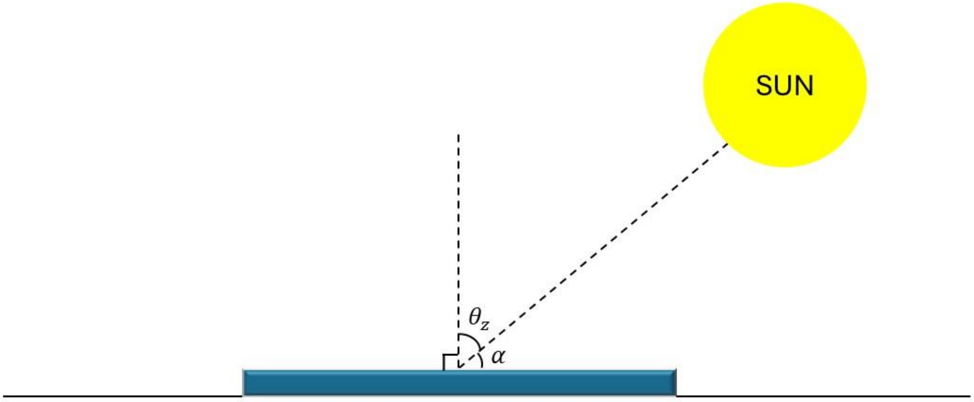

Figure 2 Solar zenith angle visualized in relation to horizontal panel on the ground. $\theta z$ is zenith angle and $\alpha$ solar elevation angle.

An important parameter to define the power output of individual PV panel is the angle of incidence $\alpha_{AOI}$ (AOI). It describes the angle between the sun's rays and the perpendicular line to the PV panel's surface. Ideally, the smaller this angle is, the better. This is because in this way a larger portion of the total plane of array irradiance is direct normal irradiance which doesn't reflect away from the surface of the panel. The larger the AOI is, the more reduced the final output of the panel is. To influence the AOI values, panel tilt angle $\beta_{Tilt}$ is introduced. It is an angle between the PV panel and the ground. By changing this tilt angle relative to the ground, the $\alpha_{AOI}$ value can also be modified. Both angles $\alpha_{AOI}$ and $\beta_{Tilt}$ are expressed in the Figure 3 below.

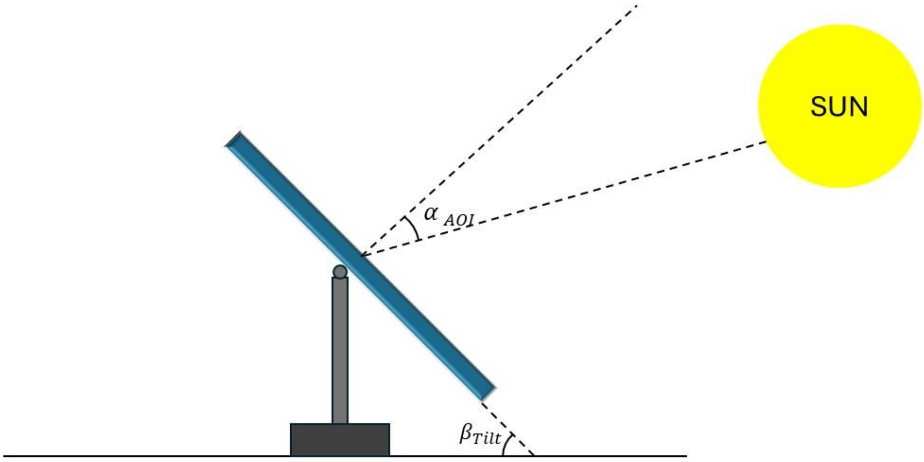

Figure 3 Angle of Incidence (AOI) visualized. In the figure αAOI is the angle of incidence, βTilt is the tilt angle of the solar panel relative to the ground.

What is also important to keep in mind is the difference between solar irradiance and solar irradiation. Solar irradiance represents the total sun's radiation affecting on a square meter [$W/m^2$], whereas solar irradiation stands for the solar radiation affecting on a square meter for a given time period. Solar irradiation is most commonly measured in kilowatt hours per square meter [$kWh/m^2$].
The POA can be calculated from DNI, DHI and GHI as follows:

$$G_{POA} = G_b + G_g + G_d, \text{ where} \tag{2}$$

$$G_b = DNI \cdot \cos\alpha_{AOI} \tag{3}$$

$$G_g = GHI \cdot albedo \cdot \frac{1+\cos\beta_{Tilt}}{2} \tag{4}$$

$$G_d = DHI \cdot \frac{1+\cos\beta_{Tilt}}{2} \tag{5}$$

in these equations, $G_b$ stands for POA beam component, $G_g$ POA ground-reflected component, albedo material specific coefficient for reflectance, and $G_d$ POA sky-diffuse component. [16]

## 2.2 Solar Panel Orientation and Temperature Influence

Typically, the orientation of the solar panel can be modified through two distinctive variables: panel tilt and azimuth. Both values are measured in degrees, and they explain the current orientation of a chosen solar panel. Panel tilt represents the angle between the panel and the ground, meaning a horizontal panel with a 0° tilt would be laying completely flat on the ground and on the other hand 90° tilt would represent a completely vertical solar panel that is standing on the ground.

Azimuth explains where the panel is facing regarding cardinal directions. For example, solar panel with 0° azimuth and 90° tilt would be facing vertically directly towards North. On the other hand, if the solar panel is installed with 0° tilt and 90° azimuth it would be laying horizontally flat on the ground "facing east". However, in this case as the solar panel is laying horizontally flat it doesn't matter what the azimuth angle is, since the panel is facing directly upwards from the ground. Panel tilt and azimuth are illustrated in Figure 4 below. Depending on the source, azimuth values can start either from North or South increasing clockwise as in compass.

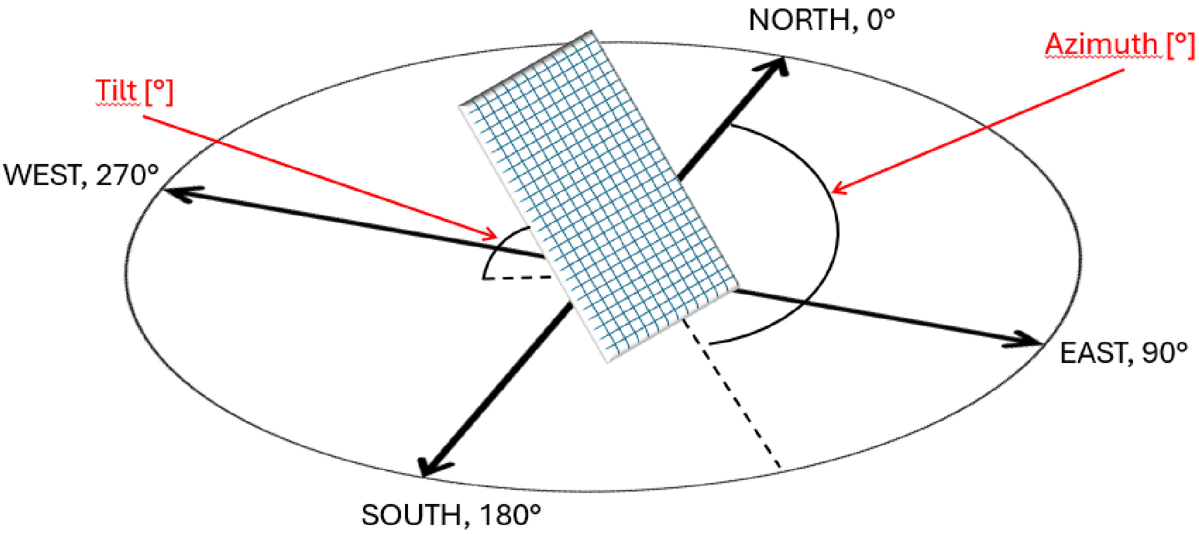

Figure 4 Panel tilt and azimuth angles visualized.

However, in this thesis, the software used (PVGIS [17]) to calculate different irradiation values globally, has 0° azimuth facing South, 90° facing West, 180° facing North and -90° facing east. The azimuth values have been changed from that to point where azimuth starts from North (0°) and increases clockwise.

The correlation between ambient temperature and PV potential has been proven and it is not to be neglected when designing PV systems on land or water areas. As the temperature increases the overall potential of individual PV cell is decreasing [18]. In general, when surpassing 25°C the PV cell starts to decrease in terms of electricity production [18, 19]. Negative thermal coefficient is introduced as the mathematical quantity that describes the loss of potential for PV cells during temperature increase. Typically, the loss is approximately 0.5% per each degree Celsius that goes above the 25°C mark [19]. In total the loss of potential in extremely high temperature environments can be as significant as 13% from the overall electricity production [18]. Negative thermal coefficient and its effect on panel performance is not be confused with general panel degradation over time. For panel degradation, different PV panel manufacturers give their own specific warranties regarding product efficiency over the lifespan of the product. Depending on the manufacturer, the warranties may contain specific terms and conditions where, and in what circumstances to operate the panels.

## 2.3 Photovoltaics

As the name suggests, photovoltaics stand for the direct conversion of light (photon) into a form of electricity (-voltaics). This effect of turning solar energy into electricity is known as the photovoltaic effect [20]. Solar energy, also known as sunlight, consist of quantized energy particles called photons [21]. The amount of energy these particles carry is defined by the wavelength of the solar spectrum. When encountering PV cells, photons have two options: to reflect or to absorb from cell surface. Photons that reflect from the PV cell are to be considered waste energy that cannot produce electricity from the cell [22]. Hence, only the photons that get absorbed can produce electricity in the cell [22].

The photovoltaic effect of converting light into electricity is based on the fundamental technology of semiconductors. The key parameter of semiconductors is the ability to change conductivity. Most common semiconductor material for PV cells made today is silicon [4]. As silicon has four valence electrons, it is perfectly suitable for a semiconductor material. It has equal amount of shortage of valence electrons and a need to disperse its valence electrons to reach octet, the energy state that is considered the most stable for atoms. This eight-valence electron energy state is the most stable formation of valence electrons; thus, atoms pursue this state of energy. Silicon is both suitable to receive and donate its valence electrons.

To manage to produce electricity, the absorbed photons energy needs to be high enough to surpass the solar cell material characteristic band gap level [20, 23]. It is the minimum amount of energy required for the cell atom's electron to break free from the valence band to the conduction band. Excess energy above the bandgap that the photons have cannot be used for electricity production. This is due to the reason these high energy photons create carriers from the cell atom electrons that contain excess amount of energy. These high energy carriers calm down eventually to the conduction band level releasing the excess energy as heat (thermalization loss) [18, 19, 25]. From the total solar spectrum, approximately 35% is lost due to thermalization losses [24]. On the contrary, photons with energy lower than the needed band gap, don't detach the electrons from the cell atoms, hence part of them take part in parasitic absorption that accumulates as extra heat in the solar panel [20, 25, 26]. These sub-band-gap losses together with thermalization losses account for over 55% of the absorbed energy that is not converted into electricity in the solar cell [27].

To enhance the semiconductor properties of silicon, doping is introduced. Doping is a technique that aims to synthetically modify the amount of electron holes on semiconductors crystal lattice. By adding impurities to the homogenous silicon crystal lattice, P-type materials and N-type materials are being created [28]. These impurities enhance the electrical properties of semiconductors by increasing either the amount of free electrons or the amount of free electron holes in each substrate. The increase in these two aspects increases the overall electron flow in the semiconductor [29, 30].

## 2.4 Different Types of PV Cells

Historically, solar power applications have been around since 7th century B.C when early humans used primitive magnifying lenses to concentrate sunlight to ignite fire. In addition to this, in the 3rd century Greeks and Romans utilized solar beams through "burning mirrors" to light up torches [31]. However, 1839 marks an important year in the evolution of solar power applications. It is the year when a French physicist Alexandre Edmond Becquerel discovered the photovoltaic effect [4]. Through his work, he discovered how certain materials create an electric current when exposed to light. After this discovery the field of PV solar power applications widened exponentially as the research for new materials capable of producing electric current with the stimulation of light started.

The evolution of solar cells can be classified into first, second and third generation:

1. First-generation solar cells are cells made from crystalline silicon. This generation of solar cells are currently dominating the consumer markets as the study behind this cell technology is most comprehensive compared to other cell technologies together with the immense global availability of main construction material, silicon. The first-generation solar cells include cells made out polycrystalline and monocrystalline silicon. [31]
2. Second-generation solar cells are the so-called thin-film solar cells. Thin-film technology involves sandwich-like designs of active PV material being squeezed between two glass panes. This generation of solar cells includes amorphous silicon, CIGS and CdTe solar cells [4]. Second-generation solar cell technology is commercially viable e.g. in terms of structure-integrated solutions. Due to their flexible nature and light weight, they are good options for integrated solutions to buildings [31].
3. Third generation solar cells are closely related to second-generation thin-film technologies. What is different between these two generations is commercial un-readiness of the third-generation solar cells. Most of them still being in development and research phase, third-generation solar cells are known for emerging photovoltaics [31]. Today, perovskite solar cells, belonging to third-generation technology, are one of most promising and interesting solar cell material studied in the field of photovoltaics [32].

## 2.5 Monocrystalline Silicon Solar Cells

From the consumer point-of-view, monocrystalline silicon (mono-Si) solar cells are the leading technology in the markets. Representing first-generation solar cells, mono-Si solar cells have been studied for decades and therefore they are the most established and widely used PV technology today [4, 31]. They are known for their high efficiency and long operational lifetime together with reliable performance profile. Currently consumer mono-Si solar cells reach efficiency levels of little under

22%, although, with some advancing technologies the efficiency rate has reached 26.81% [33]. As the name implies, mono-Si solar cells are manufactured from a single silicon crystal through a process called Czochralski method. This method creates a uniform structure for the cell, thus preventing efficiency defects caused from grain boundaries, e.g. in the case of mc-Si solar cells [33]. This monocrystal structure enables charge carriers to move more efficiently and helps to minimize recombination losses [4, 33]. What is more, because of the Czochralski process, mono-Si solar cells typically achieve higher power conversion efficiencies compared to other silicon-based solar cell technologies, making them a dominant choice for consumers in residential, commercial and utility-scale solar installations.

### 2.5.1 Monocrystalline Silicon Solar Cell Applications

As mentioned previously on different solar cell materials, the world of PV panel-based solar applications is immense. There is a lot more than meets the eye when it comes to different applications related to PV upscaling to panel/array level. Common applications regarding PV implementation to existing architectures are integrated solutions, e.g. replacing flat horizontal or vertical glass structures with PV panels. In this approach PV panels replace certain structural elements such as railings/barriers (vertical panel), ceiling windows (skylight panels) or rooftop shingles (solar shingles) [4]. Other noteworthy options for PV implementation applications are thin film implementations, such as adding additional thin film PV panel layer on the surface of different objects to reduce the total demand of energy from the main energy source.

