Development of a design tool for photovoltaic integration on superyachts

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MSc Thesis Integrated Product Design
Oktober 2025

COASE DESIGN

TU Delft

Development of a design tool for photovoltaic integration in superyachts

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Preface

Before you lies the master's thesis "Development of a Design Tool for Photovoltaic integration on superyacht", written as part of my graduation project for the master's programme Integrated Product Design at the Faculty of Industrial Design Engineering of Delft University of Technology. This thesis marks the completion of my time as a student at TU Delft and the final step towards obtaining my master's degree.

As a passionate sailor, I have always had a deep connection with boats and the maritime industry in general. I developed a strong interest in technology, innovation, and design during my studies. This interest extends beyond my academic work and into my personal life. I am particularly fascinated by superyachts, which I consider the pinnacle of technological innovation and aesthetic design.

At the same time, I'm aware of the environmental footprint that these yachts leave behind. This awareness motivated me to explore ways to reduce that impact, hoping such innovations will eventually influence the wider maritime industry.

I carried out this project in collaboration with Coase Design, a naval architect based in Norway. This partnership, shaped by many inspiring conversations, played a significant role during this project.

This project allowed me to combine my fascination for yachts with my interest in design, technology, and sustainability. Through this research, I gained valuable insight into the superyacht industry and learned to manage a complex project from start to finish.

I want to express my gratitude to my TU Delft supervisors, Arjen Jansen and Peter Kraaijeveld, for their guidance, feedback, and encouragement throughout this project.

Also, a special thanks to Rory Coase from Coase Design for the many inspiring discussions, your expertise, and for providing a yacht design that was very valuable for the outcome of this project.

Finally, I want to thank my family, friends, and girlfriend for their patience, motivation, and for reminding me to take a break now and then.

I hope you enjoy reading this thesis.

Olaf Bouwens

Summary

This thesis presents the development of a design tool that supports yacht designers in the early-stage integration of photovoltaic (PV) systems on luxury yachts. While sustainability is gaining importance in the superyacht industry, solar technology is rarely applied due to aesthetic concerns, limited suitable surface area, and a lack of practical design knowledge.

The project aims to bridge this gap by providing designers with accessible methods to explore and assess PV integration. A combination of literature research, expert interviews, and a co-design study with the Norwegian naval architect Coase Design led to the creation of design guidelines and an interactive design tool.

The research identifies three key factors determining successful integration: surface geometry, aesthetic appearance, and energy performance. Monocrystalline silicon panels offer the best balance between efficiency, durability, and visual quality among available technologies. Three integration methods: flexible stick-on, glass-laminated, and composite-laminated panels, are assessed for suitability within the luxury yacht context.

A co-design case on a 50-metre yacht demonstrates that PV can meaningfully contribute to the energy needs when applied in carefully designed surfaces. The study also reveals that early integration and visual evaluation are essential for achieving seamless design outcomes.

The resulting YIPV Design Tool lets designers explore PV configurations interactively and receive instant visual and numerical feedback. User testing confirmed that combining aesthetic and performance insights enhances informed decision-making and shows potential use in client communication.

This thesis delivers a functional and feasible concept that helps integrate solar technology into yacht design. Offering a pathway towards more sustainable superyachts and highlighting opportunities for further development of the tool.

Abbreviations & Terminology

AOI	Angle Of Incident
AR	Anti-reflective
GT	Gross Tonnage
HVAC	Heating Ventilation and Air Conditioning
LOA	Length Over All
PV	Photovoltaic
UI	User Interface
YIPV	Yacht Integrated Photovoltaics

Grasshopper – A visual programming environment integrated with Rhino, used for parametric and generative design.

Hotel Load – The total onboard electrical consumption unrelated to propulsion, including lighting, air conditioning and domestic systems.

Rhinoceros – A 3D computer-aided design (CAD) software also known as Rhino, used for modelling, visualization, and analysis of complex geometries.

Superyacht – A luxury yacht typically over 30 meters in length, designed for comfort, performance, and exclusivity.

Superstructure – The part of a vessel built above the main deck.

Solar Irradiation – The amount of solar energy receive by a surface expressed in watts per square meter (W/m^2)

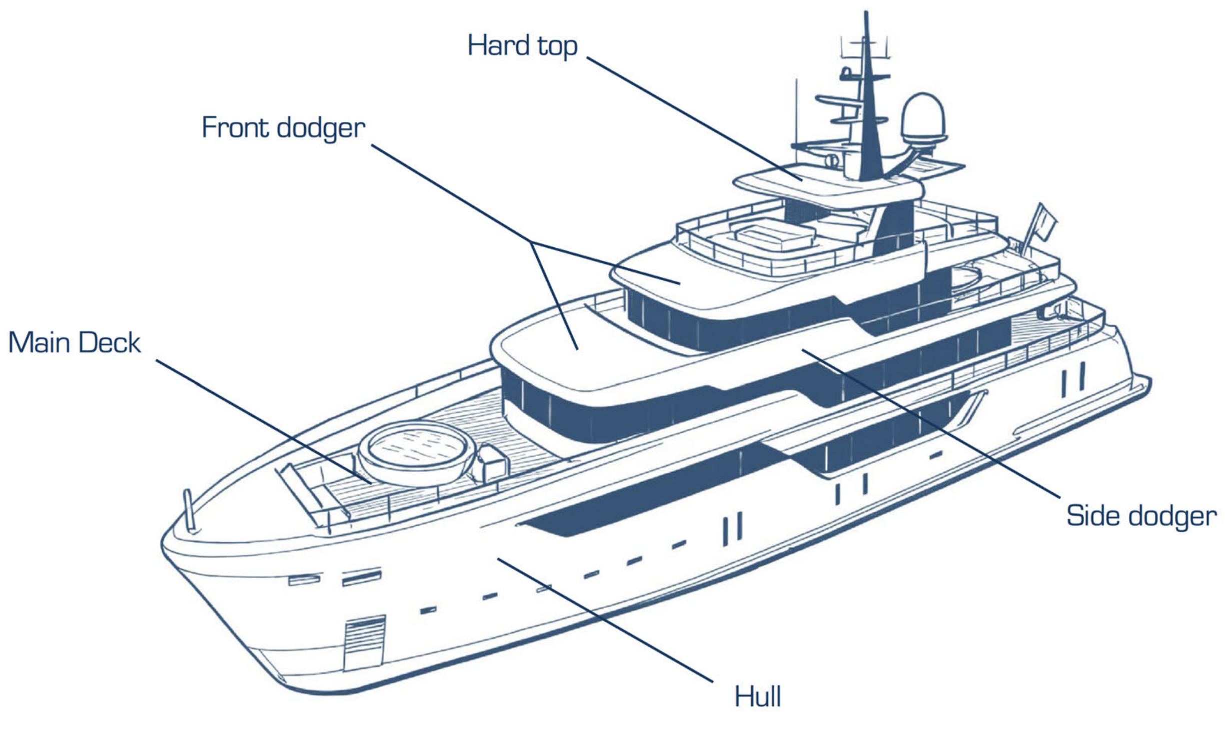

Figure 1: Terminology used throughout the report

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1. Project outline

1.1 Introduction

Sustainability has emerged as a central theme within the superyacht industry in recent years. The substantial energy consumption associated with luxury yachting, both while cruising and at anchor, has drawn increased scrutiny from regulatory bodies, environmental organisations, and public opinion (Redmayne, 2024).
At the same time, a new generation of yacht owners is emerging, placing greater value on environmental responsibility alongside traditional considerations of luxury and comfort (DNV, 2019). Consequently, yacht manufacturers and designers face growing demands to demonstrate concrete progress towards environmentally friendly and efficient designs (Ruggiero, 2020).

These changing landscapes have led to significant interest in alternative energy sources and propulsion technologies. Hybrid-electric propulsion systems, energy management systems, and increased efficiency measures are emerging strategies to reduce fuel usage and improve energy efficiency (Flannagan, 2023).

Photovoltaics is one of the technologies that is getting more attention and showing potential in this transition.

Most yachts operate in sunny climates such as the Mediterranean and the Caribbean, which makes solar generation a natural fit. In addition, PV systems are quiet, require little maintenance, and have no moving parts, making them suitable for the marine environment (Thomas, 2025).

However, PV alone is unlikely to replace the conventional energy systems on board, but it can meaningfully reduce the reliance on fossil fuels, especially for hotel loads, while at anchor.

1.2 Problem definition

Even though there is growing interest in sustainable solutions, solar panels are rarely integrated into luxury yachts. In most cases, they are either not considered or added as an afterthought, leading to missed opportunities for reducing environmental impact. This issue is within sustainable yacht design, where new technologies are needed but not widely embraced. Several factors have constrained the adoption of PV systems:

1. Aesthetics dominates the superyacht industry. Conventional PV panels often clash with the clean shapes, high-end finishes, and consistent design language that owners and designers expect (Thomas, 2025).

2. Practical limitations make integration difficult. Many surfaces are curved, shaded, or needed for other functions, which leaves little ideal space for solar panels (Gorilla Power Solutions, 2024)

3. The energy yield of PV is still relatively low compared to the total energy needs of a superyacht, especially for propulsion. As a result, PV is usually seen as a small add-on, not a complete solution.

4. There is a lack of knowledge and design culture around PV. As highlighted by an expert interview with Coase Design, many yacht designers are still unfamiliar with PV systems, and the design process tends to be conservative, sticking to proven materials and methods over newer technologies.

Because of this, sustainable energy solutions are often left out of early-stage design decisions. This slows down innovation and holds back progress toward more sustainable yachts.

However, early alignment between structural design and solar integration can significantly affect feasibility and visual quality (Solbian, 2025). That is why there is a need for tailored tools and guidelines. These can help designers identify suitable surfaces, work around design constraints, and estimate energy output from the start. As the Water Revolution Foundation (2024) highlights, designers play a key role in driving sustainability forward and giving them the right tools is essential to make that happen. Such support should provide technical knowledge and enable yacht designers to explore integration options and make well-informed early-stage design decisions.

1.3 Research question

This thesis investigates how yacht designers can be supported in the early-stage integration of PV systems on luxury yachts. While aesthetics and performance often conflict, there is an opportunity to provide designers with structural knowledge and accessible methods that help them explore possibilities and make well-informed decisions.

Main research question:

"How can design guidelines support yacht designers in the early-stage integration of photovoltaic systems on a luxury yacht, balancing aesthetics and performance? "

To address the main question, the following sub-research questions were formulated:

1. **What factors influence the integration of photovoltaic systems on luxury yachts, and how do these relate to aesthetics and performance?**
2. **How can insights on photovoltaic integration be made accessible to yacht designers in a way that supports exploration and informed decision-making?**

1.4 Approach

This project follows the Double Diamond model described by the British Design Council. This well-known design framework divides the design process into two main phases: exploration and refinement (Design Council, n.d.). The first diamond identifies key factors within the context, while the second translates them into practical design guidelines.

DISCOVER

The discovery phase explores the problem space to understand the context. It examines three key domains: photovoltaic technologies, superyachts, and solar applications in the maritime industry. This was done through desktop research of relevant literature and expert interviews.

DEFINE

The insights are synthesised and distilled into key findings in the define phase. These findings answer the first sub-research question: what factors are essential for PV integration and how they relate to aesthetics and performance. This resulted in a design vision and a list of guideline development requirements.

DEVELOP

The second diamond starts with the development phase, which focuses on developing methods to make the key findings accessible to yacht designers and addressing the second sub-research question. It also explores how these methods and insights can be combined into a single solution, in the form of a design tool.

DELIVER

The final deliver phase focuses on refining and evaluating the design tool. This phase results in a prototype and answers the main research question, marking the completion of this project.

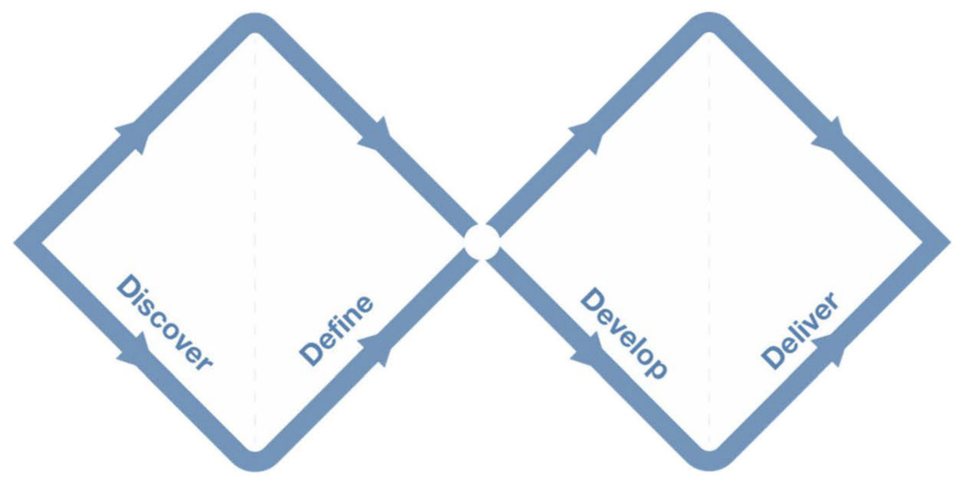


Figure 2: Double Diamond model, (Design Council, n.d.)

1.5 Reading guide

After this introduction (chapter 1), the thesis is structured into eight chapters, followed by a discussion, conclusion and recommendations.

Discover and Define phase.
Chapters 2 and 3: provide the fundamental knowledge, covering the superyacht context, photovoltaic technologies and integration methods, and marine solar applications.
Chapter 4: summarises the key findings from chapters 2 & 3, forming a design vision and defining requirements for the guidelines.

Develop phase
Chapters 5 and 6: explore how designers can evaluate and optimise their designs and how they can estimate the solar potential.
Chapter 7: presents a co-design of a solar yacht to test the guidelines in practice, identifying which are relevant and examining the application of specific methods and tools.

Deliver phase
Chapter 8: shows the development and evaluation of the design tool, which combines previous insights into one solution.

2. Yacht Design

This chapter explores the design context of superyachts to build an understanding of the environment in which PV systems would be integrated. Section 2.1 shows the context of the energy demand, while Section 2.2. examines their aesthetic principles, including general design language (2.2.1) and the use of colours and surface finishes (2.2.2). Section 2.3 discusses current exterior design trends, followed by an overview of how PV is currently applied on yachts (2.4). The specific constraints that influence integration possibilities are summarised in Section 2.5, and key insights are presented in the final takeaways (2.6). Together, these sections define the superyacht design context, forming the foundation for evaluating PV integration strategies in later chapters

2.1 Superyacht context

Superyachts are large, privately owned vessels that combine advanced engineering with luxury and craftsmanship. Typically, yachts over 30 meters are considered superyachts, while those above 60 meters fall into the mega yacht category. They are built in limited numbers and highly customised to the owner's lifestyle and preferences (McVinney, 2024).

Energy demand

Super yachts have substantial energy needs from propulsion systems, hotel loads (lighting, climate control, entertainment), navigation electronics, and auxiliary equipment. The energy consumption depends on vessel type, size, and onboard amenities.

A yacht's total annual energy use is typically divided into hotel loads and propulsion, with hotel loads accounting for approximately 45-50%, and propulsion making up the remaining 50-55%, even though the yacht is actively sailing only around 10% of the time. Within the hotel load, a substantial 40-50% is consumed by the HVAC (heating, ventilation, and air conditioning) system (Heesen Yacht, 2024). The continuous operation of HVAC is essential to maintain a stable and comfortable indoor climate, which is critical for occupant comfort and the preservation of interior finishes and furnishings.

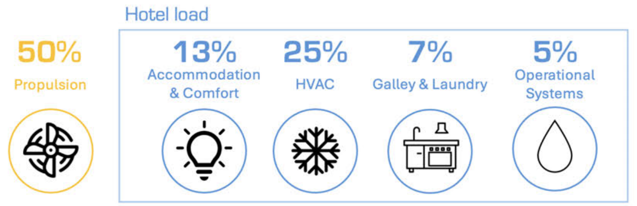


Figure 3: Average energy usage of onboard systems

A correlation between a yacht's gross tonnage (GT) and its annual power consumption was established based on insights from an expert interview with a designer at the yachtbuilder Feadship to provide an indication of the expected energy usage. As internal volume increases, larger HVAC systems are required to maintain a stable indoor climate, while onboard systems typically become more extensive and complex, resulting in higher overall energy demand.

The overview below provides typical annual power consumption based on the GT of the yacht:

Table 1: Average energy usage based on yacht's GT, based on superyacht build by Feadship

Yacht size		GWh/GT	Annual total energy GWh	Annual Hotel energy GWh	Annual Sailing Energy GWh
40-50m	~500GT	0,00216	1,08	0,48	0,60
70-80m	~2000GT	0,00199	3,98	1,75	2,23
100-140m	~4500 GT	0,00164	7,38	3,54	3,84

2.2 Aesthetics

Aesthetics play a defining role in superyacht design. Understanding the factors that define the appearance of a super yacht will be important when matching PV integration methods discussed in Chapter 3.2. This chapter explores the general aesthetics and surface finishes.

2.2.1 General aesthetics

A clear and consistent aesthetic style becomes visible when comparing several modern superyachts. Most designs have smooth, continuous surfaces, long horizontal lines, and few visible technical elements. Openings, vents, and fittings are often hidden or aligned with the main geometry. This makes the yacht look clean and balanced, focusing more on shape and smooth surfaces than decorative details.

According to Margerrison (2023), the golden rule of yacht design is that it should be obvious, naturally beautiful and easy to understand at first sight. Meaning every line and every detail needs to be right.

Figure 4: 80-metre Pegasus by Oceanco, illustrating the clean and balanced look of superyachts (YachtBuyer, 2024).

2.2.2 Colour and surfaces

Colours and surface finishes play a key role in defining the character of a superyacht. They determine how the shape is perceived, how light interacts with the surfaces, and how the overall quality is experienced.

Colour

Across most superyachts, three primary colour groups dominate: white, metallic silver or grey, and dark tones such as navy and anthracite. White remains the dominant colour in superyacht design. It highlights the yacht's geometry and maintains a clean and balanced appearance. Its reflective quality also lowers surface temperatures, making it an aesthetic and practical choice for large exterior areas (Howorth, 2022).

Openings, vents, and fittings are often hidden or aligned with the main geometry. This makes the yacht look clean and balanced, focusing more on shape and smooth surfaces than decorative details.

According to Marrison in Boat International, the golden rule of yacht design is that it should be obvious, naturally beautiful and easy to understand at first sight. Meaning every line and every detail needs to be right.

Figure 5: The 107-metre Mar by Benetti, in a typical white colour, which enhances the yacht's lines a visually enlarges the vessel (Smits, 2025)

Figure 6: The use of darker colours on modern superyachts (Çeştan, 2021) (Romeo United Yachts, 2025) (Carmassi, 2021)

In recent years, darker tones such as silver, bronze, anthracite, and black have become more common as designers aim for a stronger and more distinctive visual identity (BOAT international, 2021). These colours contrast with the sea and sky and give the yacht a more powerful presence, but they also expose imperfections and require higher precision in finishing and maintenance.