Depending on the free use of space, vertical bifacial (VBPV) solar panels are an exceptional option for effective solar energy production without paying for expensive solar tracking systems [4, 34]. When VBPV solar panel is compared with a normal monofacial solar panel in daily power production, VBPV solar panel contains two distinctive peaks (with East–West configuration) as the energy production is on its peak during the morning/forenoon and during the afternoon in comparison to monofacial solar panel's energy production peak (with South facing configuration) which is reached in the middle of the day [34].

## 2.6 Global Solar Installations

Today there are already vast amounts of solar parks installed globally. Historically some certain milestones were achieved when the first megawatt-scale PV station was installed in California, USA in 1982 [4]. What is more, 2003 "solarpark Hemau" in Germany became its time largest PV plant reaching 4–megawatt production capacity [4]. Fast forwarding the timeline into today, world's largest PV parks, preferably called solar farms in the case of commercial use hence excluding residential use, reach over gigawatt-scale (GW) in production capacity [14, 35].

When looking at solar power installations on a global scale, majority of countries in the world have joined this path to produce cleaner and more renewable energy for the future. Looking at the past, solar panel costs have dropped by over 80% since 2010 [36, 37]. This is one of the many reasons that explains the rapid solar panel installations occurring globally today. During 2024 global solar power capacity historically exceeded 2 terawatts [38]. With the yearly installation capacity surpassing over 600 gigawatts for the first time in 2025 [39], the cumulative global solar PV capacity reached roughly 2.8 TW at the end of 2025 [14].

The rapidly increasing pace of global solar power installations can be seen for example from past years. In the first six months of 2025, there were already over 380 GW of solar power capacity installed globally, which is 64% higher than during the same time period in 2024, when 232 GW of capacity was installed [40]. The same amount of capacity in 2024 was reached not until September. What is more, China alone was responsible for more than two thirds of this total installed capacity from the first half of 2025 [40]. When looking at the world's largest solar farms, 5 of the top 10 largest solar farms are located in China. India following behind China, these two countries accumulate more than half of the total solar power capacity in the world as we speak [14].

Currently, the largest operational solar farm is located in Xinjiang, China, with an installed capacity of approximately 5 GW [41]. The facility generates around 6.09 TWh of electricity annually, corresponding to the energy demand of millions of households [41]. The size of the Xinjiang solar farm can be seen in Figure 5 below. The scale of the Xinjiang solar farm highlights the rapid expansion of utility-scale PV installations in China, where hundreds of solar farms have been deployed across extensive land areas [42]. Other notable solar parks include the Bhadla Solar Park in India (approximately 2.7 GW) and the Francisco Pizarro solar plant in Spain (590 MW), the latter being one of the largest in Europe [43].

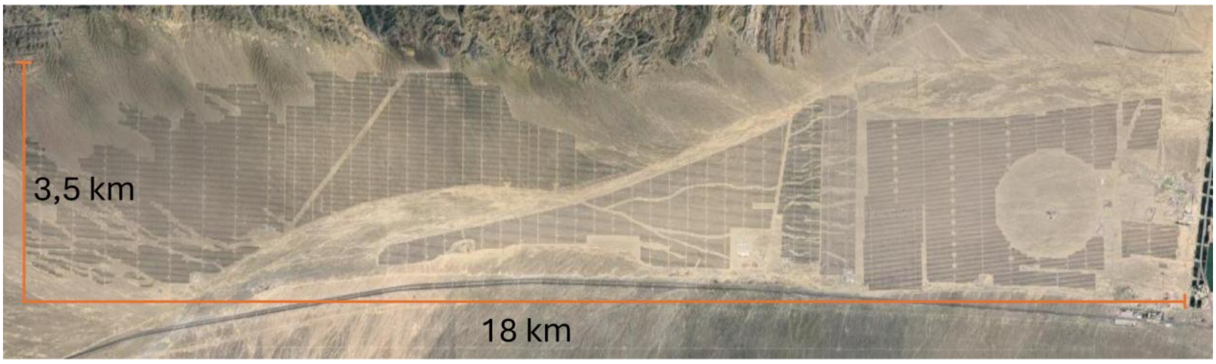

Figure 5 Satellite image from Xinjiang solar farm, the largest operating solar farm in the world. The panels are spread in a 18 km × 3.5 km area in the desert area. Image modified from Google Maps [44].

When it comes to installing solar panels, some important and limiting factors are to be considered. Typically, commercial and utility scale PV systems are installed in large fields with a fixed panel angle and azimuth angles towards South in the northern hemisphere and North in the southern hemisphere to maximize the solar irradiance capture at that specific location. Depending on the geographic locations, these angles vary. Depending on the preferences on the given location, vertical panel installation might be also a noteworthy option. By changing the panel angles, we can directly affect the amount of irradiance captured in the panel's surface. To actively change the panel angle, 1–axis and 2–axis installations are introduced. As the name suggests, 1–axis installation gives the panel the ability to rotate over one axis while the second axis is still fixed. 2–axis installation gives a total freedom to panel to track the sun actively during every hour of day. However, costs related to 2–axis installations are relatively very high compared to fixed angle or 1–axis installations and therefore they are rarely considered to be valid, especially in large scale solar farms.

## 2.7 Levelized Cost of Electricity and Payback Time

To inspect the economical side of solar panels, levelized cost of electricity (LCOE) is introduced. It is a universal tool that helps PV related energy to be more easily compared with other energy sources in terms of economic comparison. LCOE measures the average net present cost of electricity generated throughout the PV system's whole lifetime. Equations 6 and 7 below display the calculation for LCOE for PV energy production [45]. The unit that is given from LCOE is €/kWh.

$$LCOE = \frac{CAPEX + OPEX_{Lifetime}}{AEP_{Lifetime}} \tag{6}$$

More precisely,

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O_t + D_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{7}$$

In the Equation 7, $t$ refers to time in years, $I_t$ investment expenditures in time t [€ or cent], $O_t$ operation and maintenance expenditures in time t [€ or cent], $D_t$ Decommissioning and disposal expenditures in time t [€ or cent], $E_t$ total energy produced in time t [€ or cent] and $r$ discount rate [%]. Majority of all the expenditure is generated during the first year when the PV system is purchased and installed. Operation, maintenance and disposal related expenditures are marginal compared to CAPEX costs invested in the systems in the beginning. Keeping that in mind, what can also be seen from the equation is that in the first years from the installation, the PV system is operating at a loss. Over time as the PV system cumulatively produces electricity it breaks even and after that starts to make profit for the user. Typically, LCOE values are measured in €/kWh although it highly depends on the size of the system and operating time. Normal operating time given by the manufacturer for the PV system is between 20 and 30 years [46]. Keeping that in mind, the larger the total energy production during that period, the lower and better the LCOE value for the system is.

In addition to LCOE another important metric used in the economic assessment is the payback time. The payback time represents the time required for the cumulative savings generated by the PV system to equal the initial capital investment required for the installation. A shorter payback time indicates more economically attractive investment. However, due to uncertainties related to fuel prices, interest rates and operational conditions, the payback time should be interpreted as an estimate rather than a precise prediction.

# 3 Overview of Solar Power Applications in Marine Environment

As the abundant solar radiation reaches Earth’s surface equally relative to latitudes, the specific location doesn’t matter whether it is ground or water. Marine based solar panel applications are noteworthy options to capture and transform the energy of the sun into electricity in marine environments. To describe the reflectance of solar rays from specific materials surface, albedo is introduced. It is a material specific coefficient that describes the amount radiation in percentages that is reflected from the materials surface. In the case of sea water, the albedo of this material is extremely low. Sea water albedo ranges from 3% to 23%, which proposes that the material is not suitable for high reflectance applications [47, 48]. When considering installing solar panels in marine environments, one huge advantage in this environment is the horizontal freedom of space. Compared to land-based solar panel installations, in general there would be no plants or building structures to cause shading effects for solar panels.

Over the years, quite a variety of solar panel applications have been implemented in the marine environment. For instance, marine-vessel-related integrations are a standard thing for solar panels. What is more, the implementation of PV panels has been carried out to stationary marine-based structures such as oil rigs or ocean buoys. An intermediate solution between land-based solar farms and marine environment installations are the so-called floating photovoltaics (FPV). To put it simply, FPV are solar panels mounted on a floating structure that reserves space from the open water area. These floating panel units together create a floating solar farm that can be placed in any marine environment. However, the requirements for standard operating circumstances for FPV typically insist of calm water areas where big waves don’t occur. [49]

Despite some advantages marine-based solar power may also contain some crucial limiting factors as well. For example, depending on the PV cell material, whether it is mono-Si or thin-film-based CdTe solar cells, an unwanted contact with sea water might cause some harm to the cell [4]. Problems related to solar panel sealings occur as well, as the cell material degrades rapidly by the exposure with air and moisture [4]. When operating in marine environment, salt is always present. Hence, depending on the material choices used in the marine PV systems, decreased transmittance of the PV panel is possible. What is more, oxidization and rusting of the structural elements are present [50]. However, by making efficient material choices corrosion related oxidization of the solar panel structures can be prevented. For instance, by favoring aluminum-based structures, severe corrosion damage can be prevented as aluminum forms a thin oxide layer immediately after been in contact with oxygen.

## 3.1 Mein Schiff 7 Solar Panel Installation

In the world of cruise ships, one case example is the Mein Schiff 7 (MS7). Built in the Meyer Turku shipyard and released in 2024, the ship contains 217 $m^2$ worth of mono-Si solar panels installations in the roof section of the relax pool -indoor area. Having 60 installed panels with nominal capacity of 80W/$m^2$ á panel, the nominal capacity of the PV system is 17.4 kW [51, 52]. Even so the panels are integrated into publicly visible surfaces, they still please the esthetic eye and allow sunlight to pass through between the panel's edges. The illustrated picture of the installed solar panels onboard MS7 can be seen on Figure 6 below.

Figure 6 MS7 cruise ships integrated PV panels on the roof section of the relax pool -indoor area. Image courtesy of Meyer Turku.

## 3.2 Solar Buoys

Solar-powered ocean buoys are autonomous floating platforms that are equipped with PV panels to harvest sunlight and charge built-in on-board batteries in the open ocean areas [53]. PV panels combined with energy storage system enable the ocean buoy to operate independently and continuously without relying on fossil fuels. These kinds of ocean buoys are used to gather ocean related data, such as wave heights and water temperatures. By having fully autonomous operating principles, the buoys can send the ocean data via satellites [54]. What is more, the fully autonomous nature of the solar powered ocean buoy makes the deployment of the buoy suitable for distant and remote locations where maintenance procedures are difficult and costly.

## 3.3 Floating Solar Parks

The world’s largest floating solar park currently under development is located in Khandwa, India. The floating solar park harnesses sunlight while not using any valuable land, thus giving space for other land-based activities. The planned peak capacity of this floating solar park is approximately 600 MW while having an overall solar panel area-use of approximately 12 km$^2$ [55]. An illustrated satellite image of the floating solar park is given in the Figure 7 below.

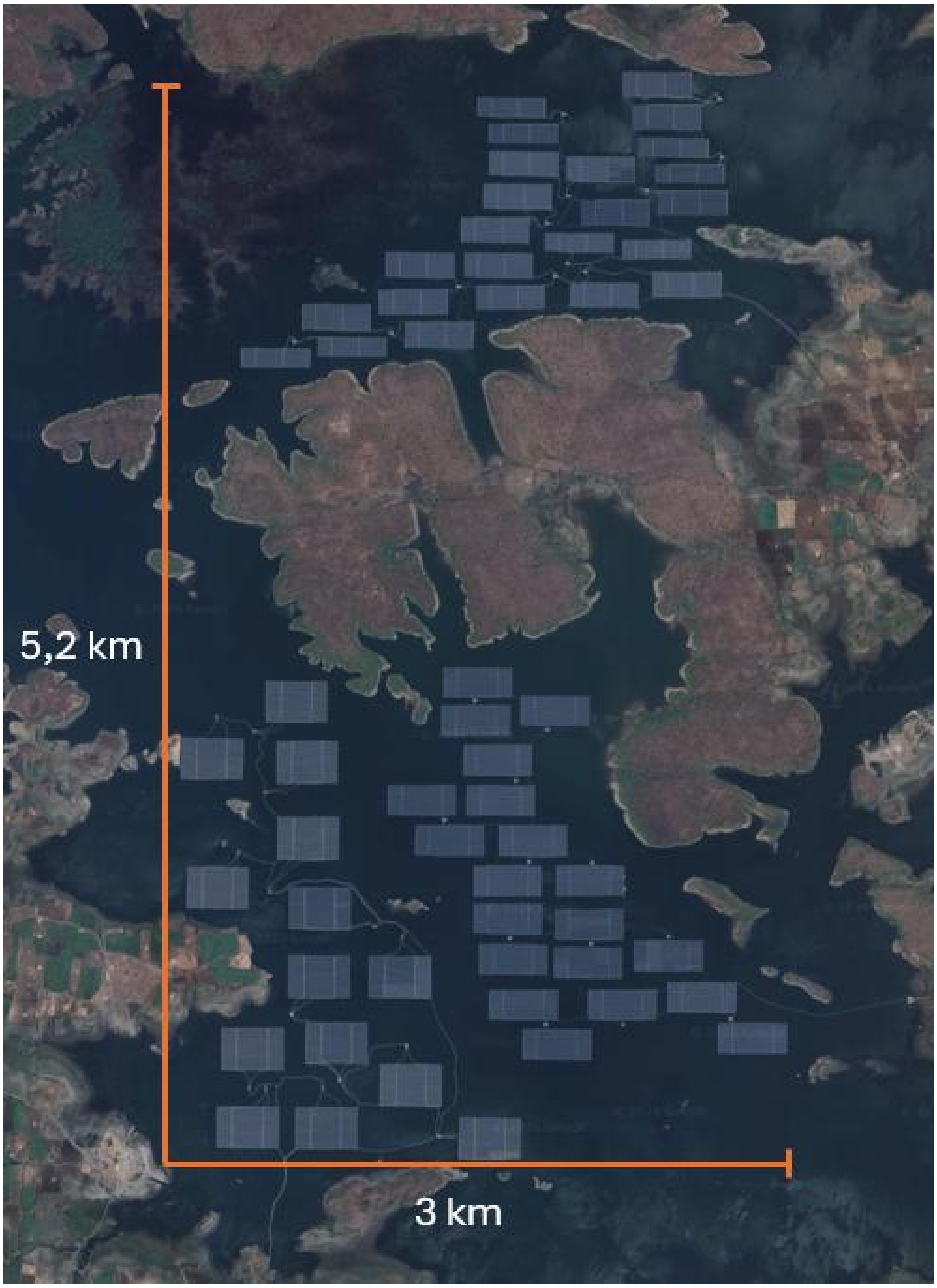

Figure 7 Satellite image from Kwanda solar park, the largest operating floating solar park in the world. The panels are spread in a 5.2 km × 3 km area in the Omkareshwar dam area. Image modified from Google Maps [44].