For designers, colour choice strongly affects how proportions, details and surface quality are perceived. Understanding how dark tones influence a yacht's overall balance and expression is essential when integrating photovoltaic surfaces with a similar appearance.

Surface finishes

Superyacht surfaces are expected to reach an exceptionally high standard of finish. Even minor irregularities or variations in gloss are easily visible on large, reflective surfaces. According to Guy and Safinah Group (2020), imperfections such as uneven reflections or slight texture differences are unacceptable in high-end yacht building. The finish must appear smooth, uniform, and continuous across the hull.

These expectations imply that photovoltaic elements must also match this surface quality level to maintain visual consistency.

Figure 7: Side of a superstructure of a superyacht, showing the high-end surface finish expected on a superyacht. (Feadship, 2024b)

2.3 Trends

This section highlights two exterior design trends shaping modern superyachts' appearance and surface design. The trends are identified through analysis of existing yachts and trend reports from major superyacht platforms like BOAT International and Superyacht Times. Offering potential opportunities for the integration of PV systems.

Sleek and minimalistic forms

Superyacht design has become increasingly clean and minimal, with long, horizontal lines and low, streamlined shapes. As shown in the timeline (Appendix A), older yachts from the 1960s show more upright, segmented superstructures and a lot of visible detailing. Throughout the years, yachts have gradually been designed with smoother, uninterrupted surfaces and lines, and integrated features that create a calmer and modern appearance.
This shift is part of a larger trend toward minimalism in luxury design. Reigner (2025) explains that owners are no longer looking for overly decorated or flashy yachts. Instead, they want open, quiet spaces focused on the experience, being on the water, enjoying the view, and spending time with others.
The minimalistic shapes and smooth surfaces present opportunities for PV integration, providing open, uninterrupted areas suitable for panel placement. However, the panel must match the surface's overall design lines.

Figure 8: 88m Zen by Feadship with long uninterrupted lines and large smooth surfaces. (ZEN Yacht - Feadship, 2024)

More use of glass

The timeline in Appendix A also shows that the use of glass in superyacht design has expanded significantly since the 1990s. Early examples like ECO (1991, Blohm & Voss) introduce large panoramic windows that began to blur the boundaries between interior and exterior. This continued with Venus (2012, Feadship), featuring floor-to-ceiling glass, and Excellent (2019, Abeking & Rasmussen), where wraparound glazing defines the entire profile (Schipper & Onboard Magazine, 2022), as shown in Figure 9.

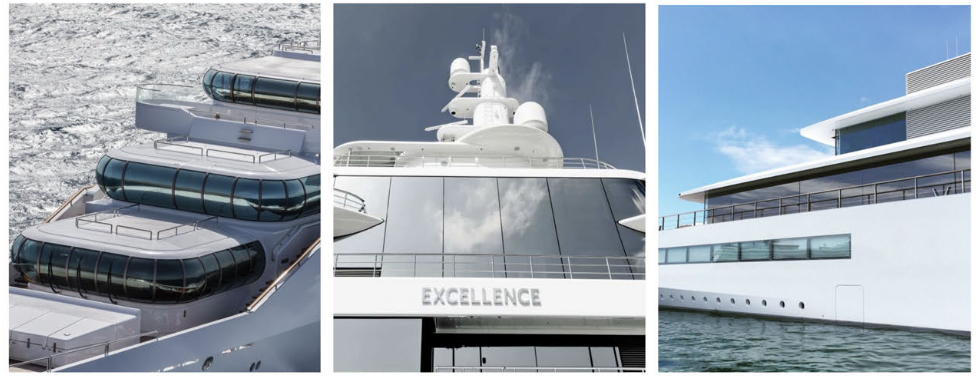


Figure 9: The use of glass as part of the design on Excellence (middle) (Romeo United Yachts, 2019), Venus (right) (Yacht Harbour, 2017) and ECO (left) (Marche, 2020)

A desire for openness, natural light, and a stronger visual connection to the sea drives this trend. Innovations in structural glass have enabled larger, uninterrupted surfaces that achieve this aesthetic while meeting marine safety standards (Lloyd's Register, 2021).
As large, glazed surfaces become more common, they create potential for using PV glass. Visually, dark or tinted PV panels often match the sleek reflective aesthetics of modern glazing, making it easier to integrate them without compromising the yacht's clean appearance.

2.4 Current solar yachts

To better understand the possibilities and limitations of solar integration, this section presents visionary concepts and real-life examples of yachts using solar power. By analysing how these vessels approach solar energy, in terms of surface coverage, technologies used, and performance, it becomes easier to identify proven strategies and common pitfalls.

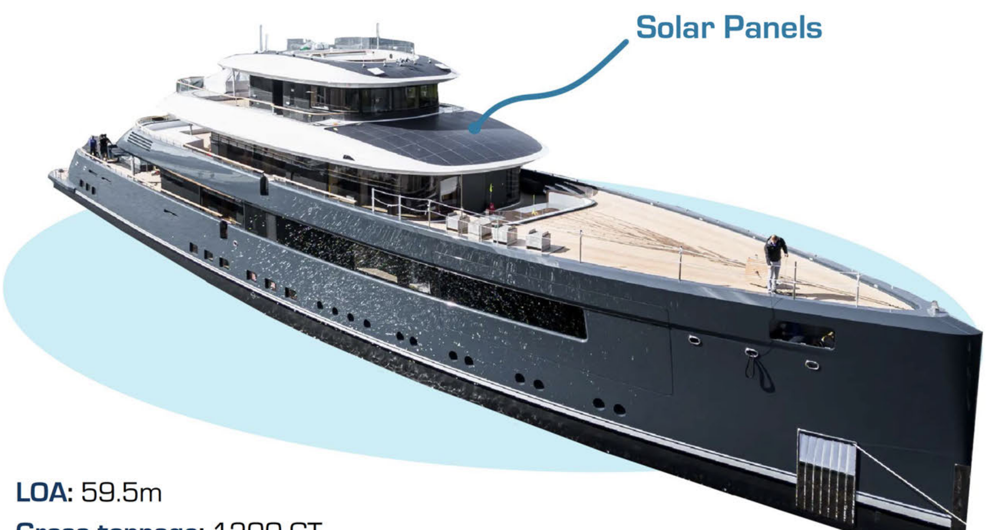
Project 713 by Feadship

Feadship's project 713 is a 59.5m superyacht launched in 2024, marking their first vessel with a significant PV system. Designed by Studio De Voogt (Feadship, 2024).

This superyacht features approximately 65 m² of solar cells integrated into the hardtop and forward dodger, generating up to 24 MWh annually. While this accounts for only around 2.3% of the total hotel load, it is sufficient to power various onboard systems and appliances.

On Project 713, solar panels were likely added late in the design process and were not a primary design driver. The aim appears to have been to integrate solar technology with minimal compromise to the original architecture, resulting in a restrained application on select horizontal surfaces. To optimise output, high-efficiency monocrystalline cells were placed on otherwise unused, well-oriented areas. The panels feature a textured surface that improves grip for cleaning and helps hide wear.

Visually, the dark, uniform panels follow the curvature of the yacht's surfaces, creating a discreet and cohesive look. This seamlessness is enhanced using dummy cells or extended laminates, complementing the yacht's dark hull colour.



LOA: 59.5m
Gross tonnage: 1200 GT
Energy system: Diesel-electric (2x main engines, 2x generators), supported by a 400kWh battery bank
Annual total energy usage (estimated): ~2.39 GWh (44% is hotel load)

Figure 10: Project 713 by Feadship, featuring solar panels on the hardtop and front dodger. (Feadship, 2024b)

Key learnings:

- When photovoltaic integration is not considered early in the design process, the available surface area for panels becomes limited.
- Following the curves and shapes of the surface results in a seamless integration.
- Using textured panels for better grip while cleaning and concealing wear over time

Sunreef 80 Power Eco Sól

The Sunreef 80 Power Eco Sól is a 23.8 m electric sailing catamaran launched by Sunreef Yachts, designed from the start around solar integration (Sunreef Yachts, 2025). It features an in-house developed "Solar Skin" system that embeds photovoltaic cells directly into the yacht's composite structure, spanning the hulls, superstructure and hardtop. This approach maximises available surface area and energy yield while preserving aesthetics and functionality.

The Sunreef 80 Eco features around 200 m² of solar panels laminated into the composite structure, with a theoretical peak capacity of up to 40 kWp. However, since the panels are spread across surfaces with varying orientations, they cannot simultaneously operate at peak efficiency. This makes the actual energy yield significantly lower than the theoretical maximum. In practice, the system provides meaningful support to hotel loads and short-range electric propulsion, but remains a supplementary power source and will heavily rely on the battery bank.

A central enabler of this integration is Sunreef's in-house lamination technique, which embeds solar cells into flat or gently curved surfaces without visible mounting or added thickness. This approach enables seamless visual integration and is completely flush.

Integrating solar into the hull is unusual in yacht design but offers potential benefits due to increased solar area and reflected light off the water surface. However, hull-mounted panels face greater exposure to saltwater, spray, and impact, increasing the risk of damage and requiring more robust protection and maintenance.

LOA: 23.8m
Gross tonnage: 1200 GT
Energy system: 2x 360 kW electric motors, 990 kWh battery bank, hydrogeneration
Solar area: 200m²
Peak solar output: up to 40kWp

Figure 11: Sunreef 80, featuring a solar panels on various places like the hull, superstructure and hard top. (Sunreef Yachts, 2025)

Key learnings:

- Laminating solar cells directly in the structure enables seamless integration.
- Hull surfaces can offer a valuable solar area
- Avoiding double-curvature surfaces increases usable area
- Rated peak output is theoretical; real-world yield depends heavily on panel orientation and shading.

2.5 Yacht specific constraints

Integrating photovoltaics into yachts presents unique challenges that differ significantly from land-based applications. Understanding these constraints is critical to making informed design decisions that balance energy performance, aesthetics, and usability.

Limited and valuable surface area

Yachts offer a highly constrained surface area compared to buildings or other stationary structures. Every square meter comes at a premium, reaching up to €1.5 million per m² on high-end superyachts (50-70m) (Insure4boats, 2023) and far exceeding even the most expensive architecture real estate, such as New York City, where construction costs average around €5,700 per m² (Fleck, 2024). This economic pressure makes it essential to evaluate where and how solar panels are placed carefully.

Suboptimal and variable orientation

Unlike buildings, where solar orientation can be optimised based on geographic location. Yachts are mobile, and their heading constantly changes. As a result, there is no fixed ideal orientation. Panels must be designed to perform reasonably well under variable angles and exposure conditions. In most cases, horizontal orientation offers the best compromise, as it remains unaffected primarily by heading.

Thermal management constraints

Photovoltaic efficiency decreases with temperature, making heat a critical performance factor. Unlike rooftops, yachts require flush and seamless surfaces, ruling out most passive cooling strategies like floating or ventilated installations. Thin, flush-mounted panels dissipate heat only from the front, which is less effective. As a result, panel temperatures can exceed 65 °C (Peninsula Solar, 2024), reducing efficiency and potentially affecting the usability of surfaces, such as making them too hot to walk on barefoot.

Environmental exposure

Marine environments are exceptionally harsh. PV systems on yachts must withstand continuous exposure to saltwater spray, UV radiation, and high humidity, all of which accelerate material degradation and can compromise adhesives, coatings, and electrical safety. These conditions also increase the risk of microcracks, delamination, and corrosion. Choosing durable, marine-grade panels is critical to ensure long-term reliability.

Structural and weight constraints

While weight is not critical on some large yachts, it is still something to consider in the system design. PV panels and mounting systems should be structurally compatible with composite or aluminium surfaces and not introduce unnecessary mass high on the vessel, which could affect stability or trim. Integration must also preserve watertightness and structural integrity, especially on curved or load-bearing surfaces.

Chapter 2 - Takeaways:

- For seamless integration, the panels must achieve the same surface finish as other yacht surfaces.
- The key to seamless integration is to conform the panels to the curves and shapes of the surface.
- Solar cells can be laminated directly into the composite structure, which provides a flush surface and a premium finish.
- Placing panels in the hull is a feasible option to capture sunlight at low sun angles and utilise the water's reflection.
- Key performance challenges:
    - Yacht surfaces are of high value, so usability, aesthetics, and access must be preserved.
    - Dealing with variable orientation requires a resilient design against dynamic light conditions.
    - The panel can get hot, impacting the surface's usability.
    - Due to harsh marine conditions and avoiding downtime and costly replacements, durability is an important factor.

3. PV Technology

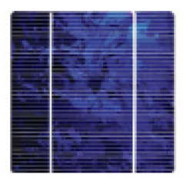
This chapter explores the photovoltaic (PV) technologies relevant to yacht integration. Section 3.1 discusses selecting the most suitable PV type and its characteristics. Section 3.2 examines the visual and practical aspects of integrating PV systems, including mounting options (3.2.1), practical considerations (3.2.2), and aesthetic appearance (3.2.3). Finally, the chapter concludes with the main takeaways summarising PV technology's implications for yacht design. Together, these sections provide the technical and aesthetic foundation for the guidelines.

3.1 PV selection

Selecting the right photovoltaic technology for superyachts requires understanding the basic principles of PV (Appendix B) and the main solar cell types and their key characteristics. Each type differs in efficiency, flexibility, aesthetics and durability.

This section compares the most relevant technologies: monocrystalline and polycrystalline silicon, amorphous silicon, and CIGS (Copper Indium Gallium Selenide)

Table 2: Overview of the characteristics of each PV type.

				
Cell type	Monocyrstalline	Polycrystalline	CIGS	Amorphous Silicon
Characteristics	Made from a single silicon crystal, uniform black or blue appearance; most efficient among	Made from multiple silicon crystals; bluish and less uniform appearance	Thin film deposited on flexible substrates; suitable for curved surfaces	Non-crystallin silicon structure; deposited in thin layers; highly flexible and light weight
Efficiency	15-24%	15-20%	12-16%	6-10%
Lifespan & degradation	25-30 years Degradation: 0.3-0.5%/year	20-25 years Degradation: ~0.5-0.8%/year	10-20 years Degradation: ~0.5-1%/year	5-10 years Degradation: ~1-2%/year
Advantages	• High efficiency • Uniform appearance • Long service life • Widely avalable in marine-certified variants	• Lower manufacturing cost • Technologically mature and reliable	• High flexibility • Good low-light and thermal performance • Unifrom appearance	• Extreemly lightweight • Flexible • Cost-effective • Can be transparant
Disadvantaces	• Higher cost • Output affected by shading • Less flexible than thin-film	• Lower efficiency • Less uniform appearance • Not commonly used in flexible or marine-specific formats	• Lower efficient than crystalline silicon • Product availability limited for marine use	• Very low efficiency • Rapid degradation • Short operational life

Each PV type offers distinct advantages and disadvantages. Selecting the most suitable option for solar integration on super yachts means balancing between efficiency, visual quality, durability, flexibility and maturity. In Section 2.5, yacht-specific constraints make efficiency particularly important due to limited surface area and suboptimal orientations. Durability is equally critical to ensure resistance against harsh marine conditions. Furthermore, as discussed in Section 2.2, the chosen PV technology must align with the yacht's surface characteristics, both in geometry and appearance.

A Harris profile is used to guide this selection (Figure 12). Each PV type is evaluated based on the following characteristics:

- **Efficiency:** How efficiently can it convert solar energy into electricity
- **Visual appearance:** How well can it match the aesthetics of superyacht surfaces?
- **Durability:** How well will it withstand a marine environment?
- **Flexibility:** How well can it conform to curved surfaces?
- **Maturity:** How mature is the technology to guarantee reliable performance and availability?

The Harris profile indicates that **monocrystalline silicon** offers the most potential for integration on yachts. It performs best in the three most relevant criteria, efficiency, visual quality and durability, making it the most balanced option among the evaluated technologies.

While CIGS and Amorphous Silicon show interesting opportunities for aesthetics and flexibility, their lower efficiency and limited marine-certified availability make them less suitable. Polycrystalline Silicon perform reasonably but lacks the visual quality and flexibility.

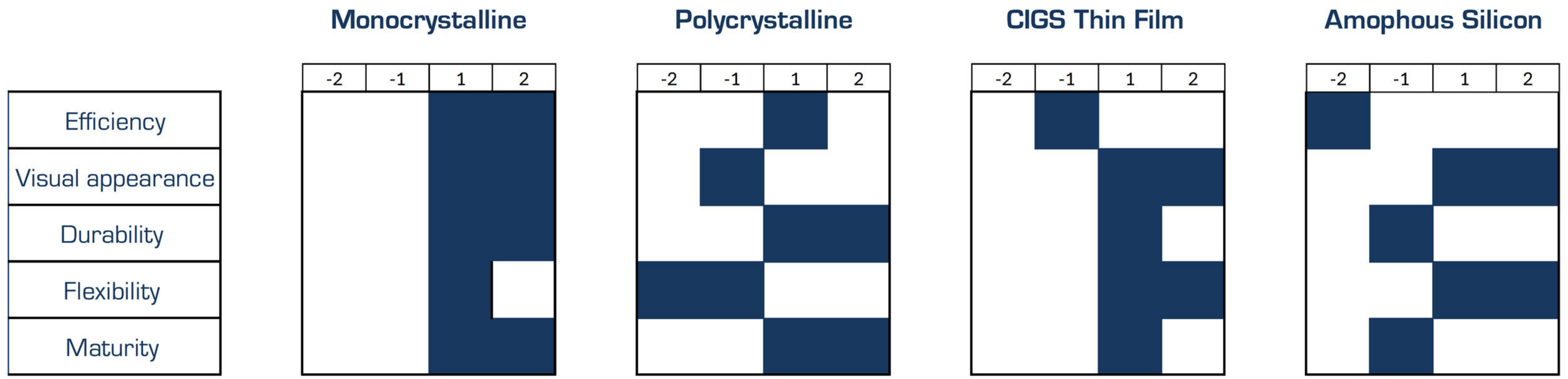


Figure 12: Harris Profile, comparing different PV technologies based on efficiency, visual appearance, durability, flexibility and maturity. This overview guides the choice of most suitable PV technology

3.2 Appearance and aesthetics

While technical feasibility defines where photovoltaic systems can be applied, their acceptance on luxury yachts is ultimately shaped by appearance. Aesthetics determine whether PV integration reinforces the yacht's architecture or disrupts it. Therefore, understanding the impact of mounting, texture, layout, and colour is essential for making informed design decisions that balance visual quality and energy performance.

3.2.1 Mounting options

The way the monocrystalline cells are mounted is crucial to the final appearance of the solar system. To fit in the luxury design context as shown in chapter 2.2, surfaces need to be smooth, without visible gaps or screws, and details must follow the visual flow of the yacht's exterior, respecting its curves, symmetry and material transitions. The solar system must appear as a natural part of the design rather than an add-on.