Gaining full operational capacity in 2021, Sembcorp Floating Solar Farm in Singapore was its time largest floating solar panel system. Consisting of 122 000 solar panels with 45 hectares of total amount of area-use, the system could reach 60MW production capacity. The project was originally developed to contribute to Singapore's future goals to quadruple its solar energy capacity by the year 2025 [56]. An illustrated satellite image of the floating solar park is given in the Figure 8 below.

Figure 8 Satellite image from Sembcorp floating solar farm, Singapore. The panels are spread in a 1.6 km × 0.63 km area located inside Singapore water-area. Image modified from Google Maps [44].

# 4 Meyer Turku Case study

As global maritime decarbonization accelerates, shipbuilders —not only operators—are becoming central actors in the transition towards low-emission shipping. From the perspective of Meyer Turku, one of the world's leading builders of large passenger vessels, integrating PV technology into next-generation cruise ships represents both strategic engineering decision and a competitive market opportunity. The shipyards portfolio already includes some of the largest cruise ships ever built, such as vessels in Royal Caribbean's Oasis class and the 365-meter Icon-class ships which can accommodate up to 7600 passengers.

That been said, this case study examines the role of Meyer Turku in advancing installation and integration of PV panel systems on large-scale cruise vessels, with particular focus for the Royal Caribbean Group (RCG) and its Royal Caribbean International (RCI) fleet, including the next-generation Icon Class ships. From industry-perspective, Meyer Turku operates as a key industrial actor as it has reached an agreement to work exclusively with RCG until the year 2036 [9]. This agreement ensures a long-term strategic partnership enabling continuity for product development inside the alliance. Within this continuum, the shipyard's design engineering and lifecycle support capabilities provide a stable platform for evaluating how solar energy technologies can be embedded into complex cruise ship architectures, thus balancing energy efficiency, operational reliability and evolving sustainability related key performance indicators [9].

Meyer Turku has actively strengthened its international research and development capabilities by establishing a dedicated Green Transition team (GT-lab), which plays a key role in advancing sustainability and driving the shipbuilding industry toward net-zero emissions. GT-lab effectively promotes innovative solutions that support the green transition across vessel design, construction and lifecycle operations. In this context, the integration of solar panels into Meyer Turku's product portfolio represents a natural and forward-looking evolvement, complementing existing energy efficiency measures and renewable energy strategies. Solar technologies can contribute to reducing fossil fuels dependency and shorten environmental taxes which are accounted by the use of fossil fuels, optimizing onboard energy usage and more importantly, securing Meyer Turku's place as an industry leader in sustainable, future-ready shipbuilding [57].

## 4.1 Meyer Turku's Geographic Operational Profile

One crucial factor for Meyer Turku is the final geographical locations where its products of current and near future orderbook are operated. Majority of Meyer Turku's products are operating globally in high-irradiance areas such as the Caribbean and Mediterranean. Without yet going into details regarding the profitable panel orientation, the sheer amount of abundant solar irradiance in these locations is immense as well as the intensity of the irradiation. As all the cruise ships follow strict itineraries in the chosen locations, a generalized yearly average of the captured solar irradiation can be accurately predicted.

From market point of view these specific locations where Meyer Turku's products are operating have been increasing in terms of cruise passengers. From 2023 to 2024 the number of cruise passengers in the Caribbean increased 17.1% from 12.80 million to 14.98 million passengers [3]. After Caribbean, the second biggest location people go to on a cruise is the Mediterranean. In this region the number of cruise passengers increased 5.8% from 5.46 million to 5.77 million between 2023 and 2024. The previously mentioned global increase in cruise passengers is reported by State of the Cruise Industry report from 2025 provided by Cruise Lines International Association (CLIA) [3].

Based on the 2025 yearly report given by CLIA, increase in cruise passengers has been growing particularly in the regions where Meyer Turku products are operating [3]. This increase in numbers supports the supply and demand relationship between Meyer Turku and its customers thus allowing a clearer future for cruise orders. What is more, substantial quantitative increase has been demonstrated in high-irradiation cruise itinerary regions. Table 1 summarizes the different cruise regions in the world in terms of market increase and irradiation conditions.

Table 1 Cruise regions separated by latitudinal values. From these latitudinal values irradiation regions A, B, C and D can be extrapolated based on the average yearly POA irradiation in the given region. This table emphasizes the particular cruise regions where CLIA State of the Cruise Industry report 2025 has shown market point of view increase.

| **Latitude** | **Ocean region** | **Yearly POA irradiation [kWh/m$^2$]** | **Market increase from 2023 to 2024 [%]** | **Irradiation region** |
|---|---|---|---|---|
| N10°–30° | Caribbean/Bahamas/Bermuda | 1600–2200 [58] | +17.1 | A |
| N30°–45° | Mediterranean | 1300–2000 [58] | +5.8 | B |
| N50°–66.3° | Non-mediterranean Europe | 800–1200 [58] | +2.0 | C |
| Polar region, >66.3° | Exploration (Antarctic, Arctic/Galapagos, Greenland, Iceland, North Cape) | 400–1000 [59] | +21.6 | D |

## 4.2 Market Drivers

In addition to having good irradiation conditions in the operating locations of Meyer Turku's products, many key performance indicators (KPI) from market point of view are present to strengthen the idea of implementing PV technology into Meyer Turku's products. International Maritime Organization (IMO) as well as international maritime laws aim to increasingly reduce emissions from marine traffic [57]. Common tool used to restrain emissions is GHG emission pricing. To put it briefly, the more an individual vessel causes emissions through its operational profile the more there is to pay for these harmful emissions. When emission free PV technology is being introduced to the vessels energy system, some amount of the ships energy production can be replaced with solar energy thus reducing emissions and therefore reducing emission pricing.

In addition to Meyer Turku's environmental values, cruise companies globally are also committing to net-zero targets through their long-term strategic planning [60]. To achieve these net-zero targets, new technologies need to be implemented to the companies' way of running. This means automatization solutions, renewable energy sources, recycling and end-of-life thinking. In terms of renewable solar energy, when companies integrate PV technology into their cruise lines, they approach these net-zero targets.

For some eco-conscious cruise passengers, it's a deal breaker if a choice is needed to be made between cruise company that uses renewable energy and shares green environmental values compared to a cruise company that has less ambitious economic goals and chooses not to pursue them as actively. Customer behavior can be monitored using different customer barometers and questionnaires. Nonetheless, today more companies are establishing their net-zero goals since climate change has been taken into account to our everyday life and choices.

Typical lifetime for cruise ship is 25 to 40 years [8]. This means that even a small reduction on a generator load can still accumulate to substantial amount of fuel savings over the ship's whole lifetime. It goes the same for reduced amount of emission fees created throughout the ship's lifetime as the savings accumulate from them as well. By choosing the option to install and integrate PV technology into the ship, Meyer Turku increases its own value proposition. For instance, by offering PV-technology-equipped ships, Meyer Turku helps to give promises for its customers to stay on top of the changing wave of tightening global emission standards. By offering these kinds of promises to its customers, Meyer Turku gains a strategic advantage in the market by being more prepared for the changing future regulations than its competitors.

# 5 PV System Integration

This chapter examines key system-level considerations related to the integration of PV technology into cruise ships. In addition to presenting the conceptual vessel used as a case study, AVATAR110, the chapter addresses practical challenges associated with PV implementation in a maritime environment. More emphasis is given to spatial integration, partial shading effects and safety related aspects.

## 5.1 Concept Ship AVATAR110

The AVATAR110 concept ship serves as a reference platform for evaluating PV integrations in this thesis. The concept represents a next-generation cruise vessel designed to demonstrate the technical capabilities of Meyer Turku in developing environmentally advanced and potential net-zero emission ships. AVATAR110 incorporates design principles that emphasize sustainability, energy efficiency and the integration of renewable energy technologies. All this together they create the net-zero concept of cruise ships. Within this context, PV systems are considered as a complementary energy source integrated into the ship’s structure. [61]

From geometric perspective, the vessel offers two primary categories of surface area for PV installations: horizontal surfaces are primarily located on sun decks and rooftop structures, and vertical surfaces located on balcony structures along both sides of the ship. For horizontal surfaces, the total available installation area is 1838 $m^2$ with additional 504$m^2$ from 30° tilt angle structure in the sun deck. The total available vertical installation area is 3086 $m^2$. In total, there are 5428 $m^2$ worth of installation area for PV panels on AVATAR110. The reserved installation area in AVATAR110 can be observed in Figure 9 and Figure 10 that display the three-dimensional model of the concept ship. The reserved installation area in these figures is painted orange.

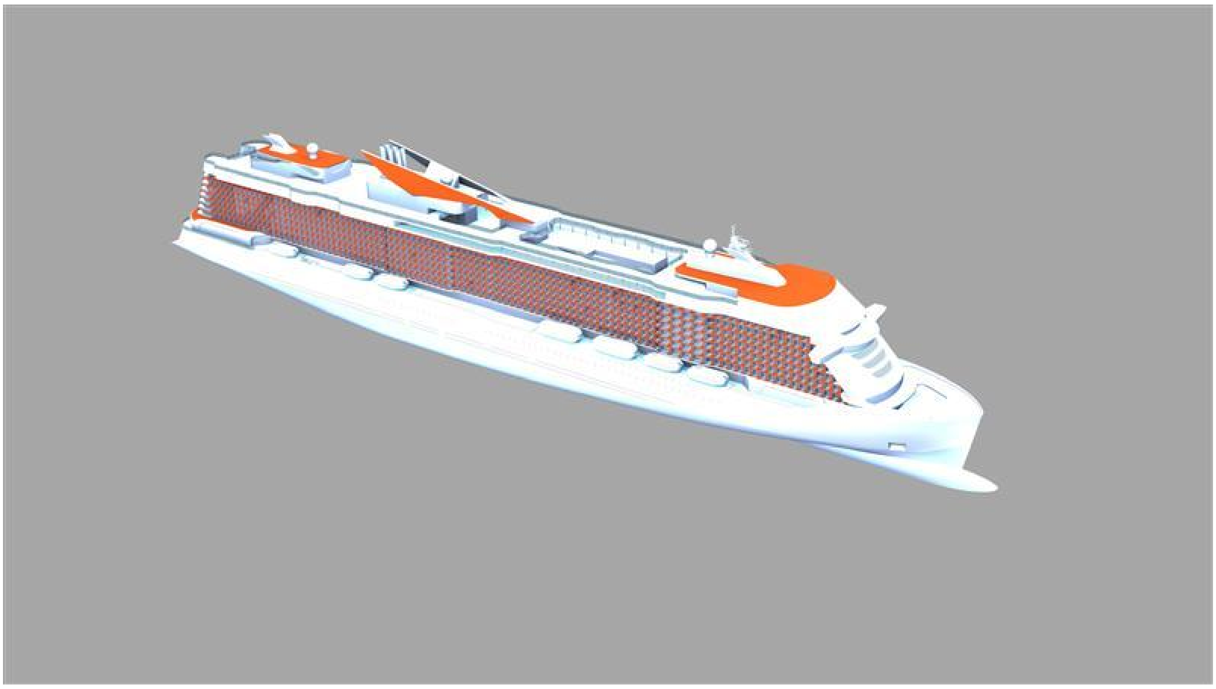

Figure 9 Illustrated picture of AVATAR110 concept ship. The reserved PV panel installation area is painted orange in the ship. In total, there are 5428 $m^2$ worth of installation area for PV panels on AVATAR110. Image courtesy of Meyer Turku.

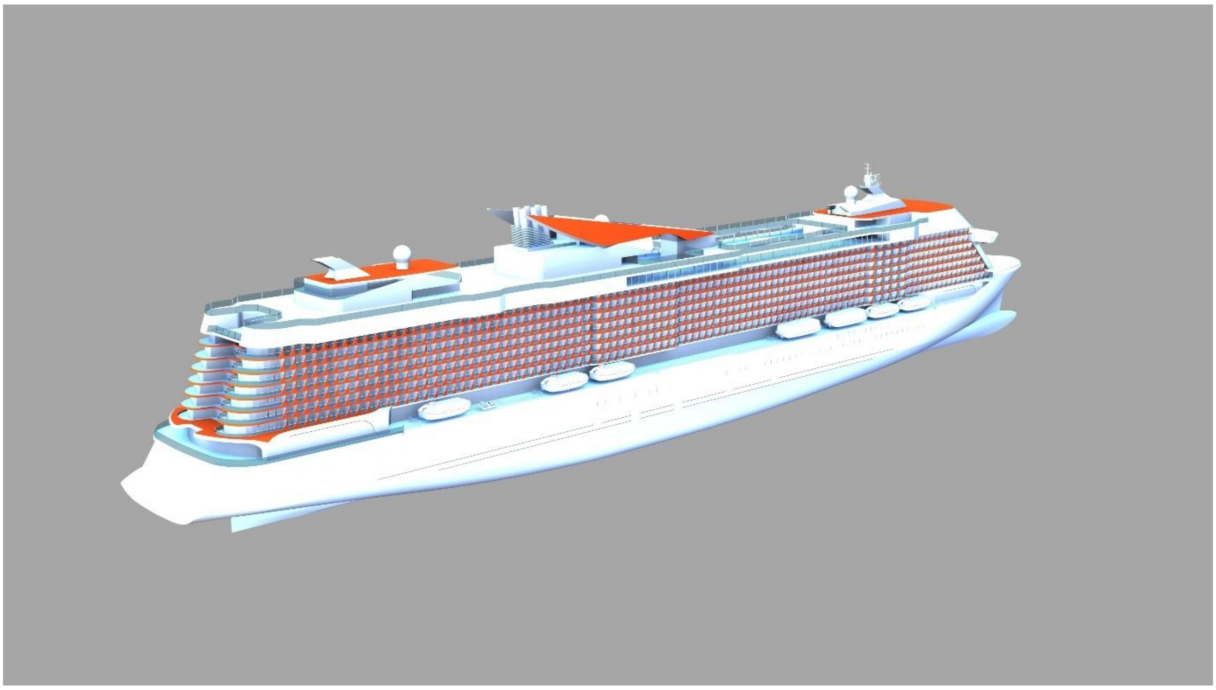

Figure 10 Illustrated picture of AVATAR110 concept ship. The reserved PV panel installation area is painted orange in the ship. In total, there are 5428$m^2$ worth of installation area for PV panels on AVATAR110. Image courtesy of Meyer Turku.

## 5.2 Spatial Integration of PV Systems

The integration of PV systems into a cruise ship requires careful consideration of available space, structural constraints and operational requirements. Horizontal PV installations on sun decks must be designed in a way they would not interfere with passenger experiences and more importantly safety pathways. This imposes limitations on the total usable surface area and may require modular or segmented PV layouts to maintain accessibility and safety. In the case of AVATAR110, every horizontal square meter reserved for PV installations is inaccessible to public.

On the contrary, the vertical PV integration into balcony structures introduces more challenges. These systems must please not only energy production requirements but also architectural, structural and safety requirements. For example, balcony-integrated PV panels must maintain aesthetic qualities and transparency in some cases, ensure passenger safety and withstand mechanical loads such as wind pressure and vibration.

## 5.3 Partial Shading

Partial shading is a significant factor not to neglect when discussing potential system performance reduction factors. Unlike land-based installations, ship-mounted PV systems are subjected to dynamic and complex shading patterns due to the movement of the vessel that might reduce the overall performance ratio of the PV system. Potential additional shading patterns reflected in the PV panels surface can be caused for example by lifeboats and safety equipment, ventilation systems, changing solar angles relative to the ship and other movable structures.

Modern PV panels are equipped with bypass diodes, which mitigate the effects of partial shading by allowing current to bypass shaded sections of the panel. This reduces power losses and prevents the formation of hot sports that could damage the cell [62]. However, despite the presence of bypass diodes, shading still results in reduced overall system efficiency. Therefore, minimizing shading through careful system layout and placement is essential. This may involve optimizing panel positioning, avoiding installation near frequently shaded areas and considering the impact of the ship structures during the design phase.

## 5.4 Safety Considerations

The integration of PV systems into cruise ships introduces additional electrical infrastructure that must comply with strict maritime safety standards. From an electrical safety perspective, key requirements include proper insulation, secure cable routing, grounding and the use of protective devices such as circuit breakers and disconnect switches. A notable characteristic of PV systems is their continuous electricity generation under solar radiation, which necessitates careful planning for safe maintenance and emergency shutdown procedures.

Fire safety considerations are also critical, although PV systems themselves are generally regarded as low-risk energy production method when properly designed and installed. Potential fire hazards may arise from electrical faults, such as short circuits or degraded connections. However, modern PV panels incorporate safety features like the bypass diodes, that mitigate overheating and prevent the formation of hot spots caused by partial shading in the panel [62]. Additionally, compliance with fire safety standards, use of fire-resistant materials and integrations with onboard fire detection and suppression systems further reduce the risk of any fire hazard.

# 6 Prevailing Conditions for PV Applications

The performance profile of PV systems aboard cruise vessels is fundamentally governed by the spatial and temporal distribution of solar irradiation in the chosen global maritime routes [5]. Unlike land-based installations, that are generally constrained by fixed geographic coordinates and static mounting geometries, cruise ships operate as mobile energy platforms capable of navigating through diverse climatic zones and adjusting their orientations relative to the sun. This orientational flexibility offers some unique properties for solar irradiation harvesting: the available solar resource is not merely a function of location, but also route planning, vessel heading and solar panel installation strategies [5]. For example, panels installed on adjustable structures or distributed across multiple deck surfaces may benefit from favorable angles of incidence during different individual legs of the voyage. Even without mechanical tracking systems, the ships own navigational adjustments can incidentally align the panels orientation closer to optimal solar orientation compared with stationary land-based installations. Hence, understanding irradiation conditions in major cruise regions, such as the Caribbean and the Mediterranean, constitutes a critical foundation for evaluating the feasibility, optimization and expected yield of ship-integrated PV technologies.

Global cruise itineraries typically span a wide range of latitudes, encompassing equatorial, tropical, subtropical and temperate regions, each characterized by distinct irradiation profiles. Equatorial and tropical waters offer consistently high annual irradiation levels with minimal seasonal variation, whereas higher latitudes exhibit pronounced seasonal contrasts: extended daylight hours during summer season and reduced solar availability during winter season. These geographic differences directly influence PV output potential and must therefore be analyzed in relation to prevailing cruise routes, voyage durations and seasonal deployment patterns. In practical terms, ships operating in regions such as the Caribbean and Mediterranean encounter substantially greater annual solar resources compared to cruise itineraries in northern or southern high-latitude waters.

Moreover, the mobility of cruise ships enables strategic itinerary selection based on the prioritization of regions with higher solar irradiance when operationally and commercially feasible. What is more, seasonal repositioning of vessels, that is already been done in the cruise industry, could enhance the maximization of renewable energy generation as voyages could be aligned with periods and locations with elevated solar availability. This introduces the possibility of integrating energy considerations into route planning, thereby linking navigation logistics with onboard sustainability objectives.

For these reasons, a comprehensive assessment of irradiation conditions across representative cruise regions is essential. The following section thereby examines the solar characteristics of selected global cruise areas while having particular emphasis on Caribbean, Mediterranean, Baltic Sea and Gulf of Alaska region. The section offers POA related substance necessary to evaluate PV system performance and feasibility and to inform design strategies tailored specifically to solar-assisted cruise ships.

The data illustrating each locations' irradiation values is calculated using PVGIS software [17]. This software is funded by the European Commission, and it provides information on solar radiation and PV system performance for any location in the world except North and South poles. However, the software is equipped with data from land areas only. The irradiation values given in this chapter's tables are only the values to describe the amount irradiation for a chosen orientated plane (1m$^2$) in a chosen location. Each table is color scaled independently and not compared to other tables, thus each table reaches the highest same color green although the quantitative values may differ between the same green cells from different tables. Ultimately, each itinerary's irradiation conditions are represented by one chosen location from each itinerary. The different locations' irradiation conditions vary inside 10% in each itinerary and therefore only one table per itinerary/region is chosen here. All the rest of the tables are added in the appendix.

## 6.1 Caribbean

From Meyer-Turku-Case-study -section, Table 1 illustrates how Caribbean belongs to region A based on the latitudes and yearly irradiation yield. From market point of view, as mentioned also in the same section, this area possesses also high amount of annual cruisegoers. Based on these factors the feasibility of investing in PV technologies in cruise ships operating in this area may be a viable solution.

The yearly POA irradiation was calculated with PVGIS for three different locations based on the RCG's *Star of the Seas* ship's Eastern Caribbean cruise route. This route is illustrated in the Figure 11 below. During this route, the vessel stops at four different locations marked in the map. The total duration of this route is seven days. The measured POA irradiation locations to represent the Caribbean and this cruise itinerary's irradiation feasibility were Coco Cay – Bahamas (RCG's own private island) (Appendix), Turks and Caicos Islands (Close range from the cruise itinerary) (Appendix) and St Thomas Island.

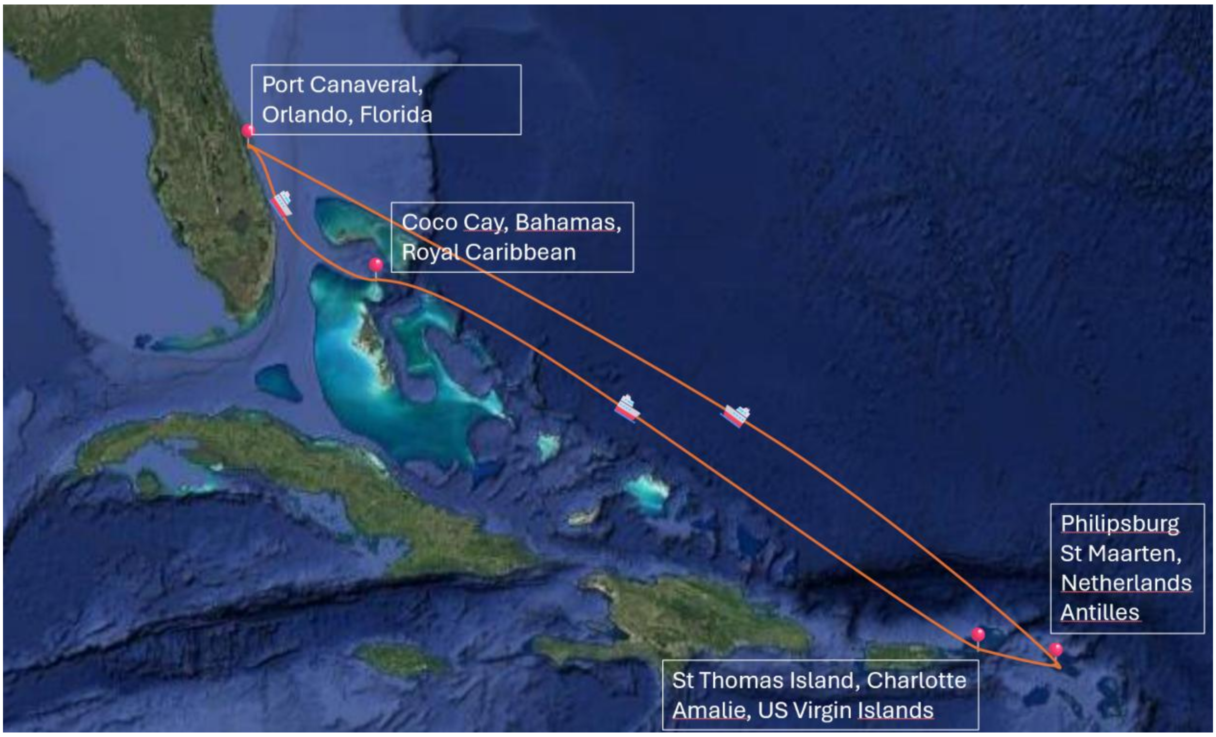

Figure 11 Illustrated picture from the Caribbean where Star of the Seas -cruise ship's Eastern Caribbean cruise route is operated. The duration of this route is seven days and during that the ship stops at four different locations in the Caribbean: Coco Cay (Bahamas), St Thomas Island (US Virgin Islands), Philipsburg (Netherlands Antilles) and Port Canaveral (Orlando, Florida). Image modified from Google Maps [44].

When looking at Table 2, the differences between panel different panel orientation can be seen. The yearly irradiation in St Thomas Island is vastly higher with low panel tilts compared to high vertical tilts. What is more, each table includes an *average* for every tilt angle on the right-hand side of the table calculating the average irradiation from every azimuth angle. By calculating the average irradiation yield across azimuth angles, the value now takes into consideration the vessel's freedom to move and turn. From feasibility and yield perspective, POA irradiation values from St Thomas Island propose the superior advantage of horizontal panel orientation angles compared to more vertical angles. However, these values only consider the absolute amount of irradiation a given one square meter of plane is receiving with different orientation, meaning that it does not take into account the installed peak PV power the whole system has as the quantitative amount of solar produced energy might exceed the horizontal values if the installed PV system chooses to favor more of the vertical installation angles in terms of installed square meters worth of solar panels. Comparing the average column on the right-hand side of every table, most productive irradiation values are reached with absolute horizontal installations when the panel tilt angle is 0° from the ground.

Table 2 The yearly POA irradiation yield per square meter in St Thomas Island [kWh/m2].

| | | St Thomas Island, yearly POA irradiation yield [kWh/m$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | 0 | 315 | 270 | 225 | 180 | 135 | 90 | 45 | |
| | | North | North–West | West | South–West | South | South–East | East | North–East | **Average** |
| Tilt [°] | 0 | 2099.3 | 2099.3 | 2099.3 | 2099.4 | 2099.4 | 2099.4 | 2099.3 | 2099.3 | 2099.3 |
| | 10 | 1979.8 | 2007.3 | 2076.5 | 2143.0 | 2171.6 | 2148.0 | 2083.0 | 2012.3 | 2077.7 |
| | 20 | 1817.0 | 1880.6 | 2023.3 | 2143.8 | 2194.1 | 2151.2 | 2034.9 | 1889.9 | 2016.9 |
| | 30 | 1617.0 | 1729.1 | 1946.1 | 2105.7 | 2166.0 | 2115.4 | 1959.1 | 1740.5 | 1922.4 |
| | 40 | 1389.1 | 1559.2 | 1845.4 | 2022.9 | 2085.9 | 2036.4 | 1861.6 | 1573.6 | 1796.8 |
| | 50 | 1158.3 | 1380.0 | 1720.4 | 1904.6 | 1955.2 | 1916.6 | 1741.3 | 1395.8 | 1646.5 |
| | 60 | 953.3 | 1197.3 | 1576.1 | 1748.1 | 1779.1 | 1763.8 | 1597.3 | 1214.9 | 1478.7 |
| | 70 | 760.2 | 1016.7 | 1415.3 | 1561.5 | 1561.2 | 1578.5 | 1438.1 | 1035.9 | 1295.9 |
| | 80 | 579.8 | 844.9 | 1231.6 | 1351.9 | 1310.3 | 1368.3 | 1264.2 | 863.9 | 1101.9 |
| | 90 | 417.3 | 685.0 | 1055.7 | 1126.3 | 1036.4 | 1144.6 | 1071.2 | 705.5 | 905.2 |

To give more holistic overview of the irradiation conditions in the Caribbean region, the average irradiation yield across azimuth angles was calculated. However, when examining individual azimuth angles, a clear advantage can be spotted for panels facing more South than those facing towards North. As the Caribbean region is in the northern hemisphere, south facing panels contain significant advantage in terms of panel yield because the sun is shining more from South. Vice versa, the same opposite latitudinal regions located in southern hemisphere would possess the same kind of advantage in terms of panel yield for the North facing panels compared to South facing panels. When examining the eastern-Caribbean route that *Star of the Seas* operates, the average azimuth values can be applied as the ship operates this route on a cycle exposing each vertical side towards direct irradiation eventually.

These tables that represent the irradiation conditions in the Caribbean region advocate the purpose of favoring more horizontal panel installations compared to vertical angles. What is more, irradiation conditions remain relatively same during the whole year [17], proposing the year-around feasibility PV installations in this region. As mentioned earlier, the difference in the yearly irradiation received in the different locations of irradiation region A in the Caribbean is less than 10%. Thus, it could be assumed that cruise ships operating in this area with the same panel configuration receive approximately the same amount of irradiation.

## 6.2 Mediterranean

In the Mediterranean a concept route used was from the RCG's *Legend of the Seas* Western-Mediterranean cruise route. The duration of this route is seven days and there are six different locations in the western Mediterranean area where the ship stops. From these five locations, three were used to calculate the prevailing POA irradiation on yearly and daily basis. The three locations calculated were Barcelona, Civitavecchia (Appendix) and Marseille (Appendix). The Western-Mediterranean-cruise route is shown in the Figure 12 below.

When looking at the irradiation conditions in the Mediterranean, some quantitative as well as qualitative differences can be spotted compared to previous tables from the Caribbean. Nonetheless, the average azimuth values favor, yet again, panel installation angles towards horizontal tilt angle. As the Mediterranean is located at higher latitudes compared to Caribbean, the individual azimuth angles that diverge from 0° azimuth, decrease significantly the POA irradiation received.