As shown in Figure 13, conventional aftermarket mounting methods will not be good enough to use on a luxury yacht. The panels need to be semi-custom or fully custom to align with the superyacht aesthetics. Figure 13 also shows mounting solutions that fit the luxury yacht context.

So, three promising mounting methods are worth further analysing. All three methods use monocrystalline cells but differ in how they are encapsulated and the material. The three methods discussed are flexible stick-on panels, glass laminated panels, and epoxy laminated panels.

Figure 13: Comparison between several mounting methods. The top row of options do not fit into the aesthetics of a superyacht and the bottom row do fit in the super yacht aesthetics. (Chicago, n.d.)(Feadship, 2024) (SuperYachtTimes, 2022)

Flexible stick-on panels

In the first method, the solar cells are encapsulated between two EVA (ethylene-vinyl acetate) layers and often with an ETFE (Ethylene Tetrafluoroethylene) top layer. The EVA layers are used to fully enclose the cells from the elements and bond the other layers during the lamination process when heated. Both materials are known for their durability, high light transmission and chemical resistance, making them ideal for this application. This laminate is then placed on a back sheet of plastic or composite material to add rigidity but still allow some flexing.

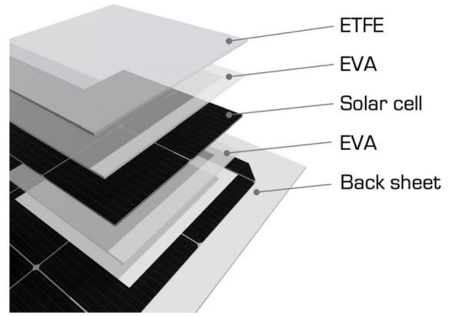


Figure 14: Construction of a flexible solar panel.

These panels are prefabricated and glued directly on top of the surface or in a recess to make them flush. It is a widely used method to mount solar panels on curved surfaces and is already used on yachts (Figures 15 and 16).

Figure 15: Example of a flexible stick-on panel mounted on a teak deck of a Spirit 44CR. (Solbian Solar, 2021)

Figure 16: Example of a flexible stick-on panel mounted on a hard top of a Baltic 146, PATH. (Solbian Solar, 2022)

Glass-laminated panels

Encapsulating solar cells between glass panels is a commonly used construction method for large, rigid solar panels commonly found on rooftops and architecture. The exact process can be used to create curved solar panels. This requires moulding glass into the desired geometry before laminating it into a panel.

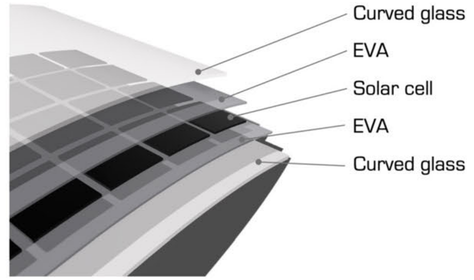


Figure 17: Construction of a curved glass-encapsulated solar cell

These curved glass panels can be found in the automotive industry to integrate solar cells into an electric vehicle's roof. It is also possible to alter the spacing of the cells, allowing more light to pass through; it is then referred to as solar glass, commonly seen in architecture with glass skylight roofs. See Figures 18 and 19 on the next page.

Figure 18: Example of curbed glass solar panels used in a car roof (Solar Roof on Kia Sorento, 2025)

Figure 19: Example of curbed glass solar panels used in the roof windows of a building (Movares, n.d.)

Composite laminated panels

Finally, solar cells can also be integrated directly into the composite structure of a yacht's surface. Instead of using a conventional front sheet like glass or ETFE, a layer of transparent resin or gelcoat is applied during the composite lamination process to encapsulate the solar cells. Sunreef was the first yacht builder to introduce this technique in its semi-custom yachts. The solar cells are pre-assembled on a thin substrate to form a panel, which is then positioned in the mould and encapsulated within the transparent gelcoat layer during lamination. This results in a completely flush integration.

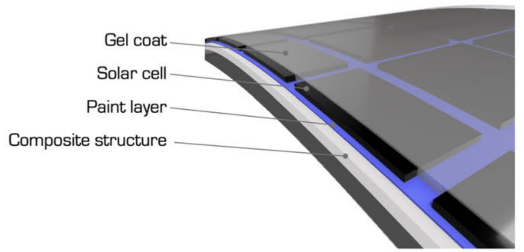


Figure 20: Construction of solar cells directly laminated in a composite structure

However, this method is still relatively new, and the long-term durability of these panels is not yet fully proven. There are concerns about the light transmission and moisture resistance of gelcoat compared to traditional encapsulation materials like EVA or ETFE, which may affect performance and lifespan.

Figure 21: Example of solar cells integrated in a composite surface (Sunreef Yachts, 2024)

Figure 22: Example of solar cells integrated in the composite hull of a Sunreef 80 ECO. (SuperYachtTimes, 2022b)

3.2.2 Practical considerations

Several practical factors must be considered beyond aesthetics and performance when selecting a solar panel integration method for a luxury yacht. These include expected lifespan, maintenance and cleaning requirements, repairability, and installation complexity. Each of these factors can influence the system's feasibility, cost, and operational convenience.

Lifespan

All solar panels experience performance degradation over time. Typically, monocrystalline silicon cells maintain functional efficiency for 25–30 years before output significantly declines. However, the actual service life of a solar system is also affected by the integration method and its exposure to environmental stressors.

- **Glass panels** are the most durable, lasting up to 30 years with proper maintenance. Their rigid, sealed structure protects against moisture, UV, and wear.
- **Flexible panels** (often ETFE-encapsulated) last around 10-15 years and are more prone to damage from abrasion, flexing, or impact.
- **Composite-integrated panels** are said to last 20-25 years. While promising in durability, this method is relatively new, and long-term performance data is not yet available.

Maintenance

Solar panels must be kept clean to ensure optimal energy output, particularly in marine environments where salt accumulation can significantly reduce performance. Studies suggest a dirty panel can lose up to 40% of its efficiency (Martz-Oberlander, 2017).

- Regular cleaning is essential, and panels must be accessible to crew members.
- In some cases, anti-slip surface treatments, more common flexible panels, may be necessary to ensure safe access during maintenance.

Repairability

In the event of damage, whether due to impact, delamination, or material failure, the ease of repair varies significantly between the three integration methods.

- **Flexible panels** offer the most straightforward repair process. Since they are typically bonded onto the surface, individual panels can be removed and replaced with relative ease and minimal downtime.
- **Glass panels**, if damaged, usually require replacement of the entire glass unit. This can be expensive and time-consuming, particularly if custom glass dimensions or curvature are involved.
- **Composite-integrated panels** are more challenging to repair than the other options due to their permanent lamination into the yacht's structure. Any damage requires extensive composite work to access and replace the affected section. This can lead to significant downtime, often more critical to owners than cost.

Installation

The complexity of the installation process also plays a role in selecting a solar integration method. While cost is not always the primary concern in the luxury yacht sector, build time and logistical challenges often are.

- Systems that require custom curved glass or composite integration involve more complex fabrication and installation, potentially extending the construction timeline.
- Simpler methods like pre-fabricated flexible panels offer faster installation and fewer technical risks.
- Additionally, the environmental impact of the installation itself should be considered. If the goal is to reduce a yacht's carbon footprint during operation, it is logical to account for the embodied energy in producing the solar system. For example, manufacturing curved glass requires significantly more energy than assembling flexible panels.

3.2.3 Appearance

The previous chapter outlined three methods for integrating solar panels into a yacht's surface. Each of these approaches has a distinct impact on the visual outcome of the system. This chapter examines the aesthetic considerations of each method, highlighting visual factors that may influence design decisions in luxury yacht construction.

3.2.3.1 Surface finish

The surface finish of the solar panel plays a crucial role in its visual integration with the yacht. It affects how light interacts with the surface, which can influence the appearance from different viewing angles, the appearance of the colour and how well it blends with the surrounding material. Depending on the encapsulation materials, the surface can appear glossy, matte, smooth or textured.

Glass panel
Glass panels typically have a smooth, high-gloss finish, but textured variations such as matte or patterned surfaces can reduce reflections and improve visual integration. Studies show that surface texturing can also enhance performance by reducing reflection and increasing light trapping at the nanoscale level (Kim et al., 2020).

Flexible panel
Flexible panels with glossy, matte, or textured surfaces offer some flexibility in visual integration. The outer material is softer than glass, making it more prone to scratches and wear. Choosing a textured finish can help reduce the visibility of surface damage and improve grip for crew members. Still, textured surfaces also tend to accumulate dirt more quickly, requiring more frequent cleaning to maintain performance and appearance.

Composite panel
Composite-integrated panels typically have a glossy finish, sharing the same gelcoat or resin layer on the surrounding yacht surfaces. This results in a fully unified appearance but limits the options for surface texture.

Figure 23: Left: various samples of textured glass, right: smooth-high gloss finish on car roof (Solarix Solar, n.d.) (Chicago, n.d.)

Figure 24: Left: samples with different textures, right: visible wear on the top surface. Samples provided by Solbian

Figure 25: Composite panels with glossy finish as seen on Sunreef yachts (Sunreef Yachts, 2024)

3.2.3.2 Colourization

Colouring the solar cells can be a key strategy to improve their visual integration. But colourisation reduces efficiency, as altering the cell's surface or adding layers reduces the amount of light that reaches the active material. This section explores the main techniques.

Anti-reflective coating
The first technique is changing the anti-reflective (AR) coating often found on solar cells. The silicon itself has a dark grey colour; the AR coating applied during manufacturing gives the cell its distinct dark blue or black colour. The colour of this coating can be changed by varying the thickness, but at the expense of the efficiency of the cell. This method can be compared with the colouring of sunglass lenses. Figure 26 shows the results of a study into the colorization of silicon solar cells through AR coatings (Rudzikas et al., 2020).

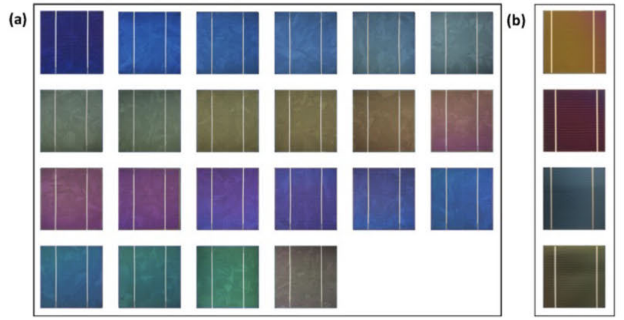


Figure 26: Wide range of colours obtained with the use of AR coatings on silicon solar cells in different colours by varying the thickness of the AR coating. On both polycrystalline cells (a) as on monocrystalline cells (b). (Rudzikas et al.,2020)

Nanostructure coatings
It's also possible to use nanostructured coatings, which have a similar effect to the AR coatings, where the coating reflects a narrow band of visible light to produce a transparent colour. However, these nanocoatings better reflect a specific colour than the AR coatings. Another difference is that this nano coating is applied as an interlayer in the laminate of a flexible solar cell, resulting in a uniformly coloured panel instead of one cell. The efficiency losses can range between 7-30% based on the colour. Figure 27 shows a few colour samples with their efficiency loss.

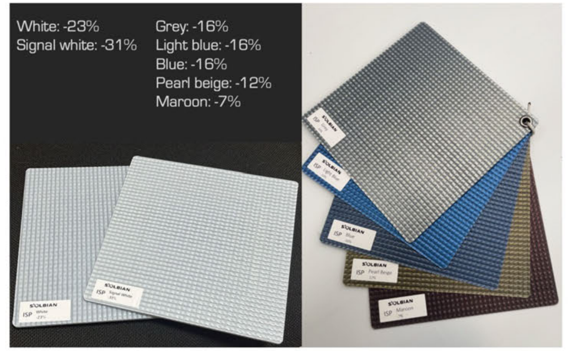


Figure 27: Colour samples of flexible solar panels with nano coating, with the efficiency loss per colour. Provided by Solbain

Masking interlayers
Instead of using a coating, printing a colour or pattern on the EVA interlayer is possible. This method allows for a wide range of designs matching the surrounding surfaces. However, this colouring method is less efficient and strongly depends on the colour and pattern used. Figure 28 shows some design options.

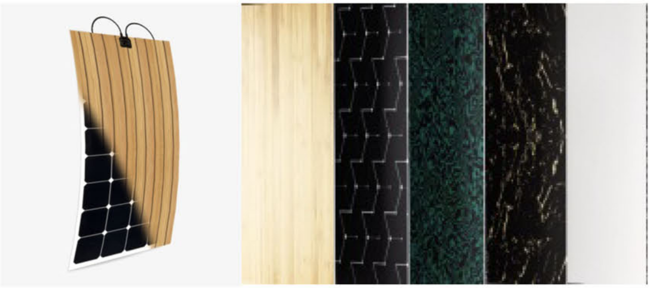


Figure 28: Various design options for a masking layer in the solar panel. (Solbian, 2025).

Coloured front glass
A similar method can be used on the front glass. It involves printing ceramic-based inks and baking them into the glass surface, creating a durable coating. It also allows for a wide range of colours and patterns. The efficiency losses can range from 3% for black panels to 40% for white panels. This technique is mainly used on flat glass panels used in architecture to create colourful facades.

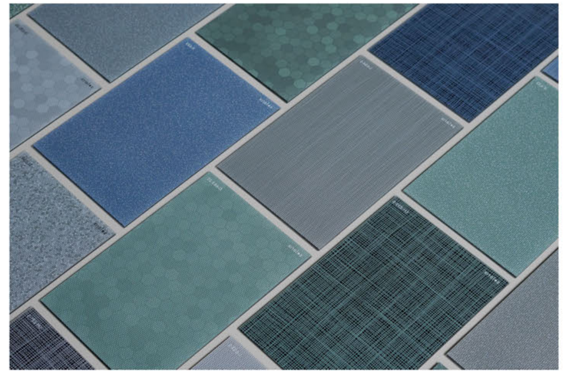


Figure 29: Design examples of coloured solar panels. Adapted from (Solarix Solar, n.d.)

Suitability

Not every colouring method can be used on every type of solar panel. The table below summarises the colourisation methods for each panel type.

Table 3: Summary of which colourisation method is suitable for which panel type

	Flexible panels	Glass panels	Composite panels
Anti-reflective coating	✓	✓	✓
Nanostructure coating	✓		
Masking layer	✓		
Coloured front glass		✓	

3.2.3.3 Layout

In addition to texture and colour, the arrangement of photovoltaic cells also shapes how integration is perceived. The layout does not radically change the identity of the surface. Still, subtle alignment, spacing, and pattern choices can influence whether modules blend with the yacht's design language, stand out as purely technical elements, or become a deliberate visual feature. Exploring these variations offers designers flexibility to make solar integration either discreet or expressive, while still balancing aesthetic and functional constraints

Dummy cells

Most photovoltaic modules are based on a regular grid of rectangular cells, providing technical efficiency and a recognisable visual structure. However, this grid does not always align neatly with the available dimensions on yacht surfaces. In such cases, designers may introduce dummy cells: non-functional replicas extending the pattern where active cells cannot be placed. While dummy cells add no energy contribution, they can help maintain visual consistency and avoid abrupt interruptions in the layout. Figure 30 shows how these dummy cells are used on a hard top.

Figure 30: Solar panels that conform to the surface with the help of dummy cells (Solbian Solar, 2022)

Spacing

Spacing between cells can influence how modules interact with their surroundings. Larger gaps reduce the active cell area but allow more light to pass through, a principle already common in architecture for skylights and solar shading. On yachts, similar layouts could be applied for skylights or shading elements, making the modules visually lighter and allowing them to serve purposes beyond energy generation. Figure 31 shows some practical applications of solar panels with wider spacing.

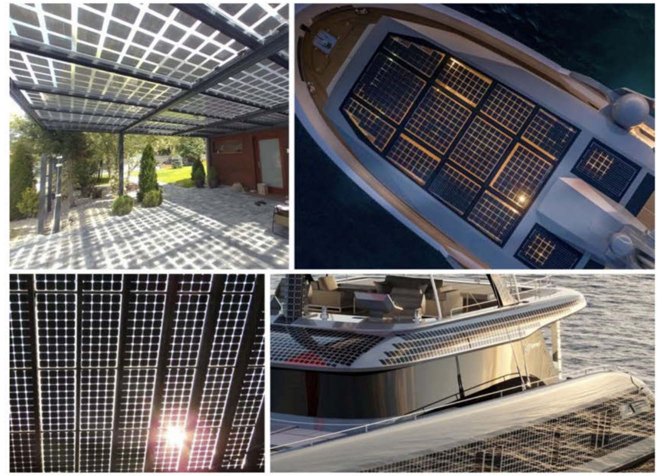


Figure 31: Practical application of panels with wide spaced cells.

Alternative patterns

Beyond spacing, photovoltaic cells can also be arranged in alternative patterns that depart from the conventional rectangular grid. Staggered, diagonal, or geometric layouts have already been explored in architecture and automotive to create distinctive visual effects, and similar approaches could be translated to yachts. Such patterns may not improve efficiency, but they can shift perception from a technical surface to a deliberate design feature, making solar integration subtle or expressive. Figure 32 shows a few of these patterns applied in architecture and automotive.

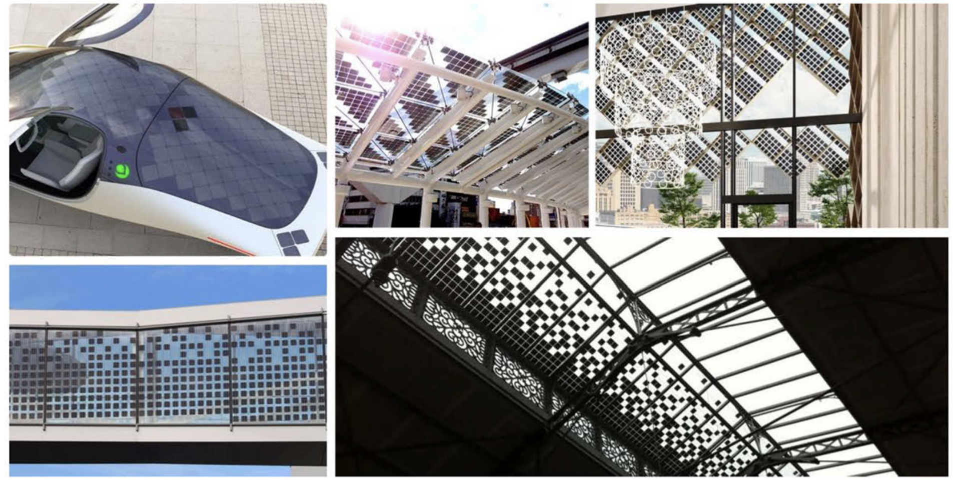


Figure 32: Practical application of patterned solar panels. Often used in architecture or automotive.