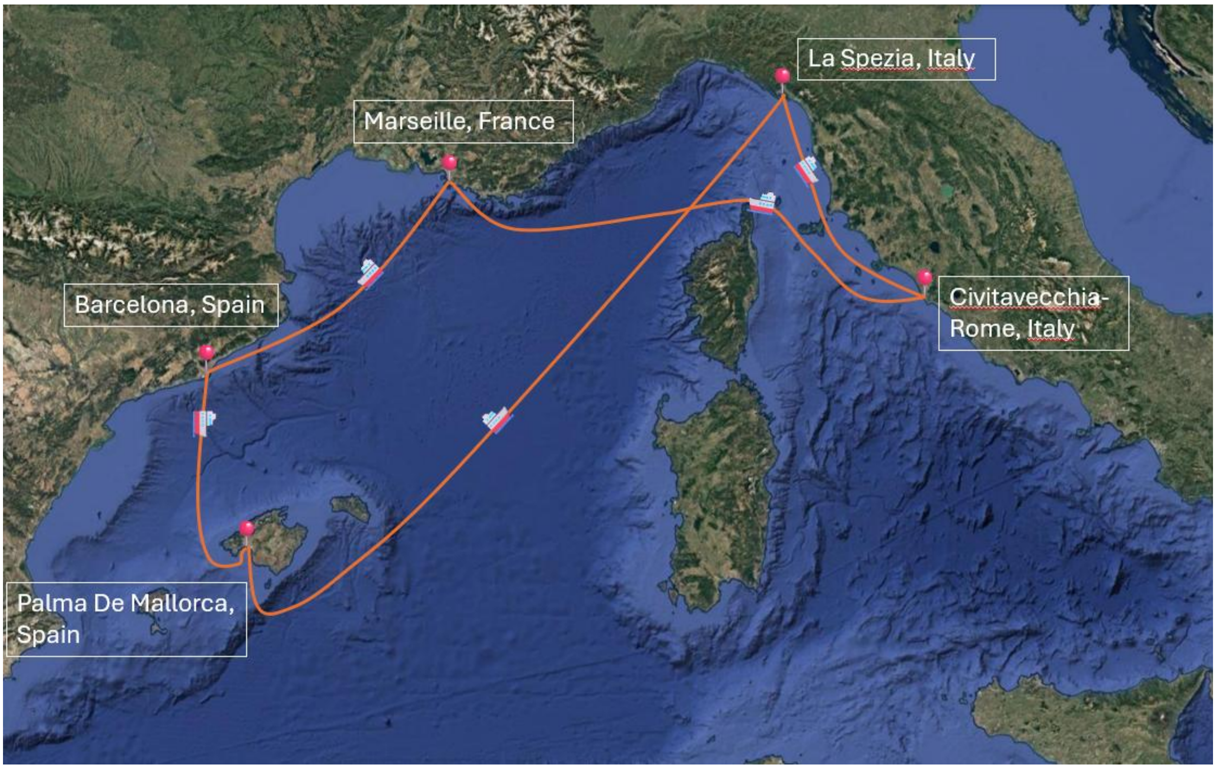

Figure 12 Illustrated picture from the Mediterranean where Legend of the Seas -cruise ship's Western Mediterranean cruise route is operated. The duration of this route is seven days and during that the ship stops at five different locations in the Mediterranean: Barcelona (Spain), Palma De Mallorca (Spain), La Spezia (Italy), Civitavecchia (Italy) and Marseille (France). Image modified from Google Maps [44].

Table 3 The yearly POA irradiation yield per square meter in Barcelona [kWh/m2].

| | | Barcelona, yearly POA irradiation yield [kWh/m$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | 0 | 315 | 270 | 225 | 180 | 135 | 90 | 45 | |
| | | North | North–West | West | South–West | South | South–East | East | North–East | **Average** |
| Tilt [°] | 0 | 1637.3 | 1637.3 | 1637.3 | 1637.3 | 1637.3 | 1637.3 | 1637.3 | 1637.3 | 1637.3 |
| | 10 | 1455.7 | 1499.9 | 1614.8 | 1730.6 | 1783.4 | 1741.7 | 1628.2 | 1509.5 | 1620.5 |
| | 20 | 1246.9 | 1346.6 | 1574.2 | 1791.5 | 1888.5 | 1808.2 | 1592.7 | 1358.2 | 1575.9 |
| | 30 | 1050.3 | 1191.4 | 1519.2 | 1818.4 | 1949.4 | 1839.5 | 1544.1 | 1205.8 | 1514.8 |
| | 40 | 872.9 | 1044.9 | 1451.0 | 1805.6 | 1962.8 | 1835.1 | 1480.9 | 1062.8 | 1439.5 |
| | 50 | 706.0 | 909.7 | 1365.6 | 1757.9 | 1926.9 | 1788.4 | 1403.2 | 932.4 | 1348.8 |
| | 60 | 551.7 | 786.7 | 1265.0 | 1667.2 | 1843.0 | 1705.8 | 1308.0 | 812.7 | 1242.5 |
| | 70 | 416.5 | 673.0 | 1145.7 | 1546.8 | 1714.3 | 1585.2 | 1194.5 | 702.4 | 1122.3 |
| | 80 | 323.5 | 568.5 | 1017.9 | 1390.0 | 1544.3 | 1432.7 | 1064.8 | 600.0 | 992.7 |
| | 90 | 265.2 | 472.9 | 874.6 | 1207.6 | 1335.3 | 1251.8 | 933.1 | 505.5 | 855.8 |

The yearly POA irradiation in Barcelona is to be considered relatively good. The average yearly irradiation in Barcelona is 1330 kWh/m$^2$ that is based on the mean value of the average values from the right-hand side of the Table 3 given above. In general, the favorable installations angles can be seen in this table. When examining the individual azimuth and tilt combinations, peak values are between the tilt angles of 20° and 60° for azimuth angles towards South. However, when looking at the average values calculated from different azimuth angles, the most productive option is suggested to be at 0° tilt angle. What is more, based on the absolute values given in Table 3, vertical tilt angles are more vulnerable for different azimuth changes whereas horizontal tilt angles are more immune to azimuth angle changes.

When considering the different irradiation regions of Caribbean and Mediterranean, the average irradiation yield difference is approximately 20% between these regions. However, the individual irradiation results from different tilt and azimuth combinations between these regions might vary greatly as the yearly POA irradiation yield with 40° tilt and 0° azimuth angle is only ~6% more in St Thomas Island compared to Barcelona while at the same time the difference is greater than 55% with 90° tilt and 180° azimuth between the two regions. What also to keep in mind, there are individual tilt and azimuth combination where the received POA irradiation is greater in Barcelona compared to Caribbean locations.

However, there are rough generalizations behind these assumptions, one being the neglection of seasonal variation. As all the tables are calculated from cumulative yearly POA irradiation, the average monthly yield is not featured meaning that the reduced irradiation in winter season is not shown in this data chart explicitly, but rather it is summed up to the annual yield. If these tables are utilized in monthly POA irradiation analysis, the data could be incorrect.

## 6.3 Baltic Sea

For the Baltic Sea, three different locations used were: Mariehamn, Turku (Appendix) and Travemunde (Appendix). By looking at the yearly POA irradiation tables of these locations in the Baltic Sea, the similarity of the quantitative and qualitative irradiation is observable. Additionally, based on the values given in the yearly irradiation tables of these locations from the Baltic Sea, the values support the assertion of these locations belonging in region C, in terms of latitudinal POA irradiation yield.

As the Baltic Sea is located on even higher latitude levels than the Mediterranean and the Caribbean, individual panel orientations start to favor even more of those of vertical tilt angles. However, in the case of Baltic Sea, the most profitable individual installation angle is still the same as in the Mediterranean: 40° tilt and 0° azimuth. The difference in the Baltic Sea compared to the Mediterranean is that the percentual decrease in received POA irradiation accelerates slower when moving away from the most profitable tilt angle towards more vertical angels. What is more, the total percentual decrease in Mediterranean is bigger when examining the change from 40° tilt angle to total vertical tilt angle of 90°. In the Mediterranean the decrease is roughly -31% whereas in the Baltic Sea the decrease from the most optimal tilt angle to 90° tilt is -24%. What is important to keep in mind is that the cumulative amount of received irradiation is approximately the same in the case of 90° worst tilt in the Mediterranean and 40° best tilt in the Baltic Sea when the azimuth angle is 180° South. This information related to the irradiation condition at the Baltic Sea can be seen from the Table 4 below.

Table 4 The yearly POA irradiation yield per square meter in Mariehamn [kWh/m2].

| | | Mariehamn, yearly POA irradiation yield [kWh/m$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | 0 | 315 | 270 | 225 | 180 | 135 | 90 | 45 | |
| | | North | North–West | West | South–West | South | South–East | East | North–East | **Average** |
| Tilt [°] | 0 | 1078.1 | 1078.1 | 1078.1 | 1078.1 | 1078.1 | 1078.1 | 1078.1 | 1078.1 | 1078.1 |
| | 10 | 945.5 | 983.5 | 1073.8 | 1160.4 | 1193.4 | 1156.5 | 1068.3 | 979.6 | 1070.1 |
| | 20 | 809.0 | 884.8 | 1064.8 | 1226.1 | 1285.0 | 1218.6 | 1053.8 | 877.3 | 1052.4 |
| | 30 | 676.4 | 790.7 | 1052.6 | 1271.4 | 1349.0 | 1261.1 | 1038.9 | 780.7 | 1027.6 |
| | 40 | 554.9 | 713.8 | 1032.8 | 1292.7 | 1382.3 | 1279.4 | 1016.9 | 703.1 | 997.0 |
| | 50 | 452.4 | 650.8 | 1001.2 | 1285.8 | 1382.0 | 1270.6 | 983.8 | 640.4 | 958.3 |
| | 60 | 386.1 | 592.4 | 955.0 | 1252.2 | 1348.8 | 1234.8 | 936.3 | 582.8 | 911.1 |
| | 70 | 337.6 | 534.6 | 892.2 | 1187.0 | 1282.4 | 1173.4 | 875.8 | 526.1 | 851.1 |
| | 80 | 293.8 | 476.6 | 819.5 | 1100.2 | 1186.1 | 1081.9 | 800.4 | 468.2 | 778.3 |
| | 90 | 253.7 | 417.3 | 727.3 | 987.0 | 1060.5 | 972.8 | 717.2 | 409.9 | 693.2 |

## 6.4 Alaska / Exploration

In the case of remote Alaska location, the measuring point was chosen to be the Gulf of Alaska from a coastal town of Seward. From latitudinal perspective, even though the location belongs to region C the irradiation values are mostly below the region standard interval of 800–1200kWh/m$^2$/year. Nevertheless, based on the Table 5 below, the high latitudinal values for this location propose the importance of tilted panels compared to horizontal panels. In addition to Table 5, a table representing the yearly POA irradiation per square meter in Kenai – Alaska is added in the appendix. The most favorable tilt angle remains roughly in the 40° angle, although in certain azimuth combinations, extreme 90° tilt angles may come close and or even surpass the average values achieved in with more optimal angles.

Table 5 The yearly POA irradiation yield per square meter in Gulf of Alaska [kWh/m2].

| | | Gulf of Alaska (Seward – Alaska), yearly POA irradiation yield [kWh/m$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | 0 | 315 | 270 | 225 | 180 | 135 | 90 | 45 | |
| | | North | North–West | West | South–West | South | South–East | East | North–East | **Average** |
| Tilt [°] | 0 | 752.8 | 752.8 | 752.8 | 752.8 | 752.8 | 752.8 | 752.8 | 752.8 | 752.8 |
| | 10 | 659.2 | 661.4 | 712.9 | 784.5 | 833.6 | 831.4 | 778.6 | 706.1 | 746.0 |
| | 20 | 563.3 | 571.4 | 671.5 | 805.0 | 896.8 | 891.9 | 787.9 | 647.8 | 729.4 |
| | 30 | 470.9 | 489.0 | 631.6 | 813.0 | 940.1 | 932.2 | 781.7 | 584.3 | 705.4 |
| | 40 | 387.7 | 421.9 | 591.1 | 806.7 | 961.9 | 950.9 | 766.9 | 527.9 | 676.9 |
| | 50 | 317.6 | 367.7 | 547.3 | 786.0 | 962.0 | 949.8 | 742.1 | 480.2 | 644.1 |
| | 60 | 267.8 | 319.8 | 499.4 | 749.0 | 939.5 | 926.8 | 706.5 | 435.1 | 605.5 |
| | 70 | 231.2 | 275.0 | 447.1 | 697.6 | 894.7 | 883.9 | 660.1 | 390.1 | 559.9 |
| | 80 | 197.8 | 233.1 | 390.2 | 635.1 | 828.2 | 822.9 | 601.2 | 344.5 | 506.6 |
| | 90 | 170.5 | 195.7 | 334.1 | 557.8 | 744.1 | 741.1 | 538.8 | 300.5 | 447.8 |

# 7 Effects and Requirements on Ship Design

This chapter focuses on the aftermath when considering PV technology installations to a cruise ship. Several key performance indicators have been brought up for consideration regarding their function in ship design. Important factors include weight assessment, mass-power-relation from solar panels, requirements for the electrical integration, spatial requirements and visual and architectural considerations. As this thesis uses AVATAR110 as a reference ship, both horizontal PV panels and vertically integrated PV panels are taken into consideration when creating a holistic review for the effects and requirements on ship design. While the previous chapters POA irradiation tables propose a significantly higher energy output from the horizontal installation angles in the major cruise regions such as Caribbean and Mediterranean, vertical installations remain relevant from a design perspective due to their potential integration into existing ship structures and large available surface area in addition to their function to decrease the ships emission even more.

## 7.1 Impact of PV Technology on Ship Weight

The installation of additional PV systems inevitably increases the total mass of the vessel. In addition to the actual PV panels, the system consists of supporting structures from the mounting the panels, cabling, power electronics and protective components such as additional membranes in the panel surface. In general, solar panels weight-surface-ratio ranges between 20–25 kg/m$^2$ depending on the technology used and mounting solutions in the total system. [63]

For a large cruise ship, as in the case of AVATAR110, the available installation area can reach several thousand square meters when considering both horizontal and vertical surfaces in the ship. Consequently, the cumulative mass of the whole PV system installation could reach tens or even hundreds of tons depending on the selected coverage area. For AVATAR110, the weight of the installed PV system is around 122 000kg. This value is calculated using average weight-surface-ratio of 22.5kg/m$^2$ for the chosen PV technology and total of 5428 m$^2$ of potential surface area for PV installations [63]. In the context of AVATAR110 and modern cruise ships the additional weight remains relatively small. Continuous weight reduction initiatives throughout the whole vessel are carried out to support decarbonization. Example of this is alternative fuels that are heavier and have lower energy density. Distribution of additional mass must be considered carefully to identify effects on the vessel’s center of gravity and overall stability characteristics. In the context of PV installations, the weight addition is relatively small and evenly distributed in the ship.

Horizontal installations on sun deck areas typically add weight primarily to the highest deck structures. For vertical installations, mass is distributed more evenly along the vessel’s sides across many deck levels. This well distributed arraignment of mass may reduce localized structural loads but increase the overall structural integration requirements for vertical surfaces of vessels.

## 7.2 Mass Increase in Relation to Energy Output

A key consideration is the relationship between the additional mass introduced by the PV system and the electrical power generated from the installed system. From a naval architecture perspective, any added mass must be justified by the operational or environmental benefits it provides. Thus, it is important to establish the profitability factor for the installed PV system.

Based on the POA irradiation tables given in Section 6, horizontally oriented PV installations generally achieve significantly higher annual energy yield compared to vertical installations. This is largely due to the invulnerability of horizontal installations related to azimuth angles. Horizontal surfaces are oriented more favorable relative to the sun throughout the day across different latitudes in typical cruise regions [3]. As a result, the power output per kilogram of installed PV system mass is substantially higher for horizontal systems.

In the case of vertical installations on the sides of the cruise ship, they can experience reduced solar irradiation due to narrower optimal azimuth angles. In addition, depending on the location the ship is operating, shading effects from the ship's own superstructure might reduce even more the received solar irradiation. All this been said, on average the energy yield per unit mass of vertical solar panel installations is considerably lower compared to horizontal solar panels. However, in terms of numbers, vertical surfaces offer great amount of potential installation area in a cruise ship. In the case of AVATAR110 concept ship, there is approximately 30% more vertical surface area to install solar panels compared to horizontal surface area. Even with lower efficiency per square meter, the cumulative installed capacity is still competitive with horizontal surfaces.

Therefore, when evaluating PV integration in cruise ship design, it is important to balance the additional mass of the system with the expected electrical production over the vessel's operational profile. While having a more profitable energy output per kilogram of installed PV system with horizontal PV panels on average, the sheer amount of cumulative energy production for vertical surfaces might still be worth the installation, despite the significantly lower energy output per kilogram of installed PV system. The economic feasibility of vertical installations relies on the available surface area and more importantly the vessel's operating region.

## 7.3 Visual and Architectural Considerations

The visual appearance of a cruise ship is also an important design aspect, as cruise vessels are designed not only for technical performance but also for passenger appeal and brand identity. The PV technology integration must therefore be considered from an architectural and visual perspective as well. Hence, they need to make sense both ways in order to justify the installation of the PV system onboard.

Horizontal PV installations on sun deck areas and especially on rooftop structures have less visual impact since they are inaccessible to the passengers onboard and are left largely invisible. One key parameter left for open interpretation is the PV panels' potential effect of enhancing the public's view towards the ship's modern and environmentally conscious image. As the horizontal PV panels are not visible to passengers onboard, they still enhance the environmental image of the ship.

Vertical PV installations on the sides of the cruise ship, more specifically on the balcony railings, have more impact on the visual appearance since they are seen by the passengers onboard and offboard. Depending on which PV technology is used, it is possible to alter the visual characteristics of these PV integrated balcony structures by altering the transparency or the color [64] of the PV panels for example. By altering, especially the actual color of the PV panels, the cruise line is capable to reaching its own desired signature public facade colors.

From a branding perspective, visible and large PV installations may also communicate environmental responsibility and sustainability to passengers and stakeholders. As cruise operators increasingly emphasize environmental performance, visible renewable energy technologies may become a relevant part of ships, and therefore the shipping companies, identity. By messaging big visual environmental investments to the public, individual cruise operators may gain an advantage in the competition.

# 8 Economic Assessment and Product Lifetime

The economic feasibility of integrating PV systems into cruise ships is an important consideration when evaluating their practical implementation. While solar power is expected to contribute only a portion of the total onboard energy demand, having it onboard may reduce fuel consumption, operational costs and environmental impact over the vessel's operational lifetime. This section evaluates economic aspects and product lifetime considerations associated with PV installations onboard large cruise ships.

For the economical assessment, AVATAR110 has been used in terms of potential dimensions and surface areas where to install PV panels. What is more, Ralos RLS-525 solar panel with 22.1% efficiency rate has been used for calculating potential energy production for AVATAR110 in the Caribbean, Mediterranean, Baltic Sea and Gulf of Alaska. Nevertheless, values given in this chapter are highly optimistic and do not consider various environmental factors that affect the solar panel energy production rate. Few important factors that affect the overall energy yield from the PV system are shading effect, negative thermal coefficient, precise azimuth variations and inverter and cabling losses. These aspects mentioned here and several other aspects affect the total energy yield of the PV system individually and case-by-case depending for example on the location of the PV system. To form an optimistic estimate, relatively the most optimistic scenario is presented here where the energy yield is calculated only with efficiency factor of the given panel type and AVATAR110 surface areas reserved for solar panel installations as well as the fixed installation angles of those surface areas. The equation used to calculate the following energy production values for AVATAR110 is given below:

$$E = POA_{Tilt\&Azimuth} \cdot A \cdot \eta_{panel} \cdot \eta_{reduction\ rate} \tag{8}$$

Where $POA_{Tilt\&Azimuth}$ stands for the yearly POA irradiation in a given location, $A$ the chosen oriented surface area reserved for PV panel installations on AVATAR110, $\eta_{panel}$ the efficiency rate of the Ralos RLS-525 solar panel and $\eta_{reduction\ rate}$ the general reduction rate PVGIS uses.

## 8.1 Energy Produced with the PV System

To address the actual economical values of the PV system, it is necessary first to discuss the amount of energy the system can produce. As mentioned above, the energy data expressed here is calculated with highly optimistic scenarios and doesn't take into consideration specific internal losses every individual system possesses. To take the internal losses into account, -14% reduction rate has been used for the optimistic values given in the Section 6 tables. Validity for the -14% reduction rate comes from PVGIS, as it uses the same reduction rate as a default value [17]. However, this is a generalized reduction percentage and the actual reduced amount of produced energy from the PV system is depended on various factors such as, cabling, the used PV technology, dirt on the panel surface, geological location the system is located, PV system temperature etc. What is more, the energy yield expressed in the following tables in this chapter represents the average energy output from AVATAR110 PV system when it operates in the Caribbean, Mediterranean, Baltic Sea and Gulf of Alaska regions. As mentioned before, the POA irradiation difference is less than +/- 10% in each region's different locations, thus only one table per region represents the theoretical energy production for AVATAR110 concept ship. What is more, in the following energy yield tables, 30° and 90° tilt angle values have been calculated with half amount of vertical solar panel area. This is due to reason the other half of the vertical solar panel area is on the other side of the ship and therefore always facing the opposite direction. All four azimuth pairs have been grouped in the tables making it easier to understand the opposite directions.

Table 6. The yearly energy production from AVATAR110 in Caribbean irradiation region [MWh].

| | | Caribbean (St Thomas Island), yearly energy production from AVATAR110 PV system [MWh] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | N&S | | NE&SW | | E&W | | SE&NW | | |
| | | 0 and 180 | | 45 and 225 | | 90 and 270 | | 135 and 315 | | **Grouped average** |
| Tilt [°] | 0 | 733.36 | | 733.36 | | 733.36 | | 733.36 | | 733.36 |
| | 30 | 77.445 | 103.74 | 82.815 | 100.85 | 93.83 | 93.21 | 101.32 | 82.815 | 184.14 |
| | 90 | 122.365 | 303.93 | 206.91 | 330.31 | 314.14 | 309.59 | 335.675 | 200.89 | 530.95 |

Table 6 above represents the annual average energy production for AVATAR110 in the Caribbean. As the ship is equipped with total of 5428 m$^2$ of monocrystalline silicon solar panels, the yearly combined average is well over 1.3 GWh of produced electricity, nearly reaching 1.5 GWh. Judging from this, the average daily production is roughly 3.97 MWh. The average daily energy consumption for AVATAR110 in the Caribbean is expected to be approximately 390 MWh [65]. The daily compensated energy coverage from the PV system ranges approximately between 1-3 %, according to operational conditions. From the 5428 m$^2$ of solar panels, 57% are vertically installed solar panels (3086 m$^2$), 34% are horizontal solar panels (1838 m$^2$) and the rest 9% are with a 30° tilt installed solar panels (504 m$^2$). As seen in the following tables, vertical solar panels produce roughly 37% of the total amount of average electricity produced by the PV system.

Furthermore, as the main energy source for AVATAR110 is bio methanol, the current calculated average price in the Caribbean with 390 110 kWh daily energy consumption for this fuel type is 40 snt/kWh [66]. If the supplementary PV system is capable of compensating 3.97 MWh/day worth of energy for the main power generation, daily fuel savings are on average 1.8m$^3$ worth of bio methanol which estimates roughly 1600 € and 580 000 € on a daily and yearly basis, respectively. The previous values were calculated using the following intermediate values: in the case of AVATAR110 the specific fuel oil consumption of a marine engine operating on methanol (SFOC MeOH) 362g/kWh, density of bio methanol 792kg/m$^3$ and the average global price of bio methanol 1100€/t [66].

Table 7 The yearly energy production from AVATAR110 in Mediterranean irradiation region [MWh].

| | | Mediterranean (Barcelona), yearly energy production from AVATAR110 PV system [MWh] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | N&S | | NE&SW | | E&W | | SE&NW | | |
| | | 0 and 180 | | 45 and 225 | | 90 and 270 | | 135 and 315 | | **Grouped average** |
| Tilt [°] | 0 | 571.96 | | 571.97 | | 571.97 | | 571.97 | | 571.97 |
| | 30 | 50.305 | 73.955 | 57.065 | 87.095 | 88.1 | 57.755 | 72.76 | 93.365 | 145.10 |
| | 90 | 77.785 | 273.65 | 138.685 | 354.14 | 367.095 | 148.24 | 256.5 | 391.59 | 501.92 |

For Barcelona, and the whole Mediterranean, the average yearly energy production is approximately 1.2 GWh. As the value is based on the average energy production on the right-hand side of the Table 7 above, the value can still fluctuate highly if the annual prevailing conditions in the Mediterranean change. In the Mediterranean, the average daily energy consumption for AVATAR110 is expected to be approximately 222.58 MWh with propulsion and 121.53 MWh without propulsion. Thus, the daily compensated energy coverage from the PV system is roughly 1.5% and 2.7%, respectively. In the case of Mediterranean, the same amount of vertical solar panels are now responsible for 41% of the total amount of average energy produced by the PV system. This increase suggests the importance of vertical solar panels onboard.

As the fuel price of bio methanol for AVATAR110 is not affected by the operational routes of the ship, the rough estimate of 40snt/kWh can be applied to every operational region the ship is operating. Furthermore, the average yearly and daily energy productions for AVATAR110 in the Mediterranean are expected to be 1.218 GWh and 3340 kWh, respectively. This proposes the daily fuel savings of bio methanol to be roughly 1.5m$^3$ in volume which equals 1330 € in price. On a yearly basis the saved amount of bio methanol in the Mediterranean accumulates to 485 000 €.

Table 8 The yearly energy production from AVATAR110 in Baltic Sea irradiation region [MWh].

| | | Baltic Sea (Mariehamn), yearly energy production from AVATAR110 PV system [MWh] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | N&S | | NE&SW | | E&W | | SE&NW | | |
| | | 0 and 180 | | 45 and 225 | | 90 and 270 | | 135 and 315 | | **Grouped average** |
| Tilt [°] | 0 | 376.61 | | 376.61 | | 376.61 | | 376.61 | | 376.61 |
| | 30 | 32.395 | 64.61 | 37.39 | 60.895 | 49.755 | 50.41 | 60.405 | 37.875 | 98.43 |
| | 90 | 74.41 | 311 | 120.195 | 289.46 | 210.33 | 213.28 | 285.275 | 122.39 | 406.59 |

For the Baltic Sea, the average yearly energy production is approximately 880 MWh. This value is based on from the Table 8 above which represents the annual average produced energy with AVATAR110 PV system in Mariehamn. As the average value is a rough estimate, it can still fluctuate based on the prevailing weather conditions in the Baltic Sea. In the Baltic Sea, the importance of vertical solar panels is even greater. In the case of Baltic Sea, of the total amount of energy produced, 46% comes from vertical solar panels. This proposes the feasibility for vertical solar panels as the output increases when the system is operating at even higher latitudes.

Table 9 The yearly energy production from AVATAR110 in Gulf of Alaska irradiation region [MWh].

| | | Gulf of Alaska (Seward – Alaska), yearly energy production from AVATAR110 PV system [MWh] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | N&S | | NE&SW | | E&W | | SE&NW | | |
| | | 0 and 180 | | 45 and 225 | | 90 and 270 | | 135 and 315 | | **Grouped average** |
| Tilt [°] | 0 | 262.98 | | 262.98 | | 262.98 | | 262.98 | | 262.98 |
| | 30 | 22.55 | 45.03 | 27.985 | 38.94 | 37.44 | 30.255 | 44.645 | 23.42 | 67.57 |
| | 90 | 49.99 | 218.215 | 88.13 | 163.575 | 158.005 | 97.99 | 217.33 | 57.39 | 262.66 |

In the case of extreme regions such as Alaska, the annual average energy produced with AVATAR110 PV system is roughly 590 MWh. The values are expressed in the Table 9 above. In these very high latitudes, the presence of vertical solar panels is equally important as horizontal solar panels. Roughly 44% of the total energy produced by the PV system comes from vertical solar panels. In the case of AVATAR110 and its designed surface areas reserved for solar panel installation, the relevance of vertical solar panels increases as the ship moves on higher latitudes, proposing even greater feasibility for vertical solar panels. It goes the same way for other directions, as the feasibility of horizontal solar panels increases when moving towards lower latitudes closer to the equator.

Table 10 All the different irradiation regions summarized in the case of AVATAR110 yearly average energy production.

| Region | Yearly average energy production from AVATAR110 PV system [MWh] |
|---|---|
| Caribbean | 1448.45 |
| Mediterranean | 1218.99 |
| Baltic Sea | 881.63 |
| Gulf of Alaska | 593.21 |

In the Table 10 above, the yearly average energy production with AVATAR110 for all four different regions are summed up. In general, the latitudinal importance can easily be seen as the energy output increases significantly when moving toward smaller latitudes closer to the equator.

## 8.2 Capital and Installation Costs

The implementation of PV systems onboard a cruise ship requires an initial capital investment which includes the cost of PV panels, mounting structures, power electronics and system integration with the ship's electrical grid. What is more, some additional costs may arise from structural adaptations needed to install solar panels on the vessel. In the context of the AVATAR110 ship, there are two primary installation configurations analyzed: horizontal PV installations located largely on sun deck areas and vertical PV installations integrated into balcony structures such as railings along both sides of the ship. What is more, as the 30° tilt angle installations in the ship represent significantly smaller portion of produced PV energy, hence they are bundled up together with horizontal installations in this particular review.

When taking an example from land-based rooftop-installations, horizontal installations typically require mounting structures that allow secure attachment to deck surfaces while minimizing interference with passenger areas and ship operations. In contrast, vertical balcony installations involve integration of PV panels into architectural elements such as balcony railing in this case. Even so, such integration provides large total installation area due to high number of balcony cabins on the ship. One downside of the vertical installations is that their energy production is highly dependent on the ship orientation relative to the sun.