Impact

The impact of alternative layouts can be illustrated by comparing different patterns and the percentage of surface they cover with working cells. Such comparisons clarify how aesthetic choices directly influence appearance and the share of active solar area. Figure 33 shows six different layouts with the amount of surface covered by working solar cells.

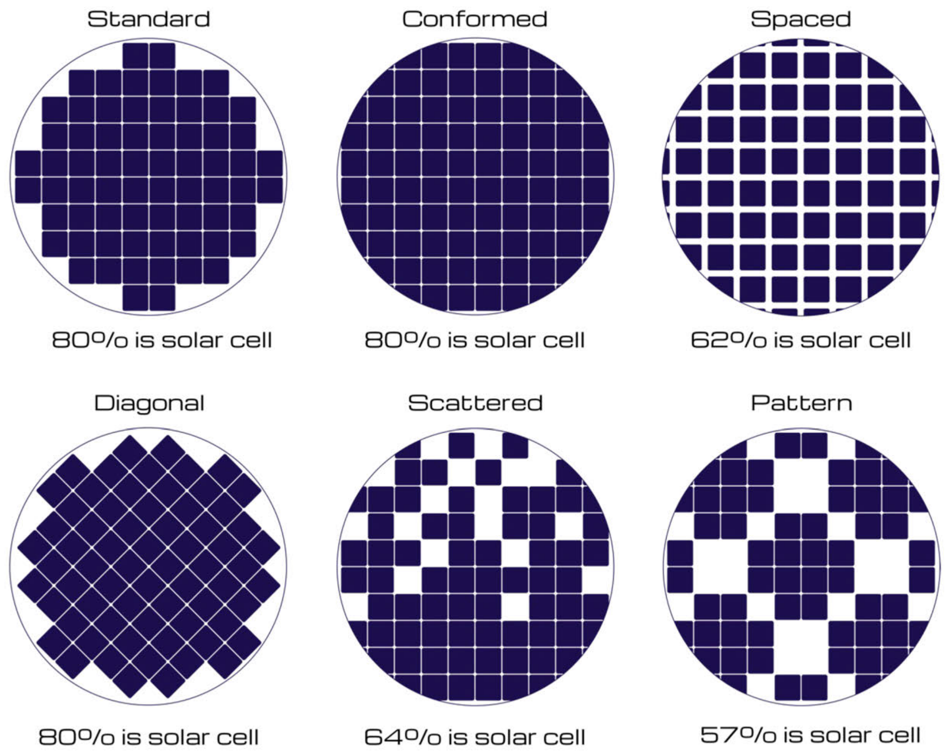


Figure 33: Comparison of different cell layouts, showing the amount of surface covered with working cells

Chapter 3 - Takeaways:

Mounting options

- Conventional solar panel mounting methods are unsuitable for luxury yachts due to visible frames, exposed cables, and poor visual integration
- Three integration methods align best with the luxury yacht context:
  - Flexible stick-on panels
  - Glass-encapsulated panels
  - Composite-encapsulated panels

Practical considerations

- **Lifespan:** Glass offers the longest proven service life; flexible panels degrade faster; composite integration shows promise but lacks long-term data.
- **Maintenance**: all panels require cleaning to maintain output, especially in a marine environment; anti-slip treatments may be needed for safe access for the cleaning crew.
- **Repairability**: Flexible panels are easiest to replace; glass panels require entire unit replacement; composite panels are very time-consuming to repair.
- **Installation complexity**: Flexible panels are quickest to install; glass and composite methods require custom fabrication and longer build times.

Appearance

- **Surface finish:** Glass offers smooth or textured finishes; flexible panels offer texture options but scratch more easily; composite panels match the surrounding gelcoat but have limited texture variety.
- **Colourisation:** Colour modification improves visual integration but reduces efficiency. Options include antireflective coating changes, nanostructure coating, printed interlayers, and coloured front glass, each with varying efficiency losses.
- **Layout:** The layout of the cells can be altered to match the surface or create interesting patterns. Contours can be matched by adding dummy cells to fill the empty spaces.

4. Vision and requirements

4.1 Design Vision

The previous chapters showed that integrating PV systems on superyachts is constrained by limited suitable surfaces and the industry's high aesthetic standards. Yacht design demands seamless forms and flawless surface finishes, which restricts where and how PV can be applied. However, developments in PV technology enable closer alignment with these design standards, though customizable options in mounting, colouring and surface finishes. Realising seamless integration requires incorporating PV considerations early in the design process rather than just a technical add-on.

This thesis assumes that PV should not be treated as an afterthought but as a part of the yacht's design. Achieving this requires support for yacht designers in three interconnected domains. First, **suitable surfaces** must be considered, since successful PV integration relies on identifying and optimising yacht surfaces that can realistically host panels. Factors like orientation, shading, and geometry determine feasibility and visual quality. Second, **appearance and aesthetics** are central in the design of luxury yachts, meaning that PV integration requires awareness of the available appearance options, such as colour, finish, and cell layout, and their impact on visual quality and energy performance. Finally, **performance** must be made transparent. Clear information on energy yield is crucial for balancing aesthetics and functionality, and designers should be able to immediately understand the performance implications of their choices, including the effects of surface orientation, shading, and panel type.

This can be combined in the following vision statement:

The integration of PV on luxury yachts is approached as a seamless extension of yacht architecture rather than a technical add-on. Designers are supported with accessible insights into surfaces, aesthetics, and performance, enabling them to explore integration possibilities and make well-informed decisions from the earliest stages of the design process.

4.2 List of Requirements

To translate this vision into practical guidance, the following list of requirements defines what the guidelines and the design tool must address. These requirements ensure that the envisioned support for yacht designers is conceptual but also concrete and actionable.

Table 4: List of requirements

Category	Requirements	Key aspect
Aesthetics	The guidelines must provide strategies for visual integration that align with luxury yacht standards, such as form continuity and discreet placement	Yield estimation, solar accessment
Surface	The guidelines must support designers in identifying which yacht surfaces are suitable for PV integration, taking into account both functional use and design quality	Surface suitablility
Performance	The guidelines must provide tools or references to help estimate realistic energy yield based on surface orientation and shading	Yield estimation, solar accessment
	The PV technologies discussed in the guidelines must have a Technology Readiness Level (TRL) of 6 or higher	Technical feasibility
	The guidelines must help designers identify optimal geometries for PV placement, so that they can be considered or adapted early in the design process.	Geometry suitability, early-stage integration
Cross-cutting	The guidelines should help designers balance performance, usability, and aesthetics by providing structured trade-off considerations	Integrated design decision-making

5. Surface Design

This chapter defines what makes a yacht surface suitable for PV integration and where to pay attention to while designing. It covers the effect of orientation and shape on irradiation, the mechanical limitations of the solar cells, and strategies to use during design.

5.1 Surface irradiation

The angle at which sunlight strikes a solar panel, referred to as the angle of incidence (AOI), significantly impacts the panel's energy output. Maximum direct irradiation (G_B) is achieved when sunlight hits the panel perpendicularly, and it and decreases as the AOI increases. The direct irradiation on the panel can be calculated with the following equation:

$$G_B = G_{B_n}\cos(\emptyset)$$

G_B = *Direct irradiation*
G_{B_n} = *Direct normal irradiation*
$\emptyset$ = *Angle of incident*

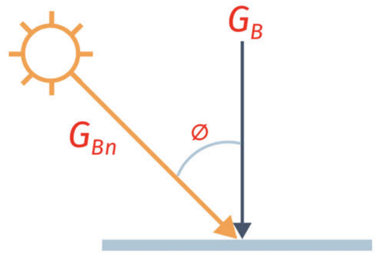


Figure 34: Direct irradiation on horizontal surface

As the angle deviates from perpendicular, the same amount of solar energy is spread over a larger surface area, reducing the energy density and thus the panel's output. This effect is visualised in Figure 35.

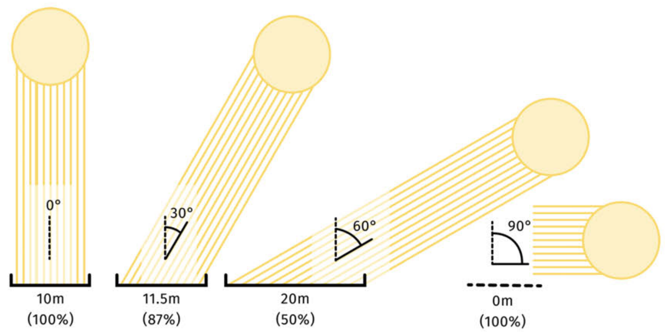


Figure 35: The effect of angle of incidence on the area illuminated and the amount of energy

Horizontal panel orientation

Horizontally mounted panels perform best around midday, when sunlight hits them nearly perpendicularly. Their output is less affected by the vessel's rotation, making them stable under movement. Therefore, horizontal surfaces such as hardtops or dodgers are ideal for steady power generation throughout the day.

Vertical panel orientation

Vertically mounted panels are more sensitive to the yacht's orientation. Their steep angle reduces efficiency at midday, but they perform better in the early morning and late afternoon when sunlight is lower. They can also gain 10–15% extra output from reflected sunlight off the water.

Curved Surfaces

Many yacht surfaces are not strictly horizontal or vertical but curved. On such surfaces, the angle of incidence changes along the curvature, leading to non-uniform irradiance across the panel. This uneven distribution can lower overall panel power output, as weaker sections reduce the production of stronger ones when connected within a single module. The effect is minor on large radii, but smaller radii can be mitigated by dividing the surface into multiple smaller modules, each with its own charge controller, so they operate more independently.

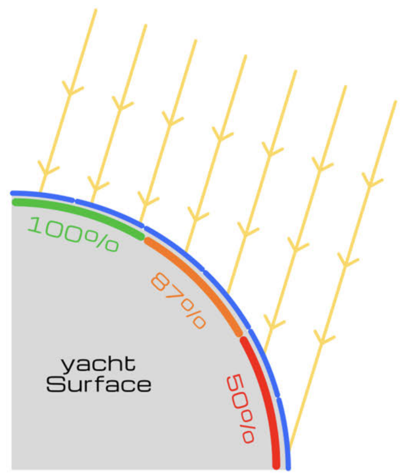


Figure 36: The uneven irradiance across a curved surface.

Design considerations

While horizontal surfaces should be prioritised for their stable and efficient energy production, vertical and curved surfaces can complement overall performance, particularly when horizontal panels are less effective. A hybrid approach that strategically combines panels of different orientations can help distribute energy generation more evenly throughout the day, as seen in the graph below (Barbour, 2020).

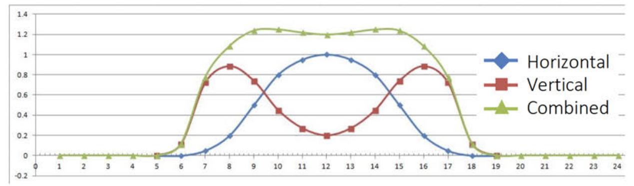


Figure 37: Result of a test installation with horizontal and vertical panels. Adapted from Barbour (2020)

Ultimately, achieving optimal solar yield on a yacht is more complex than in stationary applications. Designers should focus on maximising the use of horizontal surfaces while recognising the value of vertical and curved areas in increasing energy generation throughout the day and improving system resilience in dynamic lighting conditions.

5.2 Mechanical limits PV cell

The curvature of the integration surface is a primary constraint for applying photovoltaic (PV) technology on yachts. Flexible PV modules are generally limited to single-axis bending, with manufacturers such as Solbian specifying a minimum bending radius of 1 m to prevent mechanical stress and microcracks in the cells or interconnections. For a module length of 1 m, this corresponds to a maximum arc height of approximately 122 mm (Figure X) (Solbian, n.d.).

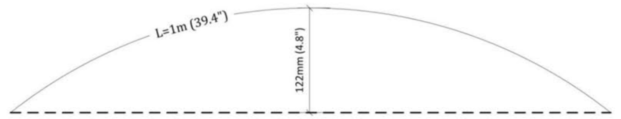


Figure 38: maximum bend radius of a flexible PV module, as specified by suppliers. Adapted from Solbian (n.d.).

Experimental validation by Vallerotto et al. (2023) on modules with cylindrical curvature also confirms that modules with a 1 m radius can maintain electrical performance within ±0.5% of the ideal cosine response when illuminated with a collimated solar simulator (Vallerotto et al., 2023).

Double-curved surfaces present additional challenges. Standard flexible PV modules are designed for cylindrical curvature only, as spherical shaping subjects the brittle crystalline cells to simultaneous tensile and compressive stresses, significantly increasing the likelihood of fracture or delamination.

Tests conducted for this study using single monocrystalline cells adhered to 3D-printed spherical jigs (Figures 39 and 40) showed no visible cracks or deformations when the radius exceeded approximately 2 metres.

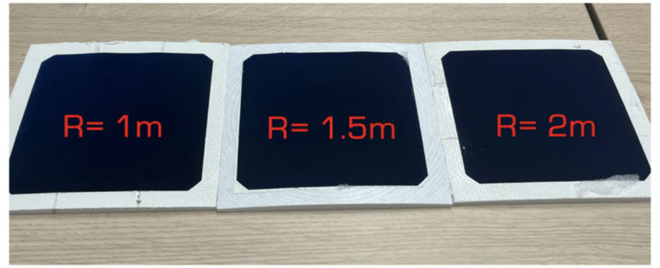


Figure 39: three test sample, monocrystalline cells on spherical surface with radii ranging from 1m to 2m

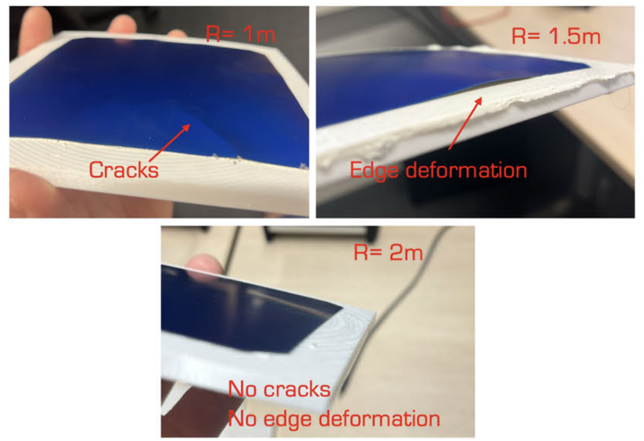


Figure 40: sample 1 and 2 did not conform to the spherical surface. Sample 3 seemed to conform to the spherical surface without cracks or deformation

Nonetheless, this experiment did not replicate the constraints of a complete module, where cell interconnections, busbar layout, and encapsulation impose additional mechanical limitations.

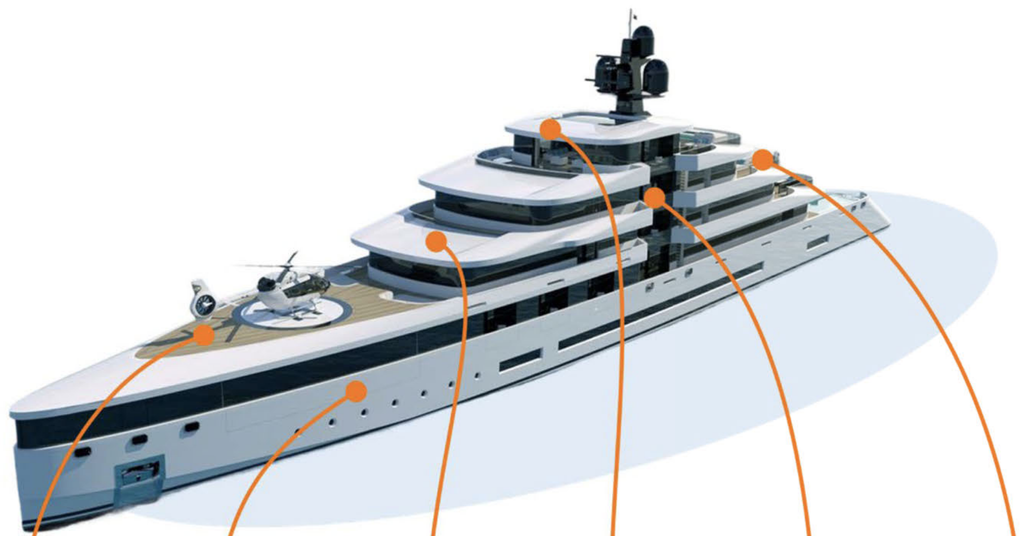
In conclusion, pre-manufactured flexible panels should be restricted to single-curved surfaces with radii of at least 1 metre for practical yacht applications. Double-curved integration may be feasible through custom cell placement and post-installation encapsulation, but this approach requires further testing before it can be considered a reliable option.

5.3 Design strategies

This section outlines how yacht surfaces can be optimised for effective PV integration, focusing on identifying suitable areas and understanding how geometries can be optimised for more solar area.

5.3.1 Surface locations

Some yacht surfaces offer much greater potential for solar integration than others. These high-value areas should be prioritised in the design, depending on exposure, shading, and accessibility, while still considering their other functions. Figure 41 highlights these surfaces and compares their suitability for PV integration.



	Deck	Hull	Front Dodger	Hard top	Window	Canopies
Pro's	• Performs best at high sun angles • Flat surface • High exposure	• Large area • Preforms best at low sun angles • benefit from reflection of water	• Preforms best at high sun angles • High exposure • No other functionalities	• Preforms best at high sun angles • High exposure • No other functionalities • Flat	• flat surface • preforms best at low sun angles	• Performs best at high sun angles • High exposure • No other functionalities
Cons	• High risk of damage • Generate to much heat for bare feet	• Higher risk on damage	• In direct line of sights • Often curved	• May encounter shadows from navigation equipment.	• Low efficiency when transparancy is desired • Often in shade	• May need to be retractable • Often not rigid
Suitability	--	+	++	++	-	+

Figure 41: suitability of several yacht surfaces compared. Adapted from (SuperYachtTimes, 2021)

5.3.2 Surface geometry

The deck layout largely determines how much suitable surface area remains available for solar integration. Yachts with long, open decks and few vertical structures offer broad, unshaded regions that can be efficiently equipped with solar arrays. In contrast, designs with multiple deck layers introduce overhangs and vertical elements that reduce the proportion of usable surface area. Figure 42 compares a low-profile and a multi-deck design, showing how additional layers gradually fragment potential solar regions and lower the overall efficiency of integration.

Figure 42: Comparison between low-profile and multi-deck yacht designs in terms of loss effective horizontal PV surface area

Favourable surface geometries

Surfaces with minimal double curvature, large horizontal spans, and smooth, unobstructed geometry offer the most significant potential for integration of PV systems.

Examples can be found in yachts with expansive hardtops and flush foredecks, where the geometry allows for continuous module placement with minimal interruption (Figure 43).