Furthermore, installation costs may vary for both, horizontal and vertical, installations depending on whether the PV system is integrated into the ship during the construction phase or retrofitted later in the ship's lifetime. Integration during ship construction is generally expected to reduce installation complexity and associated costs. This been said, the installation costs especially for vertically integrated PV panels may reduce significantly if done during the construction phase compared to retrofitting afterwards the ship is constructed.

## 8.3 Fuel Cost reduction

One key performance indicator from economic aspects of the PV systems onboard cruise ships is the reduction of total fuel consumption of the vessel. In the case of cruise ship concepts that utilize alternative fuels such as bio methanol for energy production, solar energy can partially compensate for the energy that would otherwise be generated by the ship's main engines. The electricity produced by the PV systems reduces the load on the ship's generators, leading to decreased fuel consumption and lower operational costs. Over the operational lifetime of the vessel, these savings may accumulate to a significant amount of money depending on the installed PV capacity and operational conditions.

The magnitude of fuel cost savings is strongly influenced by several factors including solar irradiation levels in cruise regions, system efficiency, operational patterns of the vessel and future price development of bio methanol fuel. Given that future fuel prices remain uncertain, economic evaluations often rely on scenario-based analyses.

## 8.4 Maintenance and Operational Costs

Although PV systems generally have relatively low operational costs compared to conventional power generation technologies, maintenance requirements must still be considered in maritime environments. The marine environment presents several challenges for PV installations, including salt accumulation, high humidity, additional wind loads and potential mechanical stresses caused by ship motion. Maintenance activities may include occasional cleaning of PV panels to remove salt deposits and other contaminants that reduce the system's efficiency. Additionally, routine inspections are necessary to ensure electrical connections and mounting structures remain in proper condition.

Certain system components, particularly power electronics such as inverters and converters, may require replacement during the lifetime of the ship. These replacement cycles should be incorporated into long-term economic analysis. PV manufacturers may also provide maintenance agreements or service contracts that cover periodic inspections, performance monitoring and component replacements. Such agreements may help to reduce operational risks and provide predictable maintenance costs estimations over the system lifetime.

## 8.5 Product Lifetime Considerations

The economic viability of PV installations onboard cruise ships must also consider the expected operational lifetime of both the ship and the PV system. Modern cruise ships are typically designed for operational lifetimes of approximately 25–30 years [8]. PV panels, depending on the technology used, often have performance warranties extending up to 25 years with gradual efficiency degradation over time [46, 67].

Typical PV panel degradation rates are approximately 0.3–0.7% per year [46, 67]. This gradual reduction in performance must be considered when estimating total energy production over the vessel's lifetime. Power electronics components such as inverters typically have shorter lifetimes and may require replacement during the ship's operational life. Ensuring that PV system components are designed to withstand the harsh marine environment is essential for achieving the expected operational lifetime and maintaining system reliability.

## 8.6 Comparison of Installation Configurations

As discussed in previous chapters, two primary PV installations configurations have been considered: horizontal installations on sun deck areas and vertical installations integrated into balcony railings. Horizontal installations generally provide higher energy production due to more favorable orientation relative to solar radiation, particularly lower latitude cruise regions such as the Caribbean and Mediterranean. Vertical installations may offer significantly larger potential installation areas but are more vulnerable to azimuth angle changes and shading effects.

Despite the lower expected energy production from vertical installations, their inclusion in the economic assessment remains important due to the large number of balconies presented in the modern-day cruise ships. In certain operational scenarios, even modest electricity generation from vertical installations could contribute significantly to the overall energy savings.

## 8.7 Uncertainty and Future Developments

Economic assessment of PV integration in cruise ships must account for several uncertainties, including future fuel price developments, interest rates and technological advancements in PV related technology systems. The future price trajectory of bio methanol fuel remains uncertain and may significantly influence the economic competitiveness of solar energy onboard cruise ships. Similarly, continued reductions in PV panel costs [11] and improvements in efficiency may further enhance the economic viability of solar installations in maritime applications. For these reasons, economic analyses should ideally consider multiple scenarios to capture a range of possible future conditions.

# 9 Discussion

The results indicate that the horizontal PV installations are, in general, more efficient in terms of annual energy production per unit area. This is primarily due to their more favorable orientation relative to solar irradiation, as horizontal panels are less sensitive to azimuth angle variations compared to vertical installations. In contrast, vertical PV systems exhibit significantly lower energy yields per unit area, particularly in lower latitude regions where solar radiation angles favor more of horizontal surfaces.

However, when considering the total available installation area, vertical PV system presents an important contribution. In the case of AVATAR110, and in general in large cruise ships, the available vertical surface area is substantially greater compared to horizontally free installation area. For AVATAR110, approximately 67% more surface area is in vertical surfaces compared to the horizontal surfaces. As a result, despite the lower energy yield per unit area, vertical installations can contribute a comparable share of total energy production under certain conditions. The importance of vertical installations becomes particularly noticeable in higher latitude regions such as Baltic Sea, where the difference in energy output between horizontal and vertical installations decreases significantly, in the case of AVATAR110.

## 9.1 Economic Viability and LCOE Considerations

From economic perspective, between horizontal and vertical installations, horizontal PV installations appear to be more favorable. Their installation typically relies on conventional mounting solutions, which are more widely used and relatively more cost-efficient when compared to integrated vertical solutions. Adding to this, vertical PV systems integrated into balcony structures or ships facades in general are likely to require custom and tailored design solutions, increasing both capital and installation costs making them more adverse option compared to horizontal PV systems.

Due to lack of reliable cost data for such custom-integrated PV systems, especially in the maritime context, an accurate and precise calculation of the LCOE for vertical installations remains challenging. This limitation restricts the ability to perform a fully quantitative economic comparison between horizontal and vertical PV systems.

Nevertheless, a qualitative assessment suggests that horizontal PV systems are likely to achieve lower LCOE values due to following key performance indicators: lower installation complexity and therefore lower expenses, reduced structural integration requirements and higher annual energy yield per unit area on average. Despite this, vertical PV systems should not be neglected. Even with potentially higher LCOE values, they contribute additional renewable energy generation, reduce fuel consumption and support overall decarbonization efforts and targets. Thus, their values may extend beyond purely economic analysis, particularly the context of increasingly tightening environmental regulations on marine environments.

## 9.2 Influence on Geographic Location

The results clearly demonstrate that geographic location plays a significant role in determining the effectiveness of different PV installation strategies. In lower latitude regions closer to the equator, such as Caribbean and Mediterranean, horizontal PV installations significantly outperform vertical systems due to higher solar elevation angles. Under these conditions, vertical panels receive less direct irradiation, leading to reduced energy production.

As latitudes increase, the relative performance of vertical PV systems improves. In regions such as Baltic Sea, the difference in solar incidence angles between horizontal and vertical surfaces decreases, resulting in more balanced energy production between the two installation orientations. In these conditions, vertical installations become increasingly relevant as part of the overall energy system.

This finding proposes that optimal PV integration strategies may vary depending on the operational routes of the vessel. Cruise ships operating predominantly at higher latitudes may benefit more from combined horizontal and vertical PV systems than those operating closer to equator.

## 9.3 Implications for Meyer Turku

The findings of this thesis provide several insights for Meyer Turku in the design and development of cruise vessels. First, the integration of horizontal PV systems on sun deck areas represents a technically feasible and economically attractive solution for reducing onboard energy consumption. These systems can be implemented with relatively low complexity and provide consistent energy across different operation regions. Second, even though vertical PV systems may not currently be economically optimal, they offer significant potential from a design innovation point-of-view. The integration of PV elements into balcony structures and ship facades aligns broader trends in sustainable ship design and may enhance the environmental profile of future vessels. The calculations done in this thesis propose the correlation between viable cruise ship regions in terms of market increase in cruise goers and viable PV system adaption to cruise ships.

When incorporating PV systems into ship design at an early stage, it enables better optimization of available surface areas, structural integration and electrical systems. This approach might reduce overall costs compared to retrofitting the PV system and therefore improve system performance. One key parameter for Meyer Turku is also the overall goal of reducing emissions and fuel consumption on its products. The adoption of PV technologies supports this strategic goal. As the environmental regulations are tightening even more in the future as well as the market demand for sustainable cruise solutions, PV system adoption supports the actions to reach these future goals.

## 9.4 Limitations and Challenges

Several limitations and challenges related to PV implementation in cruise ships have been identified in this study. One significant limitation is the lack of detailed cost data related to vertically integrated custom PV system to the balcony structures and facades of the cruise ship. This uncertainty affects the accuracy of economic assessments such as LCOE and payback time for the given PV system. In addition, the marine environment poses some technical challenges or potential threats in terms of feasibility for this kind of PV system in the sea. Mechanical stresses due to ship's motion, shading from the ship's own structures and wind loads on exposed surfaces are some of the technical challenges that might affect the system performance as they are not examined thoroughly in this study although their absence is noted.

Another important limitation relates to the operational profiles of cruise ships. Energy demand onboard is high and continuous and varies throughout the different operational regions, while at the same time PV generated energy is intermittent and dependent on weather and daylight conditions. As a result, PV systems can only supplement the energy need, rather than replace conventional power generation completely. Furthermore, the integration of PV systems in cruise ships must consider architectural, safety and passenger experience requirements, which may limit the potential usable installation area in the cruise ship.

## 9.5 Effect of Tilt Angle Optimization

One of the most noticeable findings of this study is the significant impact of small changes in panel tilt angle on energy production. The analysis shows that by adjusting the tilt angle of vertical panels with only 10° unit, from 90° to 80°, the increase in yearly POA irradiation and therefore also the annual energy yield of the PV systems is substantial. Depending on the region the ship is operating, the improvement in annual energy yield can easily exceed 10% and, in some locations, even 20%. This result emphasizes the importance of optimization for PV system design. Even minor geometric modifications can lead to considerable performance gains without necessarily increasing system size or cost significantly.

From a practical perspective, implementing slightly inclined angles on balcony-integrated PV systems may represent a viable compromise between architectural constraints and energy performance as the balance is optimized even better. This finding could be particularly relevant for future ship designs where small adjustments in geometry can be incorporated early in the design process.

## 9.6 Future Prospects

Looking forward to the future, the feasibility of PV integration in cruise ships is expected to improve due to several factors. Continuous development and advancements in PV technology industry, including higher efficiency panels and better durability, will enhance energy production and system reliability [4, 8]. At the same time, based on the Swansons law's prediction, the reduction in manufacturing and installation costs may improve even more in terms of the economic viability of PV technology on cruise ships.

Uncertainty in fuel prices, particularly in alternative fuels, such as bio methanol, remains a key factor influencing the competitiveness of PV systems. If fuel prices increase, the relative economic attractiveness of PV installations will improve. In some speculations, the need for bio methanol fuel in the future is expected to triple from where it is now [68], giving a viable positive chance for PV systems as the price development for bio methanol fuel may fluctuate [69]. Furthermore, increasing regulatory pressure to reduce GHG emissions in maritime transport is likely to encourage the adoption of alternative renewable energy solutions. In this context, PV systems can play a supporting role in reducing the overall emissions and improving the environmental performance of cruise ships.

In addition, one noteworthy aspect is the future development of southern hemisphere cruise regions in relation to the irradiation regions. As the received POA irradiation is mainly determined by the geological latitude values, the southern hemisphere also contains the same irradiation regions as mentioned earlier in this study for the northern hemisphere. This proposes the feasibility of integrated PV systems in cruise ships that operate especially in these same regions A, B, and C in the southern hemisphere.

In summary, the results of this thesis indicate that PV systems can contribute to the energy production of cruise ships, although their role remains as supplementary energy provider. Horizontal PV installations currently represent the most economically viable solutions, while vertical installations offer additional potential, particularly in higher regions and when large surface areas are available for PV installations. The integration of PV systems into cruise ships design presents both opportunities and challenges. While economic and technical limitations exist, careful design optimization and consideration of operational content can enhance the feasibility of these systems. Fundamentally, PV technology should be viewed as one component of a broader strategy aimed at improving the sustainability and energy efficiency of future cruise vessels.

The findings of this thesis open several avenues for future research and development, particularly through potential collaboration between Meyer Turku and the University of Turku. A joint research initiative could focus on advancing PV technology applications in marine environments, combining industrial expertise in ship design with academic research capabilities in renewable energy systems. Such collaboration could include the development and testing of innovative PV integration concepts tailored specifically for maritime use. This may involve exploring new materials, modular installation approaches and hybrid systems combining PV with energy storage or other renewable technologies. In addition to cruise ships, research could be extended to floating PV solutions, which are gaining increasing attention as a means of utilizing unused marine or port areas for renewable energy generation in the future.

Pilot projects could be conducted to evaluate the long-term performance and durability of PV systems in real marine conditions, providing valuable data for improving system design and economic models. Furthermore, digital simulation tools and real-world measurements could be combined to refine predictions of energy production and lifecycle costs. Collaboration of this kind would not only support the development of more sustainable cruise ship concepts but also position Meyer Turku and the University of Turku at the forefront of innovation in maritime renewable energy solutions.

# 10 Conclusion

This thesis investigated the feasibility and integration potential of PV technology in cruise ships, with particular focus on large-scale vessels like those constructed by Meyer Turku Shipyard. The study examined both technical and economic aspects of PV integration, including different installation configurations, energy production potential across various regions and lifecycle-related considerations. The results demonstrate that PV systems can contribute meaningfully to onboard energy production, although their role remains supplementary rather than primary. Among the configurations studied, horizontal PV installations located on sun deck areas consistently provide the highest energy yield per unit area on average. Their performance is less sensitive to the ship's orientation and solar azimuth angles, making them a robust and reliable option across a wide range of operating conditions. In addition, these benefit from relatively simple and cost-effective installation methods, which further enhance their overall feasibility.

Vertical PV installations, integrated into the ship's sides, such as in the balcony railing structures, were found to produce less energy per unit area due to less favorable irradiation conditions. However, their importance increases when considering the large availability of surface area in modern cruise ships. In higher latitude regions, such as the Baltic Sea, the difference in performance between horizontal and vertical installations decreases, allowing vertical systems to contribute a comparable share of total energy production. This highlights the importance of considering both efficiency and available surface area when evaluating PV integration strategies. The study also identified the strong influence of geographic locations on PV system performance. Lower latitude regions favor horizontal installations, whereas the relative importance of vertical systems increases at higher latitudes. This suggests that optimal PV integration strategies should consider the operational routes of the vessel.

From economic perspective, horizontal PV systems are likely to offer more favorable outcomes due to lower installation complexity and higher energy yields. While accurate calculations of levelized cost of electricity (LCOE) for vertical systems were not feasible due to limited cost data, it is evident that custom-integrated solutions introduce additional uncertainties and expenses. Nevertheless, vertical PV systems still provide value by contributing to fuel saving and supporting emission reduction goals, even if their economic competitiveness is currently less favorable.

One key finding of this thesis is the significant impact of tilt angle optimization. Even a modest adjustment from vertical orientation of 90° to 80° tilt can result in substantial increase in annual energy production, in some cases exceeding even +20% production output. This emphasizes the importance of detailed design optimization in maximizing the performance of PV systems onboard ships.

Despite the promising results, several limitations were identified. These include uncertainties related to installation costs, particularly for custom-integrated PV systems, as well as challenges posed by the marine environment, such as corrosion, mechanical stress and shading effects. Furthermore, the intermittent nature of solar energy limits its ability to replace conventional on-board power generation, reinforcing its role as a complementary energy source.

Overall, PV technology represents a viable addition to the energy systems of cruise ships. While it cannot replace traditional or alternative fuel-based power generation, it can contribute to reducing fuel consumption, lowering operational costs and improving environmental performance. Its integration aligns well with the broader industry transition towards more sustainable and energy-efficient future solutions.

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# Appendices

## Appendix 1 The yearly POA irradiation yield per square meter in Coco Cay, Bahamas [kWh/m$^2$]

| | | Coco Cay – Bahamas, yearly POA irradiation yield [kWh/m$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | 0 | 315 | 270 | 225 | 180 | 135 | 90 | 45 | |
| | | North | North-West | West | South-West | South | South-East | East | North-East | **Average** |
| Tilt [°] | 0 | 1921.2 | 1921.2 | 1921.2 | 1921.2 | 1921.2 | 1921.2 | 1921.2 | 1921.2 | 1921.2 |
| | 10 | 1787.5 | 1822.5 | 1904.7 | 1982.6 | 2012.8 | 1980.4 | 1903.9 | 1823.1 | 1902.2 |
| | 20 | 1617.5 | 1695.1 | 1862.5 | 2005.1 | 2059.9 | 2003.5 | 1860.2 | 1695.8 | 1849.9 |
| | 30 | 1417.3 | 1547.7 | 1797.7 | 1989.8 | 2058.9 | 1985.8 | 1796.7 | 1549.1 | 1767.9 |
| | 40 | 1203.6 | 1390.8 | 1711.7 | 1935.6 | 2009.8 | 1932.4 | 1710.4 | 1390.9 | 1660.6 |
| | 50 | 1011.4 | 1229.6 | 1607.0 | 1842.2 | 1912.9 | 1838.2 | 1602.8 | 1229.1 | 1534.2 |
| | 60 | 827.1 | 1069.3 | 1479.5 | 1713.6 | 1771.0 | 1708.4 | 1477.7 | 1068.5 | 1389.4 |
| | 70 | 651.6 | 913.8 | 1336.1 | 1551.2 | 1587.4 | 1547.1 | 1333.7 | 912.9 | 1229.2 |
| | 80 | 491.0 | 767.5 | 1179.5 | 1361.8 | 1367.7 | 1359.1 | 1171.6 | 765.7 | 1058.0 |
| | 90 | 349.6 | 631.2 | 1005.7 | 1154.5 | 1118.4 | 1151.6 | 1013.0 | 631.1 | 881.9 |

## Appendix 2 The yearly POA irradiation yield per square meter in Turks and Caicos Islands [kWh/m$^2$]

| | | Turks and Caicos Islands, yearly POA irradiation yield [kWh/m$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | 0 | 315 | 270 | 225 | 180 | 135 | 90 | 45 | |
| | | North | North-West | West | South-West | South | South-East | East | North-East | **Average** |
| Tilt [°] | 0 | 2070.8 | 2070.8 | 2070.8 | 2070.8 | 2070.9 | 2070.9 | 2070.8 | 2070.8 | 2070.8 |
| | 10 | 1939.3 | 1976.2 | 2056.6 | 2129.7 | 2155.8 | 2122.5 | 2048.0 | 1971.0 | 2049.9 |
| | 20 | 1766.3 | 1848.9 | 2013.7 | 2146.5 | 2191.9 | 2134.1 | 1996.6 | 1838.2 | 1992.0 |
| | 30 | 1558.1 | 1696.7 | 1943.0 | 2120.0 | 2175.3 | 2103.3 | 1923.4 | 1682.5 | 1900.3 |
| | 40 | 1326.7 | 1529.3 | 1850.1 | 2053.8 | 2107.5 | 2032.6 | 1825.7 | 1512.2 | 1779.7 |
| | 50 | 1107.9 | 1353.6 | 1736.1 | 1943.8 | 1989.3 | 1921.6 | 1706.8 | 1336.1 | 1636.9 |
| | 60 | 906.8 | 1176.8 | 1597.8 | 1799.3 | 1823.0 | 1772.9 | 1569.6 | 1159.4 | 1475.7 |
| | 70 | 715.8 | 1003.3 | 1440.4 | 1619.9 | 1614.2 | 1594.1 | 1413.1 | 987.3 | 1298.5 |
| | 80 | 538.7 | 837.2 | 1271.8 | 1412.9 | 1369.4 | 1390.2 | 1239.1 | 824.6 | 1110.5 |
| | 90 | 380.8 | 684.1 | 1080.7 | 1189.1 | 1090.8 | 1168.0 | 1067.9 | 674.9 | 917.0 |

## Appendix 3 The yearly POA irradiation yield per square meter in Civitavecchia - Italy [kWh/m$^2$]

| | | Civitavecchia - Italy, yearly POA irradiation yield [kWh/m$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | 0 | 315 | 270 | 225 | 180 | 135 | 90 | 45 | |
| | | North | North-West | West | South-West | South | South-East | East | North-East | **Average** |
| Tilt [°] | 0 | 1625.3 | 1625.3 | 1625.3 | 1625.4 | 1625.4 | 1625.4 | 1625.3 | 1625.3 | 1625.3 |
| | 10 | 1448.2 | 1494.6 | 1608.0 | 1719.9 | 1767.4 | 1724.6 | 1615.1 | 1499.8 | 1609.7 |
| | 20 | 1246.9 | 1346.8 | 1573.1 | 1781.9 | 1869.8 | 1791.7 | 1586.5 | 1356.9 | 1569.2 |
| | 30 | 1055.0 | 1197.3 | 1525.5 | 1809.3 | 1928.3 | 1824.8 | 1543.2 | 1210.3 | 1511.7 |
| | 40 | 876.9 | 1055.8 | 1461.8 | 1802.5 | 1940.8 | 1816.8 | 1485.5 | 1071.0 | 1438.9 |
| | 50 | 708.5 | 926.7 | 1384.3 | 1752.9 | 1904.6 | 1776.2 | 1409.4 | 941.4 | 1350.5 |
| | 60 | 553.6 | 808.2 | 1289.6 | 1671.4 | 1821.8 | 1690.9 | 1315.4 | 822.7 | 1246.7 |
| | 70 | 419.9 | 698.8 | 1179.0 | 1549.8 | 1693.2 | 1573.9 | 1202.5 | 712.1 | 1128.7 |
| | 80 | 330.8 | 597.5 | 1047.8 | 1399.8 | 1523.2 | 1420.5 | 1077.6 | 609.3 | 1000.8 |
| | 90 | 272.9 | 503.8 | 921.1 | 1221.1 | 1316.9 | 1241.3 | 933.1 | 513.6 | 865.5 |

## Appendix 4 The yearly POA irradiation yield per square meter in Marseille - France [kWh/m$^2$]

| | | Marseille - France, yearly POA irradiation yield [kWh/m$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | 0 | 315 | 270 | 225 | 180 | 135 | 90 | 45 | |
| | | North | North-West | West | South-West | South | South-East | East | North-East | **Average** |
| Tilt [°] | 0 | 1663.4 | 1663.4 | 1663.4 | 1663.4 | 1663.4 | 1663.4 | 1663.4 | 1663.4 | 1663.4 |
| | 10 | 1471.1 | 1523.2 | 1648.8 | 1770.0 | 1820.0 | 1771.7 | 1651.7 | 1526.0 | 1647.8 |
| | 20 | 1255.0 | 1367.8 | 1616.8 | 1844.0 | 1935.4 | 1846.4 | 1622.5 | 1372.8 | 1607.6 |
| | 30 | 1055.8 | 1212.1 | 1571.4 | 1882.9 | 2004.2 | 1884.8 | 1580.1 | 1219.6 | 1551.3 |
| | 40 | 870.0 | 1067.3 | 1513.1 | 1880.2 | 2024.5 | 1886.3 | 1522.3 | 1076.0 | 1480.0 |
| | 50 | 696.8 | 935.6 | 1437.0 | 1841.4 | 1994.5 | 1842.8 | 1446.5 | 945.8 | 1392.5 |
| | 60 | 539.9 | 817.5 | 1342.3 | 1759.1 | 1915.0 | 1764.7 | 1352.3 | 827.3 | 1289.8 |
| | 70 | 407.3 | 708.9 | 1229.9 | 1639.1 | 1786.4 | 1642.8 | 1242.1 | 718.5 | 1171.9 |
| | 80 | 325.7 | 608.2 | 1105.5 | 1484.3 | 1612.7 | 1490.2 | 1110.7 | 616.7 | 1044.3 |
| | 90 | 269.9 | 514.3 | 958.9 | 1302.8 | 1401.7 | 1305.0 | 974.9 | 520.4 | 906.0 |

## Appendix 5 The yearly POA irradiation yield per square meter in Turku - Finland [kWh/m$^2$]

| | | Turku - Finland, yearly POA irradiation yield [kWh/m$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | 0 | 315 | 270 | 225 | 180 | 135 | 90 | 45 | |
| | | North | North-West | West | South-West | South | South-East | East | North-East | **Average** |
| Tilt [°] | 0 | 1048.0 | 1048.0 | 1048.0 | 1048.1 | 1048.1 | 1048.0 | 1048.0 | 1048.0 | 1048.0 |
| | 10 | 922.1 | 957.5 | 1043.1 | 1125.7 | 1157.5 | 1123.3 | 1039.7 | 955.2 | 1040.5 |
| | 20 | 792.4 | 863.2 | 1033.8 | 1187.9 | 1244.9 | 1183.4 | 1027.6 | 859.0 | 1024.0 |
| | 30 | 666.7 | 773.4 | 1022.9 | 1231.0 | 1305.8 | 1224.9 | 1014.9 | 768.0 | 1000.9 |
| | 40 | 551.0 | 700.7 | 1004.4 | 1251.1 | 1337.6 | 1243.4 | 995.1 | 694.5 | 972.2 |
| | 50 | 452.8 | 641.1 | 974.5 | 1243.6 | 1336.6 | 1234.9 | 964.2 | 634.8 | 935.3 |
| | 60 | 388.9 | 585.2 | 930.1 | 1211.6 | 1302.8 | 1201.9 | 918.9 | 578.9 | 889.8 |
| | 70 | 340.5 | 529.4 | 870.4 | 1150.9 | 1240.0 | 1141.5 | 859.6 | 523.4 | 832.0 |
| | 80 | 297.5 | 472.7 | 799.4 | 1064.0 | 1148.2 | 1053.5 | 788.2 | 466.9 | 761.3 |
| | 90 | 255.8 | 413.4 | 711.2 | 958.8 | 1028.0 | 949.2 | 702.9 | 407.4 | 678.3 |

## Appendix 6 The yearly POA irradiation yield per square meter in Travemunde - Germany [kWh/m$^2$]

| | | Travemunde - Germany, yearly POA irradiation yield [kWh/m$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | 0 | 315 | 270 | 225 | 180 | 135 | 90 | 45 | |
| | | North | North-West | West | South-West | South | South-East | East | North-East | **Average** |
| Tilt [°] | 0 | 1073.6 | 1073.6 | 1073.6 | 1073.7 | 1073.7 | 1073.7 | 1073.7 | 1073.6 | 1073.6 |
| | 10 | 956.7 | 984.9 | 1060.1 | 1136.5 | 1170.8 | 1144.7 | 1071.6 | 993.2 | 1064.8 |
| | 20 | 835.9 | 889.9 | 1039.2 | 1182.1 | 1244.6 | 1197.7 | 1060.9 | 905.5 | 1044.5 |
| | 30 | 717.6 | 798.2 | 1014.2 | 1208.3 | 1292.3 | 1229.4 | 1043.1 | 820.0 | 1015.4 |
| | 40 | 603.9 | 716.1 | 980.9 | 1212.4 | 1310.9 | 1238.1 | 1015.9 | 741.4 | 977.5 |
| | 50 | 500.1 | 644.2 | 936.5 | 1190.7 | 1299.5 | 1221.6 | 976.3 | 670.5 | 929.9 |
| | 60 | 412.2 | 577.2 | 880.3 | 1145.7 | 1258.0 | 1179.5 | 922.5 | 603.5 | 872.3 |
| | 70 | 351.4 | 511.8 | 813.6 | 1077.9 | 1187.4 | 1109.4 | 854.1 | 537.5 | 805.4 |
| | 80 | 301.3 | 448.8 | 732.6 | 984.2 | 1089.3 | 1021.5 | 776.5 | 472.1 | 728.3 |
| | 90 | 257.9 | 387.6 | 650.3 | 877.5 | 966.3 | 908.5 | 682.1 | 406.4 | 642.1 |

# Appendix 7 The yearly POA irradiation yield per square meter in Kenai – Alaska [kWh/m$^2$]

| | | Kenai - Alaska, yearly POA irradiation yield [kWh/m$^2$] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Azimuth [°] | | | | | | | | |
| | | 0 | 315 | 270 | 225 | 180 | 135 | 90 | 45 | |
| | | North | North-West | West | South-West | South | South-East | East | North-East | **Average** |
| Tilt [°] | 0 | 960.0 | 960.0 | 960.0 | 960.0 | 960.0 | 960.0 | 960.0 | 960.0 | 960.0 |
| | 10 | 831.9 | 865.7 | 953.1 | 1040.6 | 1076.7 | 1042.9 | 956.9 | 868.4 | 954.5 |
| | 20 | 711.7 | 776.0 | 945.1 | 1107.3 | 1172.6 | 1112.4 | 952.8 | 781.6 | 944.9 |
| | 30 | 602.2 | 696.1 | 936.4 | 1155.9 | 1243.7 | 1162.8 | 946.9 | 704.0 | 931.0 |
| | 40 | 505.2 | 633.3 | 922.3 | 1181.6 | 1286.0 | 1191.2 | 934.1 | 641.7 | 911.9 |
| | 50 | 423.5 | 582.1 | 896.8 | 1184.0 | 1299.1 | 1194.7 | 909.8 | 589.8 | 885.0 |
| | 60 | 366.3 | 533.5 | 858.9 | 1158.2 | 1280.8 | 1171.0 | 872.1 | 540.0 | 847.6 |
| | 70 | 322.3 | 484.0 | 808.1 | 1109.9 | 1230.6 | 1119.9 | 819.8 | 489.1 | 798.0 |
| | 80 | 281.6 | 432.1 | 740.5 | 1036.5 | 1149.3 | 1047.6 | 755.3 | 437.2 | 735.0 |
| | 90 | 244.3 | 381.0 | 669.5 | 937.5 | 1041.9 | 948.2 | 677.3 | 384.9 | 660.6 |