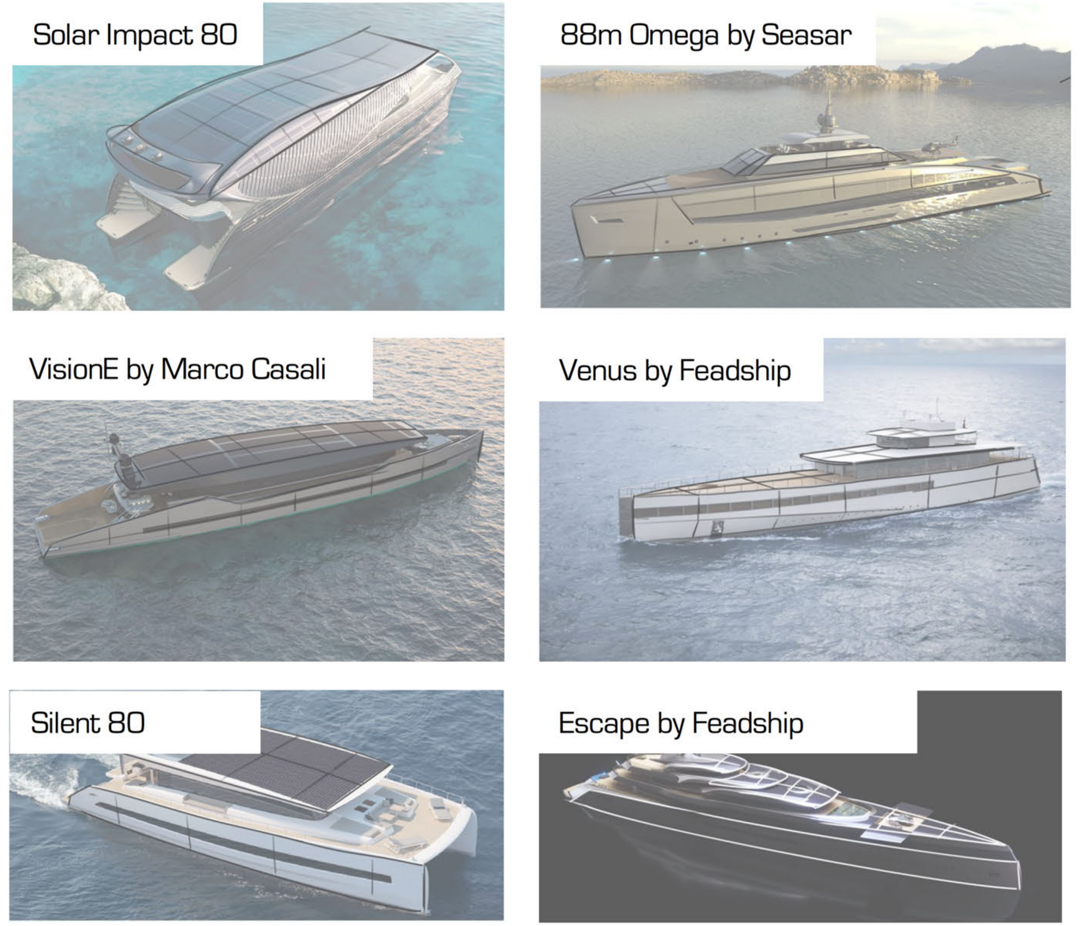


Figure 43: Example of a yacht design with large, flat surfaces suitable for PV integration.

Figure 44 illustrates how surfaces could be optimised by showing two front dodger designs. The first, with a double-curved surface, cannot accommodate solar panels, while the second has a single curvature, which is ideal for panel integration, while maintaining a similar aesthetics.

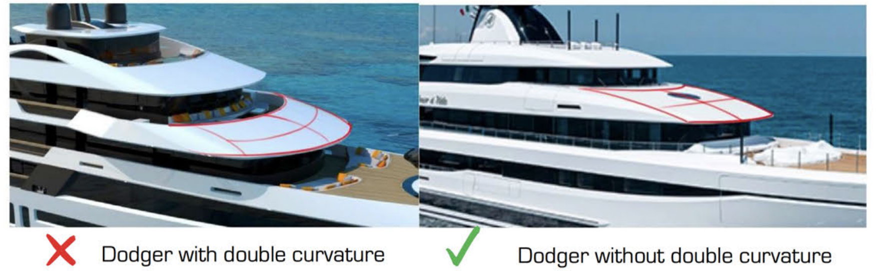


Figure 44: Comparison between double-curved and single-curved dodger designs.

Proportions

From a practical layout perspective, designing the PV integration in multiples of the typical cell dimension (approximately 130x130mm) is advantageous. This avoids gaps or unused space that cannot host a whole cell, thereby maximising coverage and energy yield. Consider a long, narrow surface such as a side dodger with a size of 650x8000mm: this space ideally fits a panel of 5x60 cells of 130mm each. If, however, the height was only 600mm, one entire row would be lost. So, an 8% reduction of the surface area results in a 20% loss in solar area (Figure 45).

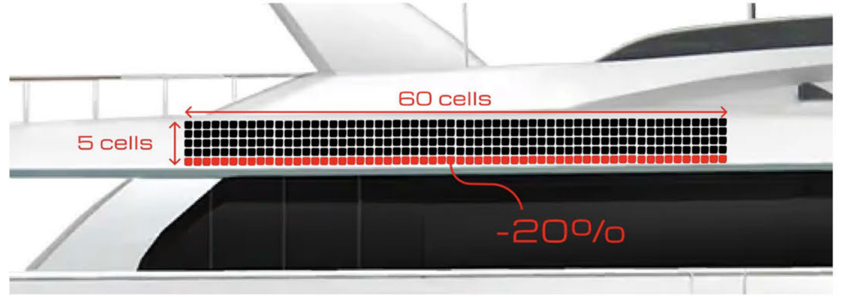


Figure 45: loss of cells due to an inadequate sizing of the surface

The same principle applies when solar panels are used with standard sizes: Consider an available surface of 22.3 m². Filling it with 26 large panels (104 W each) covers 15.73 m² and delivers 2704 W, equal to 172 W per m² of panel surface. Adding ten smaller panels (52 W each) to use more space delivers 3224 W over 19.03 m² of panel surface, or 169 W per m². Although the total output increases by 19%, the specific power per square meter of panel surface decreases. This illustrates that filling gaps with smaller panels does not necessarily lead to proportional gains in energy density.

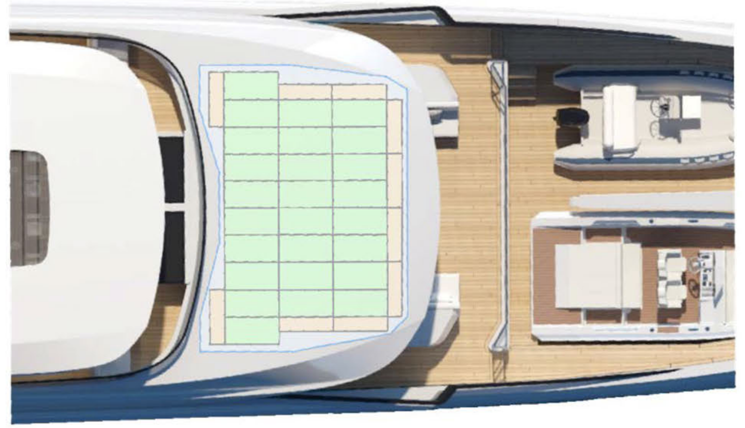


Figure 46: Available surface area filled with large and small panels

In conclusion, PV integration is most effective on large, well-proportioned surfaces that fit complete cells. While smaller panels can increase total output by filling fragmented areas, they often lower efficiency per surface and add complexity. Therefore, balancing contiguous layouts with the selective use of smaller panels is key to maximising performance and integration quality.

6. Surface analysis and solar potential

An essential step in a solar yacht's design process is assessing each surface's suitability for PV integration and estimating its potential energy yield. This assessment provides valuable feedback for designers, enabling informed decisions and helping to balance aesthetics with performance, directly contributing to the main research question.

6.1 Surface evaluation

This section evaluates whether a given surface geometry is suitable for PV integration by checking if it's within the curvature constraints and analysing its solar exposure.

These evaluations can be done with the help of 3d CAD software with building analysis and simulation features. For this thesis, Rhinoceros 3d is used due to its frequent use by yacht designers and its extensive features, as well as the option to use plugins like Grasshopper for additional features like a solar irradiation study.

Three analyses are relevant to evaluate a surface for its suitability for PV integration:

- Curvature Analysis: provides visual feedback on surface geometry and curvature limits
- Shadow Analysis: provides visual feedback on whether a surface is shaded in certain conditions
- Irradiation Analysis: provides both visual and numeric feedback on surface irradiation and received solar energy

Curvature Analysis

To determine where solar panels can be safely integrated on a 3d surface, the method of Sato et al. (2024) was followed. The approach analyses the local curvature of the surface and links it to the mechanical stress in crystalline silicon (c-Si) as a bending force is applied.

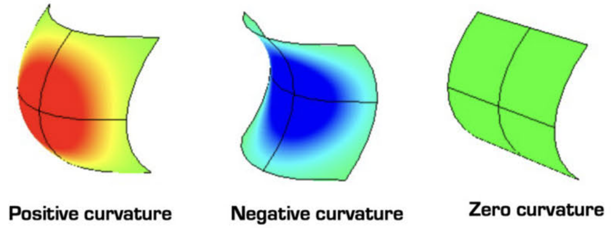


Figure 47: Gaussian curvatures

Curvature Analysis in Rhino in Gaussian mode, a maximum range corresponding to the stress range that a solar cell can endure, can be set. In the study of Sato et al. (2024), it was determined that, for a monocrystalline cell, this range is between -0.30 < K < 0.35 m-2. Figure 48 shows what this will look like in practice. In this example, the surface curvature shows no double curvature, which is suitable for solar panels.

The mean curvature calculation determines if the curvature is larger than a 1-meter radius limit, as discussed in Chapter 4.1.1. Cells can be applied safely as long as H < 0.5 m-1. This means that red-coloured areas cannot be used as solar surfaces. Figure 49 shows what this will look like in practice. In this example, the surface is suitable for solar panels.

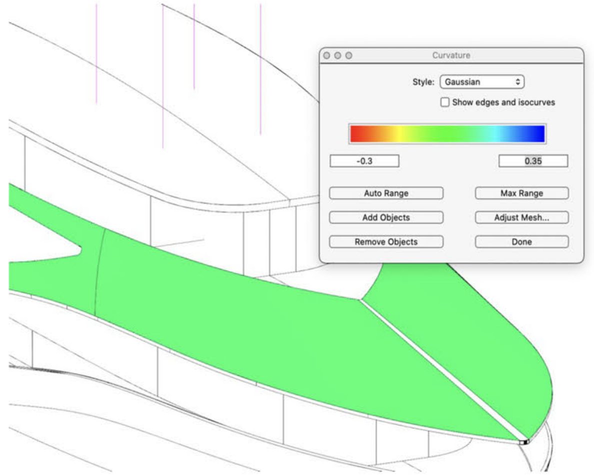


Figure 48: Gaussian curvature analysis performed with a range of -0.30 < K < 0.35 m^{-2}

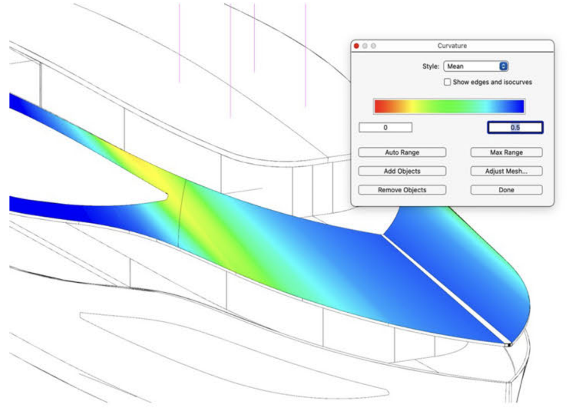


Figure 49: Mean curvature analysis performed with 0 < H < 0.5m^{-1} which corresponds to a 1m radius limit

Shadow Analysis

The shadow analysis can be used to get a better understanding of how structures around the surface affect the exposure of that surface. This allows designers to be more mindful of the area around the surface. This evaluation can be performed in various 3d software with rendering features. Figure 50 shows how an obstruction casts a shadow at different times of the day. As this evaluation can be helpful to understand how the sun moves around the yacht, it will not provide information about the amount of exposure. For that, an irradiation analysis is needed.

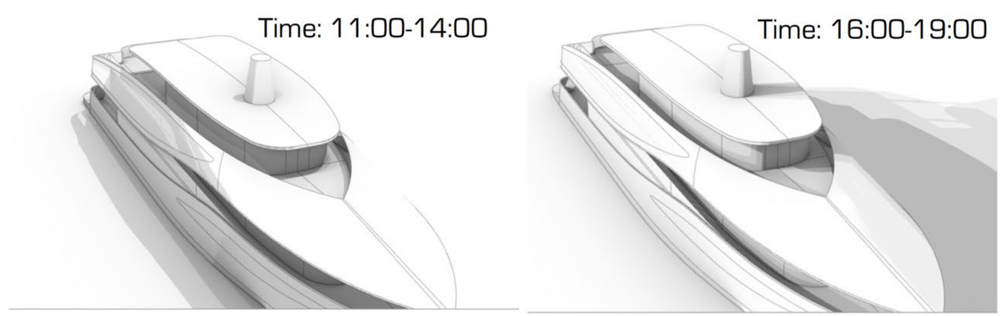


Figure 50: Comparison of shadows of structures during different times of the day

Irradiation Analysis

The primary method to evaluate the potential of a surface is through irradiation analysis. For this purpose, the Grasshopper plugin is combined with the Ladybug extension. Ladybug enables the visualisation and analysis of weather data within Grasshopper, including sun paths and irradiation studies.

Ladybug uses EPW (EnergyPlus Weather) files as its primary source of environmental data. These files provide hourly values of direct standard, diffuse horizontal, and global horizontal solar radiation over a full year (8,760 hours), along with location and time data for irradiation analysis. Although developed for buildings, they can also be used for yacht surfaces to evaluate the solar irradiation and energy potential.

The irradiation analysis is set up in Grasshopper with attributes that handle the EPW data, date and time, sun path visualisation and the irradiation analysis itself. Figure 51 shows the Grasshopper structure of such an analysis.

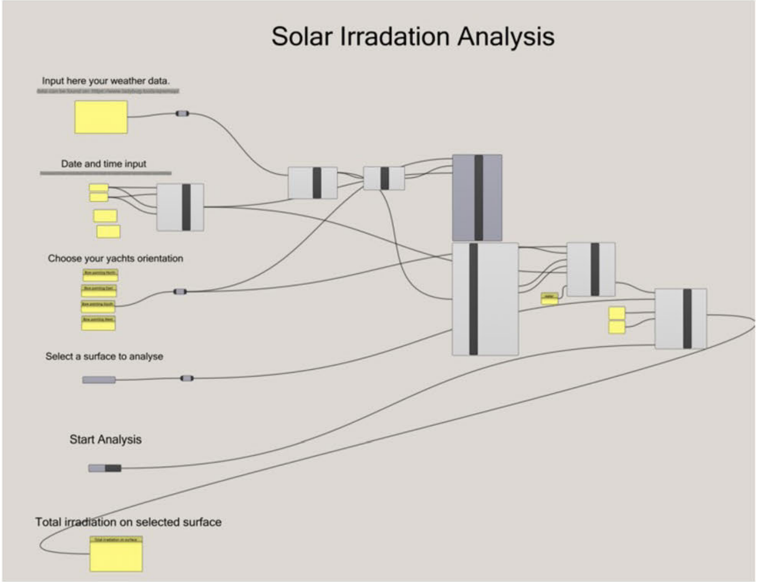


Figure 51: Structure of a Solar irradiation Analysis in Grasshopper using the Ladybug plugin. The full grasshopper structure can be found in Appendix C.

This irradiation analysis allows the designer to understand better how the surfaces are irradiated in various scenarios, such as different orientations and other times of the day. Figures 52 and 53 on the next page show the results of such scenarios, with red showing the highest amount of irradiation and blue the lowest. Chapter 4.3 will show how an irradiation analysis can be used to estimate the performance of the PV system.

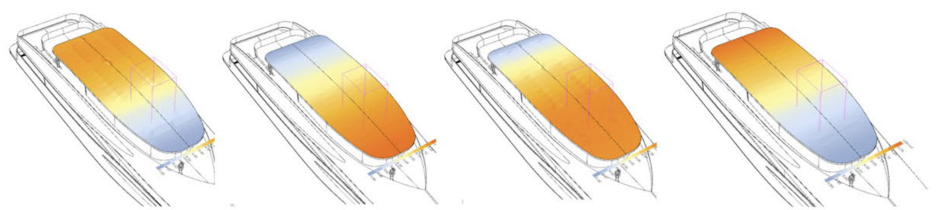


Figure 52: Comparison of irradiation on the hardtop with different yacht orientations

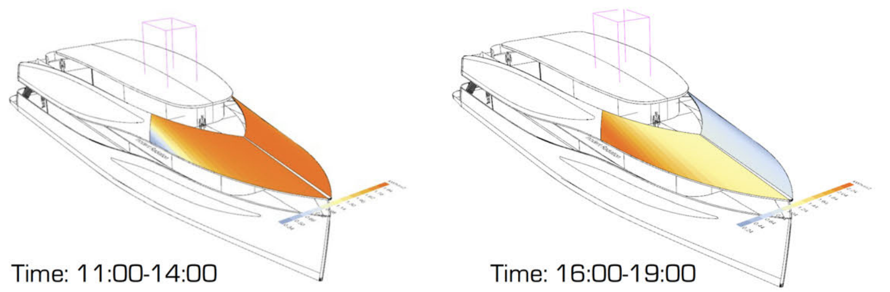


Figure 53: Comparison of Irradiation on the front dodger at mid-day and the end of the day

6.2 Solar energy yield estimation

To evaluate the performance of a yacht design, it is necessary to estimate how much solar energy falls on a surface and how much electricity this generates.

6.2.1 General estimation

In the early stages of the design process, a quick estimation of the potential solar energy yield is valuable for evaluating different design configurations without relying on time-consuming simulations. This general estimation requires only the following input parameters:

- The average annual solar irradiation on both horizontal and vertical planes
- The available surface area for photovoltaic integration
- The panel efficiency
- Performance factor to account for real-world losses

Horizontal and vertical planes

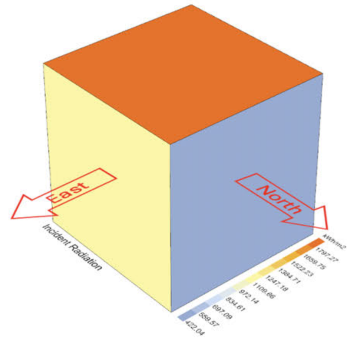
To simplify the general estimation, we assume that the yacht's surface consists only of horizontal and vertical planes. A solar irradiation analysis was performed to determine an average value for annual solar irradiation on a horizontal and vertical plane.

The weather data for the irradiation analysis operating area must be chosen as input. The Mediterranean Sea is selected for demonstration purposes, as approximately 70 per cent of the world's superyachts are in the Mediterranean year-round (Mancini et al., 2020).

In the Mediterranean, the annual average irradiation on a horizontal surface is approximately 1800 kWh/m2 yearly (Polo, 2015). By trial and error, the Greek island of Mykonos was the best reference location, matching the Mediterranean annual average irradiation. The weather data from this location was used in the solar irradiation analysis.

A cube was modelled for the analysis, and the irradiation on each surface was measured. The average of the four vertical sides was then taken as the annual average vertical irradiation.

This approach assumes that a vertical surface is equally exposed to sunlight from all directions yearly. The resulting average vertical irradiation was approximately 960 kWh/m² per year. Figure 54 shows the results of this irradiation analysis. The same analysis was performed, as shown in Table 5, for several popular superyacht operating areas, according to Tutino Yachts (2025)



annual irradiation on vertical surface		
direction	**irradiation**	
Horizontal	1797	kWh/m2/year
north	422	kWh/m2/year
east	1103	kWh/m2/year
south	1323	kWh/m2/year
west	980	kWh/m2/year
average	957	kWh/m2/year

Figure 54: Solar irradiation analysis performed on a cube to determine the average vertical irradiation.

Tabel 5: Average annual irradiation values for horizontal and vertical surfaces of several popular superyacht operating areas. More detail can be found in Appendix D.

	Average Irradiation (kWh/m2/year)	
Operating area	**Horizontal**	**Verticaal**
French Riviera	1420	887
Greek Islands	1797	957
Caribbean	2042	929
Arab Gulf	2150	1003
Malidives	2060	888
Florida	1816	879

A panel efficiency of 24 per cent was used for the remaining parameters, representing a high-quality monocrystalline photovoltaic cell. A performance factor of 0.85 was applied, assuming a 10 per cent annual loss due to shading effects and an additional 5 per cent loss from electrical system inefficiencies. All these inputs were combined into a calculation tool, as illustrated in Table 6.

Tabel 6: General solar energy estimation tool, can also be found in Appendix E

Solar energy assumptions				
Annual horizontal irradiation			1800 kWh/m2/year	
Annual vertical irradiation			960 kWh/m2/year	
Conversion efficiency			24%	
Performance factor			0,85	
Cell density			100%	
Loss due to colouring			0%	
	m2 solar area	GWh/year	kWh/year	
Horizontal Solar energy harvest	0	0,000		0,000
Vertical Solar energy harvested	0	0,000		0,000
Total	0	0,000		

This method provides a quick indication of potential solar energy yield, but it relies on several simplifications:

- **Single-location climate data:** Uses average irradiation from one Mediterranean location, not accounting for seasonal variation, unusual weather, or other cruising regions.
- **Vertical irradiation approximation:** Assumes equal exposure for all vertical surfaces based on four cardinal orientations, which may not reflect real operational patterns.
- **Panel efficiency assumption:** Uses nominal efficiency under standard test conditions, ignoring variations from temperature, partial shading, and degradation.
- **Performance factor uncertainty:** The 0.85 value is an educated guess of the impact of shading and electrical losses, which may differ.
- **Surface area assumption:** Assumes full PV coverage of the evaluated area, which may not be possible due to fittings, curves, or integration constraints.
- **No inter-surface shading:** The shading effects between yacht surfaces are not considered.
- **Simplified geometry:** Treats surfaces as flat planes, ignoring curvature effects on irradiation.
- **No dynamic effects:** Vessel motion, rolling, and pitching are not included.

Conclusion

Although simplified, this method is effective for early-stage evaluations where the goal is to compare surfaces quickly. It provides valuable relative insights without complex simulations, acknowledging that detailed modelling should follow in later design stages.

6.2.2 Detailed estimation

The detailed estimation method is applied once the PV surface areas have been defined. At this stage, the analysis is conducted on the 3D model of the yacht (Figure 55).

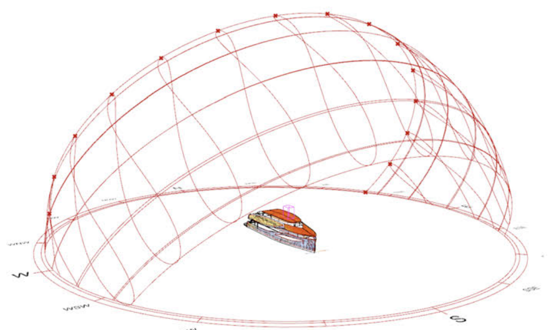


Figure 55: Solar irradiation analysis on the 3D model of the yacht.

The solar irradiation analysis is performed for all four cardinal orientations, and the results are averaged to approximate the expected annual exposure. Unlike the general estimation, the different surfaces are analysed separately to provide higher accuracy.

Two additional parameters are introduced in this stage:

- **Cell coverage**: the percentage of the surface area covered by photovoltaic cells
- **Colour loss:** the percentage of performance loss caused by colouring treatments applied to the cells.

These parameters allow the estimation to reflect the integration design rather than idealised conditions accurately.

The analysis produces estimated yields for three scenarios:

- **The maximum yield:** assumed during the summer solstice
- **The minimum yield:** assumed during the winter solstice,
- The annual average yield

These results are then compared to the yacht's energy demand using the calculation tool described in Chapter 2.1. The comparison (Figure 56 on the next page) provides insight into how much energy demand can be met by the integrated photovoltaic system under realistic operating conditions. The complete tool can be found in Appendix F.

scenario	total energy harvesting		hotel load covered
Highest day	524	kWh	58%
Lowest day	178	kWh	19%
Daily average	359	kWh	39%

Surface	Area (m2)	Coverage	Colour loss
Hard top	192	73%	0%
Front dodger	103	75%	0%
Side dodger	140	40%	0%
Hull	280	75%	0%
Deck	90	0%	0%
Balustrates/windows	146	0%	0%

Average energy usage			Annual total ene	Annual Hotel energy	Annual Sailing Energy
	GT	GWh/GT	GWh	GWh	GWh
50m yacht	350	0,00216	0,756	0,33	0,42
			Daily average	Daily average Hotel energy	Daily average sailing energy
			kWh	kWh	kWh
			2071	911	1160

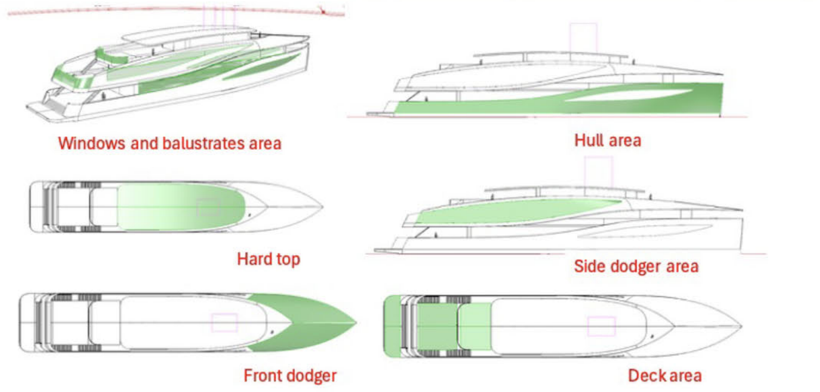


Figure 56: Result of detailed solar energy estimation of a yacht design by Coase Design

Assumptions

- The yacht's orientation over time is equally distributed among the four cardinal directions.
- Weather data and solar position models accurately represent the selected operational region.
- The specified cell coverage percentage is achievable within the integration constraints.
- Losses due to cell colouring are constant and independent of lighting conditions.
- The defined surface boundaries in the model match the real integrated photovoltaic areas.
- All other losses (such as shading and electrical inefficiencies) are covered by the correction factor defined earlier.

Limitations

- Seasonal and daily variations are represented only by the solstice extremes and the annual average, simplifying the real solar availability variability.
- The assumption of equal orientation distribution may not reflect actual operational patterns, especially if the yacht spends prolonged periods at anchor or in specific cruising routes.
- The accuracy of the results depends on the precision of the 3D model and how closely it reflects the final integration design.
- The analysis assumes static conditions for each orientation and does not include dynamic effects such as vessel motion, pitching, or rolling.

7. | Co-Design

A co-design session was conducted in collaboration with Coase Design. This co-design aimed to explore a solar-powered yacht's potential and apply the knowledge gained in previous chapters. Furthermore, it provided insight into how this knowledge supports yacht designers in the early-stage integration of PV systems on luxury yachts, balancing aesthetics and performance, thereby contributing to answering the main research question.

The collaboration in this co-design session is as follows: the yacht designer is provided with new guidelines and feedback in each step of the design process. These feedback moments are in the form of design meetings. After each meeting, the current iteration is discussed, and feedback and new guidelines are provided. In between the meetings, the designer works on the next iteration of the yacht design.

7.1 Initial concept

This section outlines the development of an initial concept for a 50-meter solar yacht. It assesses the solar potential, defines the design goal, and presents the first iteration.

7.1.1 Solar Potential

To establish a realistic view of the design of a solar-powered yacht, a calculation was conducted on a typical 50-meter yacht. The B.Now 50M Oasis by Benetti was chosen as a reference yacht because it represents a typical modern 50-meter superyacht in size, proportions, and operational profile. The estimated average annual energy usage is based on the GT of the yacht, as described in chapter 2.1. The GT is 499 as shown in the yacht's specs (source). Figure 67 gives an overview of this data.

The estimation for solar energy harvesting described in Chapter 6.2 determines how much solar area is needed to make this yacht fully solar powered. The estimations assume horizontally oriented panels. Figure 68 shows the result of the calculations.

Figure 57: B. Now 50m Oasis by Benetti specs and energy usage (estimated with the method described in chapter 2.1.

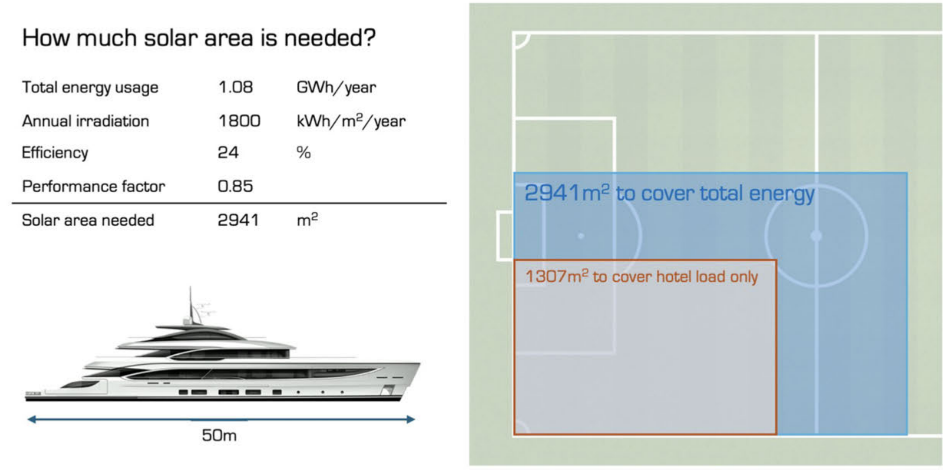


Figure 58: How much solar area is needed to cover the energy demand of a typical 50m yacht. Estimation is based on the method shown in Chapter 6.2.

Figure 68 shows the exposed surface area of the 50-metre yacht. In the theoretical scenario that the entire surface area could be utilised for a PV panel, the resulting area would still fall short of the area needed to cover the hotel load. In reality, only a fraction of these surfaces is practically available for integration due to aesthetic, functional, and technical constraints. This shows that relying solely on solar energy to cover the yacht's energy needs is not feasible. Nevertheless, assessing how much energy can realistically be generated through solar integration remains valuable, as it can meaningfully reduce the yacht's dependency on fossil fuels and support more sustainable operations.

7.1.2 Design goal

The concept design aims to design a superyacht with optimised surface areas for PV integration. The yacht should fit the following specs.

- Length: 50m
- Beam: 10m
- Gross Tonnage (GT): <500
- Operating area: Mediterranean Sea

The following instructions were given to the yacht designer, based on previous chapters:
Design a yacht with enlarged external surface areas and avoid small radii and double curvatures, yet ensure the result remains a realistic and credible superyacht.

7.1.3 First iteration

The design goal and instructions resulted in Coase's initial surface design. Figure 69 shows different views of the design, which features long continuous surfaces which show potential for PV integration.

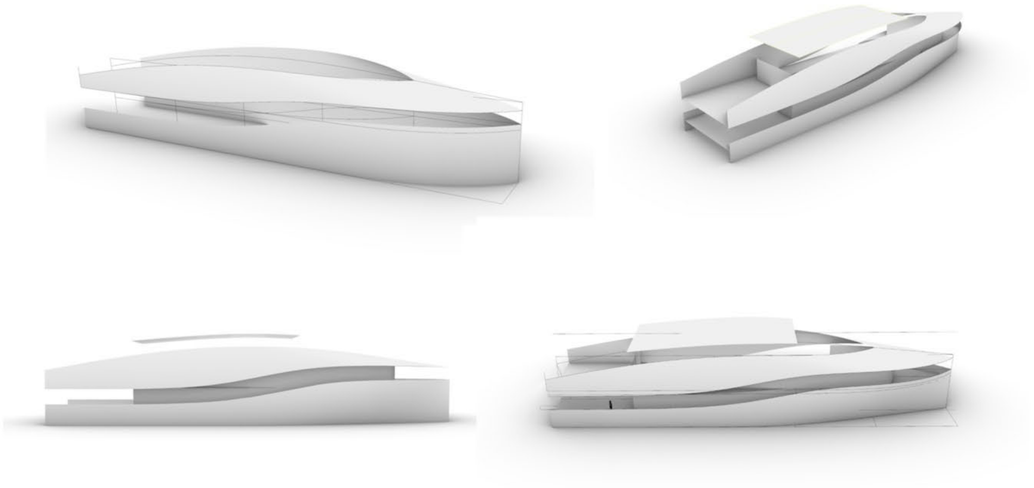


Figure 59: Initial design solar yacht by Coase, featuring basic shapes and proportions

7.2 Evaluation

The second step in the design process is to evaluate the surfaces of this first iteration. Here, the analysis methods described in Chapter 6.1 will be used to assess the geometry of the surfaces. The yacht designer will receive the analysis results and decide to optimise the surfaces further or continue to more details.

A curvature analysis is performed on these surfaces, and the results are shared with the yacht designer.

Curvature analysis

First, the curvature analysis uses the Gaussian style, which shows if there are any areas with double curvatures that could cause a problem with PV integration. The model only shows green areas, meaning no double curvatures exist.

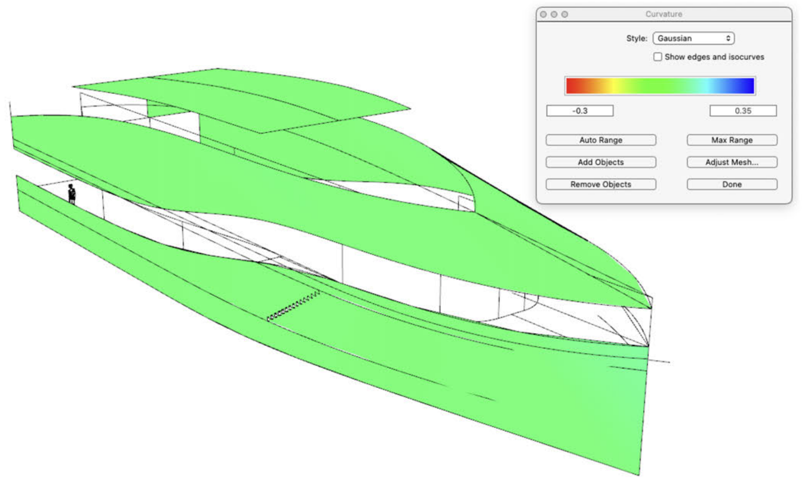


Figure 60: Results of the Gaussian curvature analysis.

The second analysis uses the mean style, which shows if there are radii smaller than 1 meter. The model shows critical red areas but also some less ideal yellow regions in the transition between the front dodger and the side dodger.

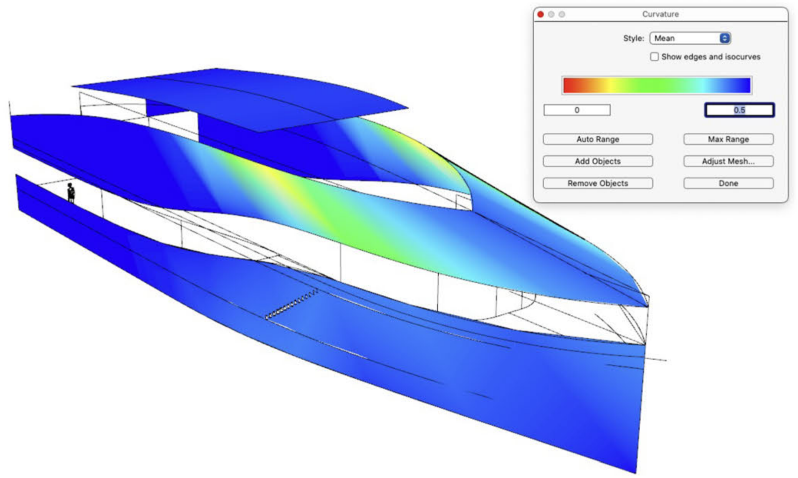


Figure 61: Results of the Mean curvature analysis.

Result: No changes are needed in the geometry, as they meet the requirement of being a single curvature and having radii greater than 1 meter.

Irradiation analysis

In addition, an irradiation analysis was performed. In this design stage, this analysis will be about the visual aspect of the irradiation on a surface rather than on the quantitative data. Figure 72 shows the results of this analysis. During early surface design irradiation analyses, surfaces must be assigned a thickness to ensure proper results.

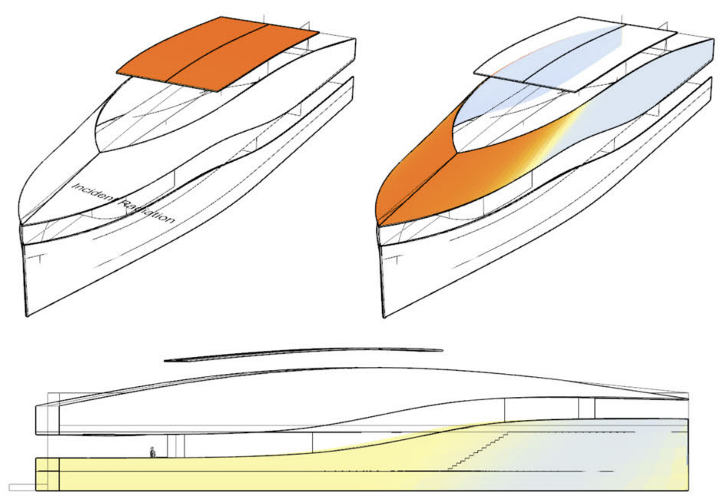


Figure 62: Irradiation analysis on the first iteration. Focused on the hardtop, front dodger and hull.

Results: According to the designer, the visual representation of irradiation proved to be not that informative at an early stage in the design process. It only confirmed to the designer that the horizontal surfaces received the most irradiation.

With this information, the designer decided to add more detail to the design. Figure 73 shows the second iteration of the design, including a more defined exterior design with realistic features such as windows, decks, and balustrades, representing the intended design language more closely.

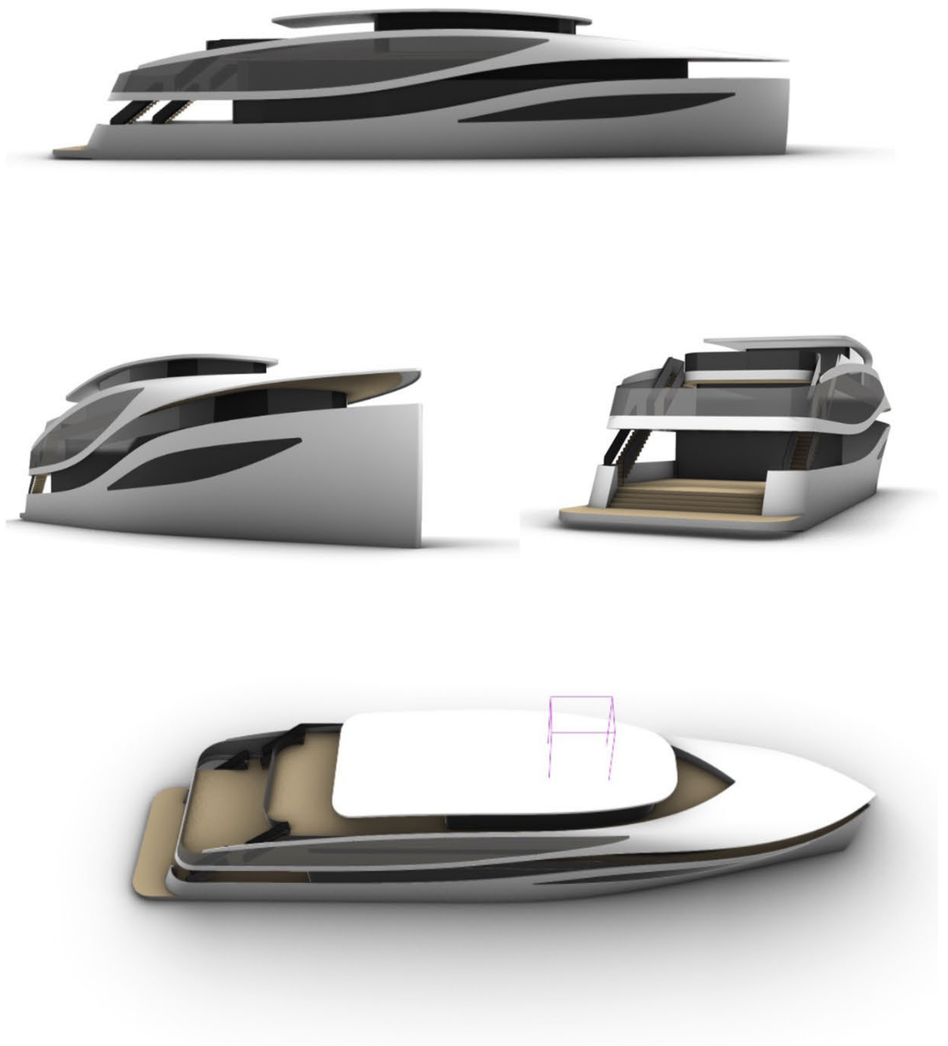


Figure 63: Improved yacht design with more detailed surfaces and features.

7.3 PV integration

The second iteration took the next step: integrating solar panels. The model was broken down into the most promising surfaces, based on the insights from Chapter 5.3. Figure 74 shows the focus areas.

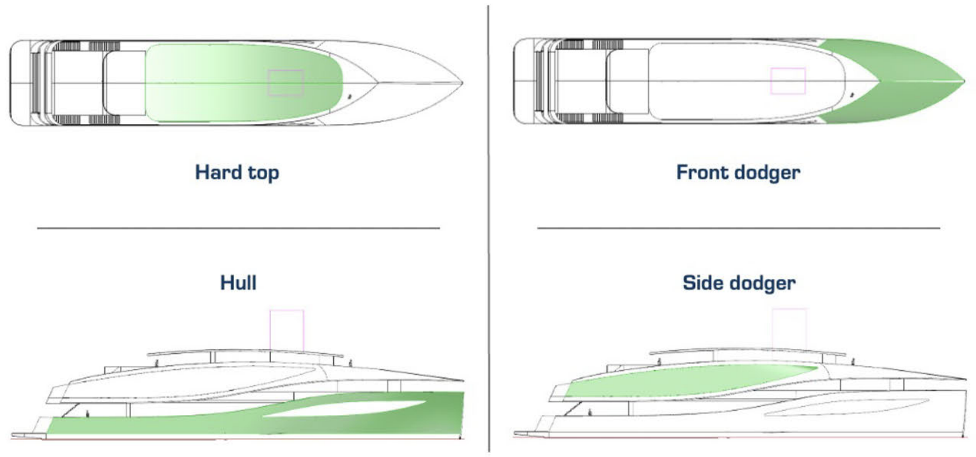


Figure 64: Focus area for PV integration based on Chapter 5.3

The designer was given various options and designs for PV integration for each surface. These options were presented as illustrations and references from Chapter 3.2, and only visually, without performance data.

Front dodger:

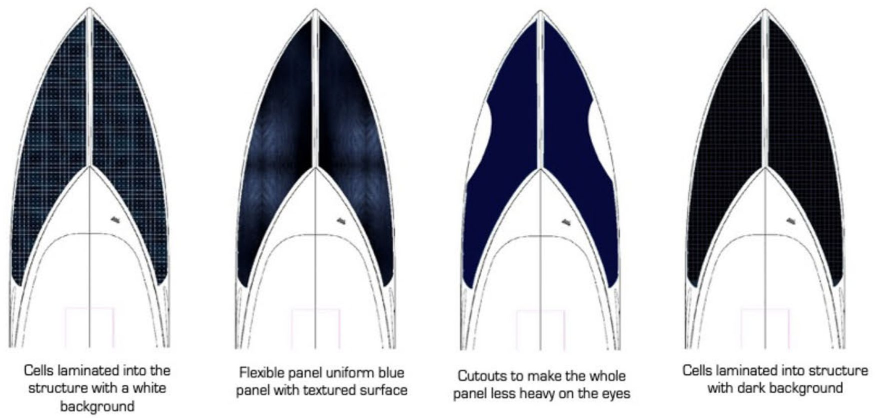


Figure 65: Various PV integration options for front dodger

Hardtop:

Figure 66: Various PV integration options for hard top

Hull:

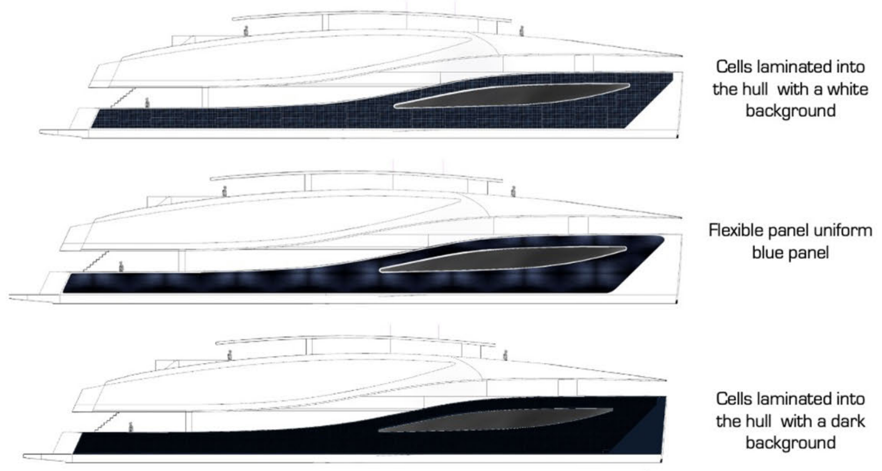


Figure 67: Various PV integration options the hull

Glass side dodger:

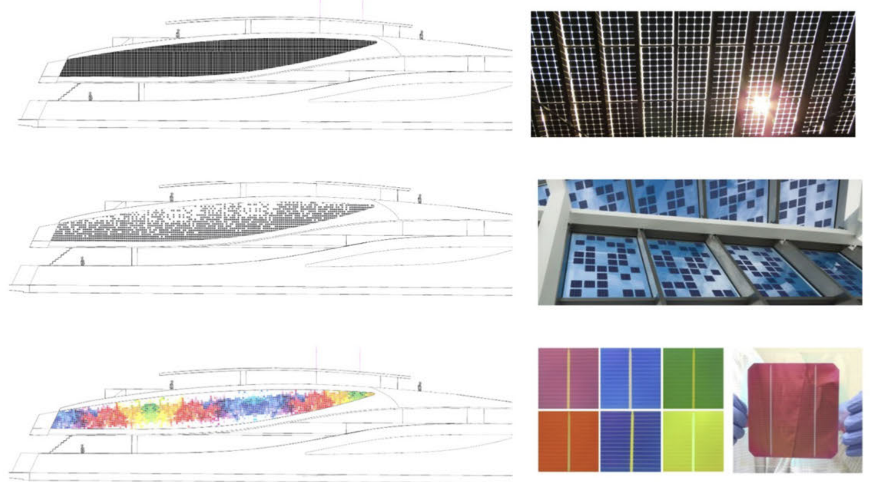


Figure 68: Various PV integration options for the glass side dodger. Using methods used in solar glass. The last option utilises coloured solar cells

Additional option

One additional option was given, because of further conversation about the PV cells integrated in glass. The option involved altering part of the hardtop to act as a glass canopy with integrated solar panels.

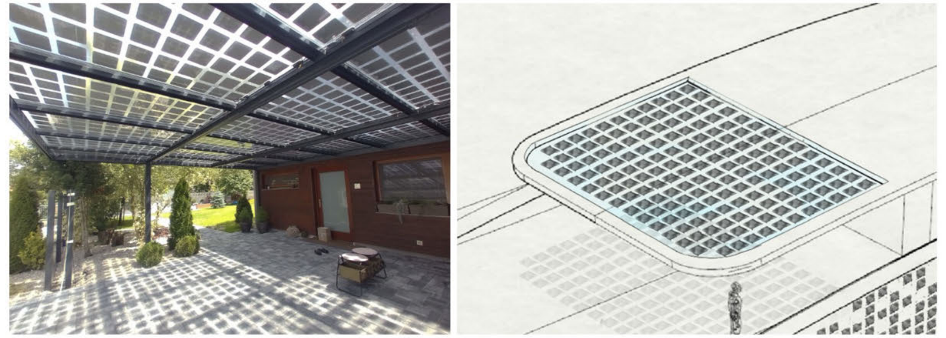


Figure 69: Design to use part of the hard top as semi-transparent canopy.

Result: With this information, the designer made a third iteration. This iteration involved many smaller iterations where he explored the visual impact of the solar panels by simplifying them to darker coloured surfaces and evaluating them with quick renders. This showed the need for more high-end visual feedback to get a feel for the overall aesthetics of the yacht. Figure 80 on the next page shows some of these iterations.

Figure 70: Result of the third iteration on the yacht design showing multiple smaller iterations to assess overall aesthetics.

This iteration step showed that the large uniform dark colours wouldn't fit the intended design language. For the fourth iteration, the designer was again informed with references from Chapter 3.2, focusing on segmenting the large dark surfaces, more realistic integration, like using recesses, and including the solar cells integrated in the side dodgers and canopy.

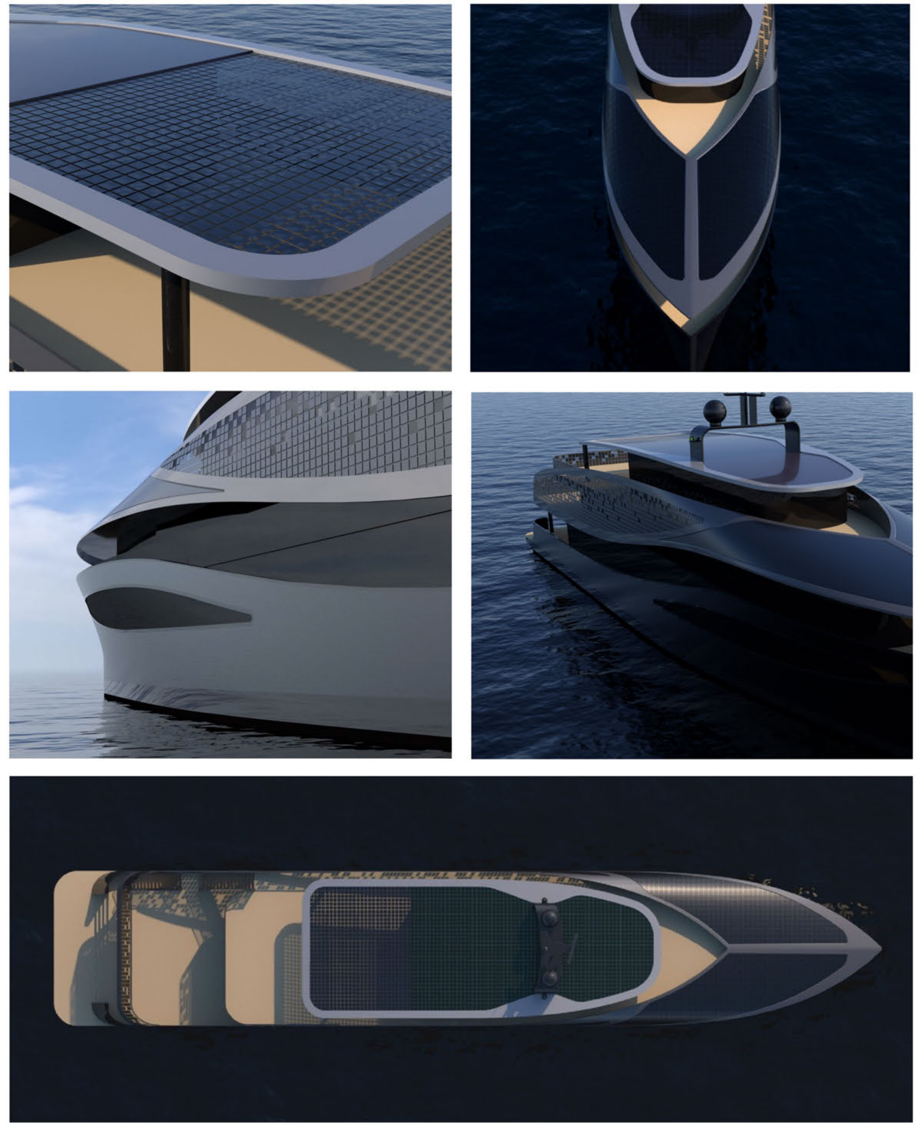


Figure 71: Fourth iteration, with the focus on more segmentation of large dark surfaces and the addition of solar cells in the glass side dodger and canopy.

7.4 Energy yield

The final step was to estimate the energy yield of the integrated PV surfaces and compare it to the yacht's total estimated energy demand. This provided insight into how much of the vessel's needs could realistically be met with solar power under different seasonal conditions.

Assumptions

- **Operating location:** Mediterranean Sea, with the Greek island of Mykonos representing typical Mediterranean solar irradiation levels.
- **Yield estimation:** The solar energy harvesting calculation tool (Section 6.2.2) was used to multiply surface area by irradiation and panel efficiency, applying cell coverage, colouring losses, and fixed correction factors to simulate realistic performance.
- **Energy demand estimation:** Using the method in Section 2.2.1, the yacht's gross tonnage was used to estimate annual energy demand, divided into hotel loads and propulsion.
- **Energy usage vs yield:** The yacht has a battery pack bridging mismatches between generation and demand.
- **Coverage ratio:** The PV output for each period was expressed as a percentage of the yacht's estimated daily energy demand, showing how much could be met by solar power during peak, low, and average conditions.

Input parameters

The calculation was based on the following fixed inputs to ensure consistency with earlier evaluations:

- **Panel efficiency:** 24%
- **Correction factors:** As described in Section X.X, accounting for shading, wiring losses, and operational conditions.
- **Cell coverage:** Percentage of the available PV surface area covered with active solar cells.
- **Colouring losses:** Additional efficiency reduction (%) due to customised colouring or surface treatments of the PV cells.
- **PV surface areas:** Measured directly from the 3D model for each integrated surface in the final iteration.
- **Weather data location:** Mykonos, Greece
- **Solar irradiation data:** Irradiation data for each surface were taken from the Grasshopper solar analysis for:
    - **Summer solstice** (longest day of the year, highest potential yield)
    - **Winter solstice** (shortest day of the year, lowest potential yield)
    - **Annual average** (mean daily irradiation over the year)

Purpose and outcome

This seasonal approach provided a more nuanced understanding of PV performance throughout the year. It highlighted the maximum potential during peak summer days and revealed the limitations in winter conditions. Comparing these seasonal yields to the yacht's energy demand helped assess the feasibility of the "fully solar-powered" vision and pinpointed where integration strategies were most effective.

Table 7: Results of energy yield calculation of case study. The full calculation can be found in Appendix F

scenario	total energy harvesting		hotel load covered
Highest day	524	kWh	58%
Lowest day	178	kWh	19%
Daily average	359	kWh	39%

Surface	Area (m2)	Coverage	Colour loss
Hard top	192	73%	0%
Front dodger	103	75%	0%
Side dodger	140	40%	0%
Hull	280	75%	0%
Deck	90	0%	0%
Balustrates/windows	146	0%	0%

Chapter 7 - Takeaways:

- Irradiation analysis is most useful when the design is further developed and shows quantitative data.
- Large glass panels have proven to be valuable surfaces for seamless design. It allows for different cell patterns and light to pass through.
- References from PV in architecture are a valuable source for inspiration, such as the sun shading in the hardtop.
- To get a feel for the final appearance of a surface, a more high-end visual tool is needed, like a rendering software.
- Large solar surfaces may need some fragmentation to make it less heavy on the eyes.

8. Development of Design Tool

This chapter shows the development of a Design Tool that combines the relevant knowledge gained in the previous chapters into a visual configurator. The tool's purpose is to aid yacht designers in early exploration and assessment of the use of solar panels in their designs. The complete design tool can be found with the link in Chapter 8.4

8.1 User interface

This section will explain how the user interface is designed and discuss the essential features.

8.1.1 Functionality

The user of the Design tool needs to be able to explore the possibilities of solar panels on a yacht and be provided with guidance for informed decision-making. To fulfil this purpose, the tool should offer a set of basic functionalities:

- **Design consideration and strategies:** provides relevant information during the design of yacht surfaces.
- **Surface evaluation:** provides a method to evaluate the designed surfaces
- **Experimentation:** Allow the user to explore multiple alternatives rapidly.
- **Visualiser:** provides a way to visualise solar panels on selected surfaces
- **PV Option:** provides the relevant PV integration options
- **3D view page:** Enables the user to rotate the model to assess aesthetics freely
- **Performance metrics:** Shows the impact of applying solar panels in the form of performance metrics like annual solar energy yield, solar area, and the percentage of hotel load energy that needs to be covered.
- **Overview:** Provides a design summary with performance metrics to enable comparison.
- **General PV Knowledge:** provides general information relevant to successful PV integration
- **Use of example model or custom model:** Enables the user to explore the possibilities on their own design or through example models during an exploratory phase.

Figure 82 shows how these functionalities are translated into the tool's workflow.

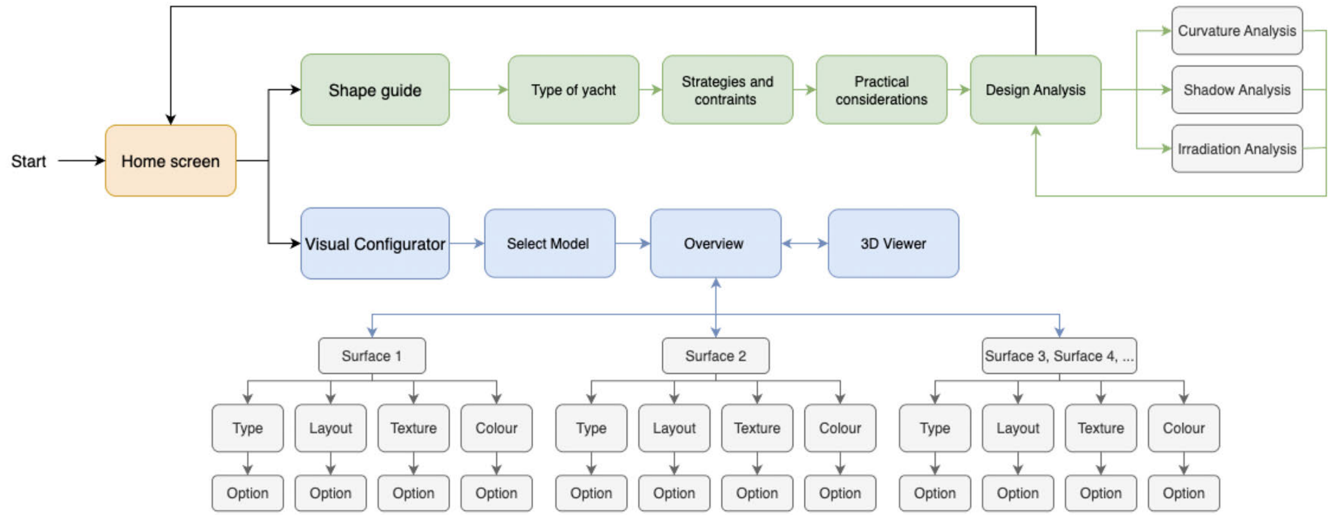


Figure 72: Overview of the workflow of the design tool. The first iteration which is used in the user test

The tool is structured in two workflows, each guiding a different phase or design goal:

Shape Guide: Focuses on creating suitable surfaces for PV integration. It will provide the required information during the synthesis phase of the design and analysis methods to test early concepts. (Appendix G)

Visual Configurator: Focuses on incorporating PV into those surfaces while aligning with design vision and aesthetics. (Appendix H)

8.1.2 Shape Guide

The shape guide provides users with design considerations and strategies applicable during the surface design phase. To keep the information clear and accessible, the pages are designed in a minimalistic style with pictograms that visually refer to key insights. Users can click on a pictogram to access additional information on topics of interest while skipping content they are already familiar with. The graphic design of these pages is shown in Figure 83.

The shape guide also supports the evaluation of designed surfaces. Users can perform various analyses on this page to assess the suitability of their surfaces. Figure 84 shows an example of a curvature analysis within the tool. Here too, the focus lies on maintaining a clean and straightforward layout.

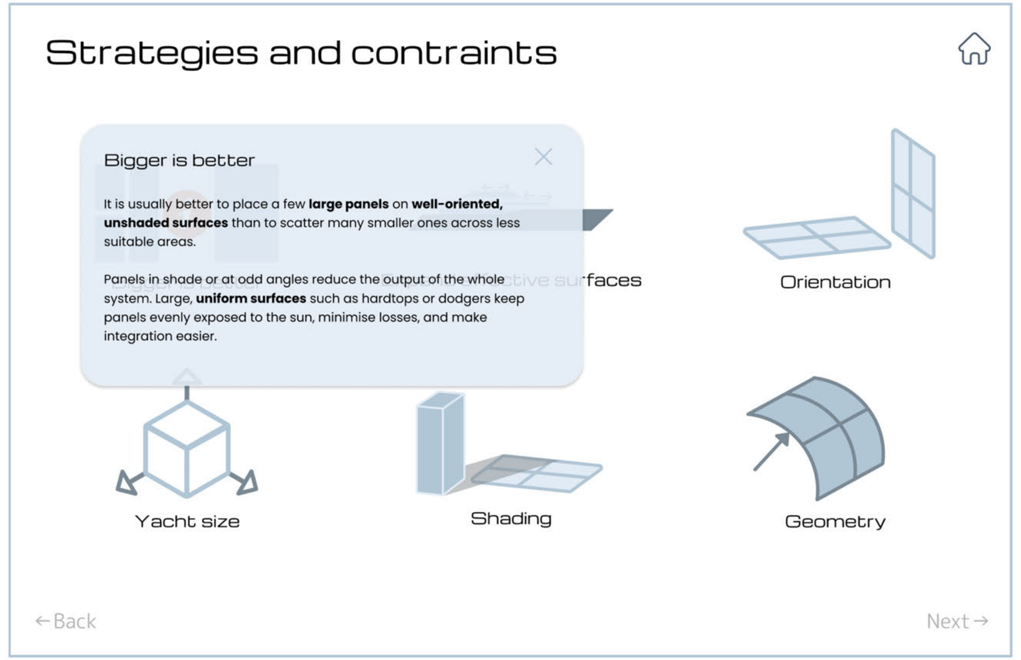


Figure 73: Screenshot of the strategies and constraints page of the Shape Guide section. Showing the information popup after click action on icon.

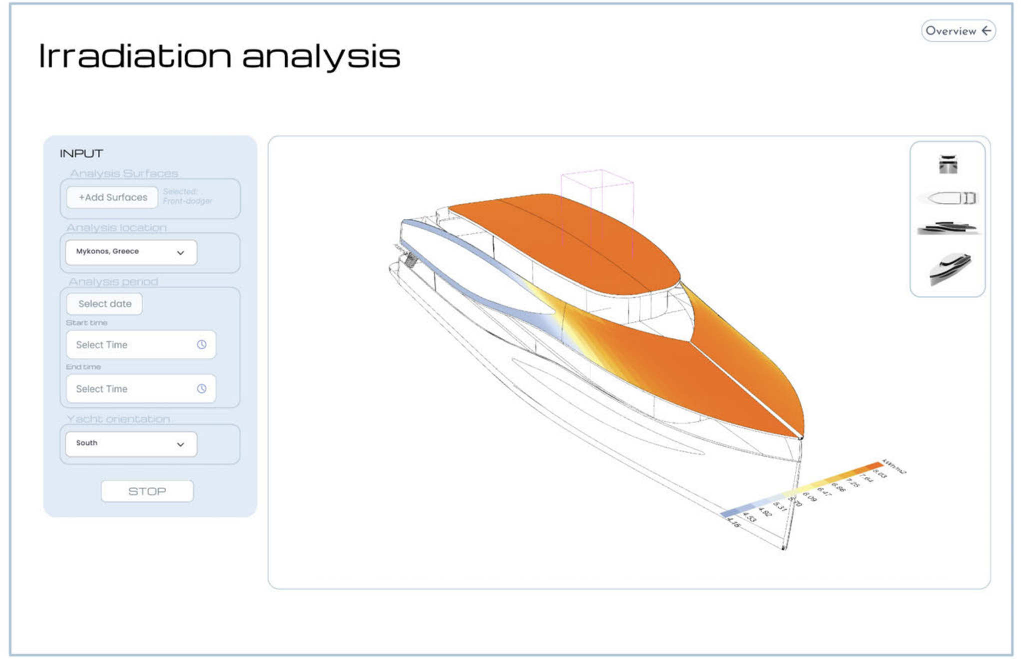


Figure 74: Screen shot of the irradiation analysis section of the Design Tool. With input parameter on the left and the visual feedback on the right.

8.1.3 Configurator

The second part of the tool functions as a configurator, enabling designers to explore alternatives and receive instant visual and numerical feedback rapidly. This interactive "what-if" process supports early-stage aesthetics, performance, and feasibility decisions. Similar tools, such as car configurators, help users navigate complex option spaces and make informed choices. Research shows that configurators improve decision-making (Hvam et al., 2008).

The tool's graphic design is kept clean and minimalistic, reflecting the style of superyacht brochures and modern configurators (Figure 85).

Figure 86 and Figure 87 on the next page show the graphic design of the overview page and the configuration page of the front dodger.

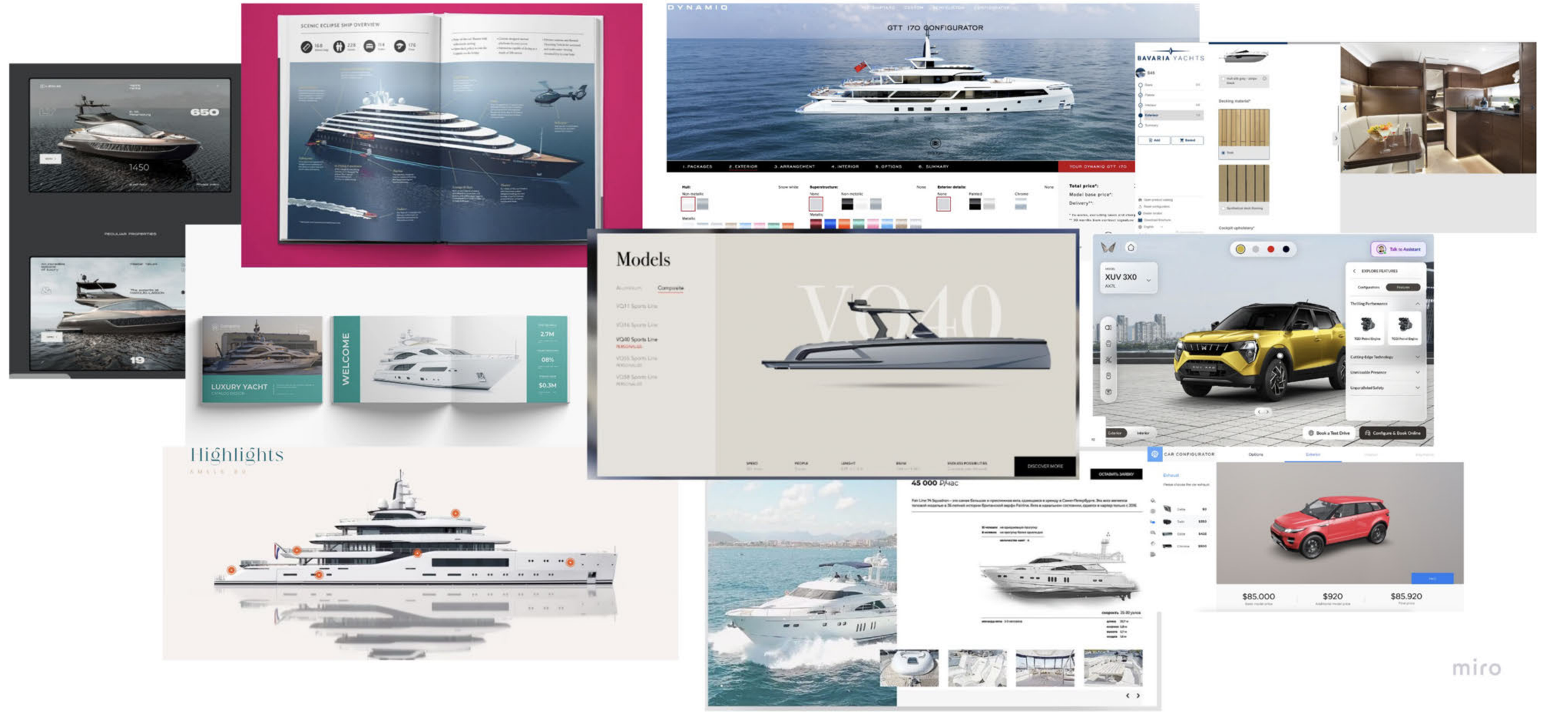


Figure 75: Collage of configurators and brochures references from the superyacht and automotive industry.

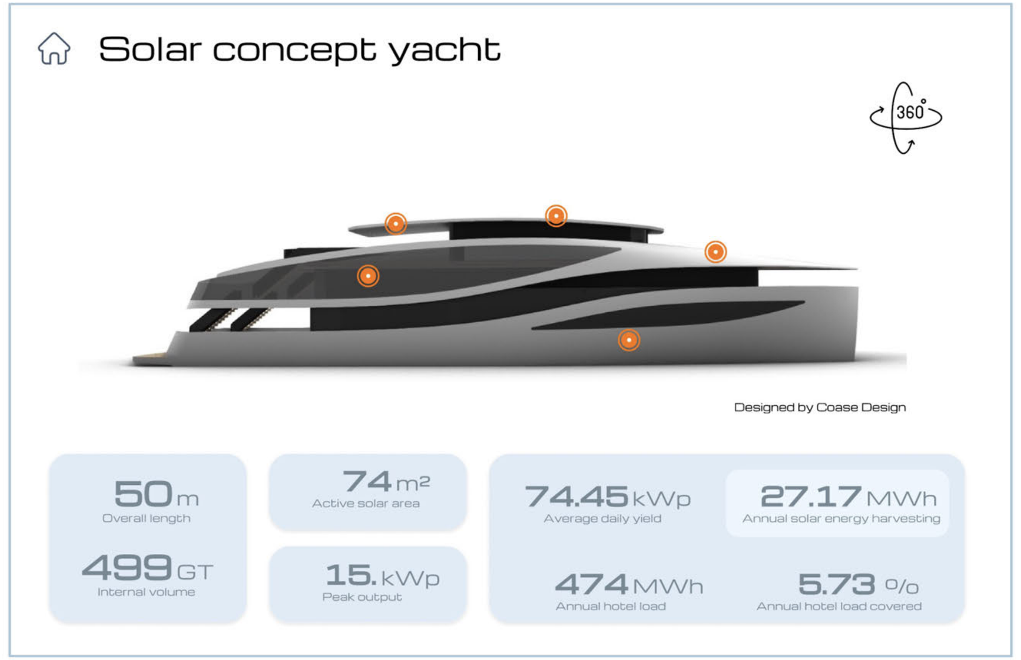


Figure 76: Screenshot of the overview page of the Design tool

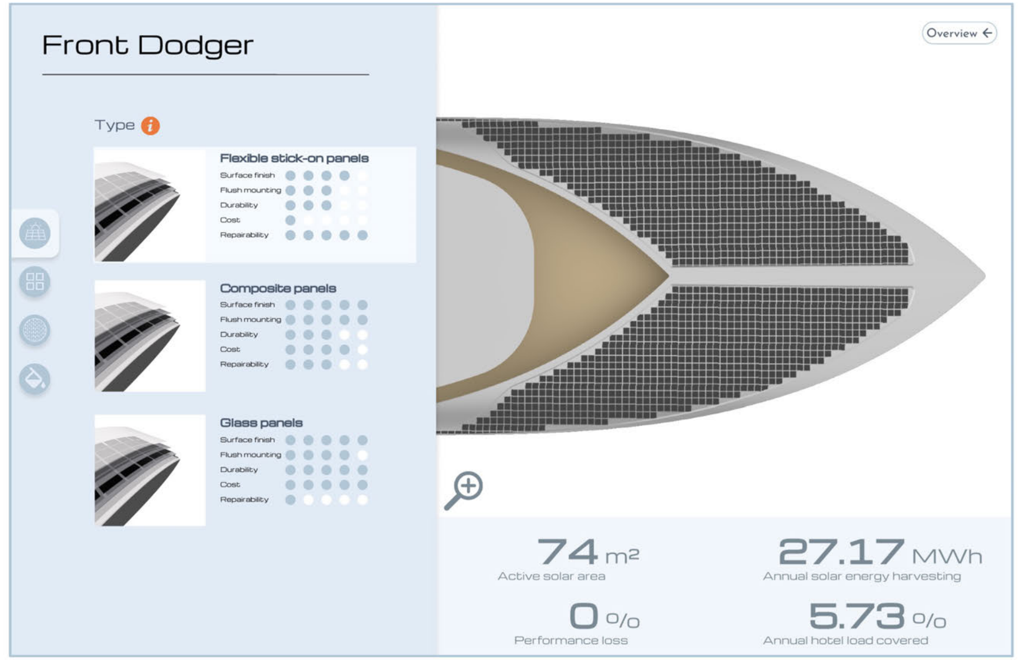


Figure 77: Screenshot of the configuration page of the front dodger, of the Design tool

8.2 System design

This section explains the system design of the tool, describing how its underlying software components interact to deliver the intended functionality.

One of the main challenges in developing this tool is enabling users to upload custom designs. Most configurator tools rely on simplified preloaded models to function efficiently within web applications using lightweight 3D viewers. This approach keeps the front end of the tool simple and reliable.

To make custom uploads possible, requires software capable of loading custom 3D models, including STEP files, allowing users to select specific surfaces, computing irradiance values per surface, generating photovoltaic layouts, and exporting all data reliably. In this thesis, Rhinoceros 3D in combination with Grasshopper was primarily used to perform the irradiance analysis. Grasshopper also provides an ideal environment for the parametric design needed to efficiently generate and adjust PV layouts. Rhino is a well-known platform among yacht designers, making it a practical and accessible choice for this application.

Rhino Compute can be used as the computational engine behind the tool to streamline this process and integrate it directly into the configurator. Rhino Compute enables Rhino and Grasshopper scripts to run on a server, allowing the complex geometry processing and irradiance simulations to occur automatically in the background.

When a user uploads a 3D model to the configurator, the file is sent to the Rhino Compute server. Here, predefined Grasshopper definitions handle the import, identification of potential solar surfaces, irradiance analysis, and generation of a photovoltaic layout. Once completed, the processed geometry and associated data are returned to the web application, where the model is visualised in a lightweight 3D viewer. This viewer will handle the appearance changes of the PV surfaces. Figure 88 shows the flow of this process.

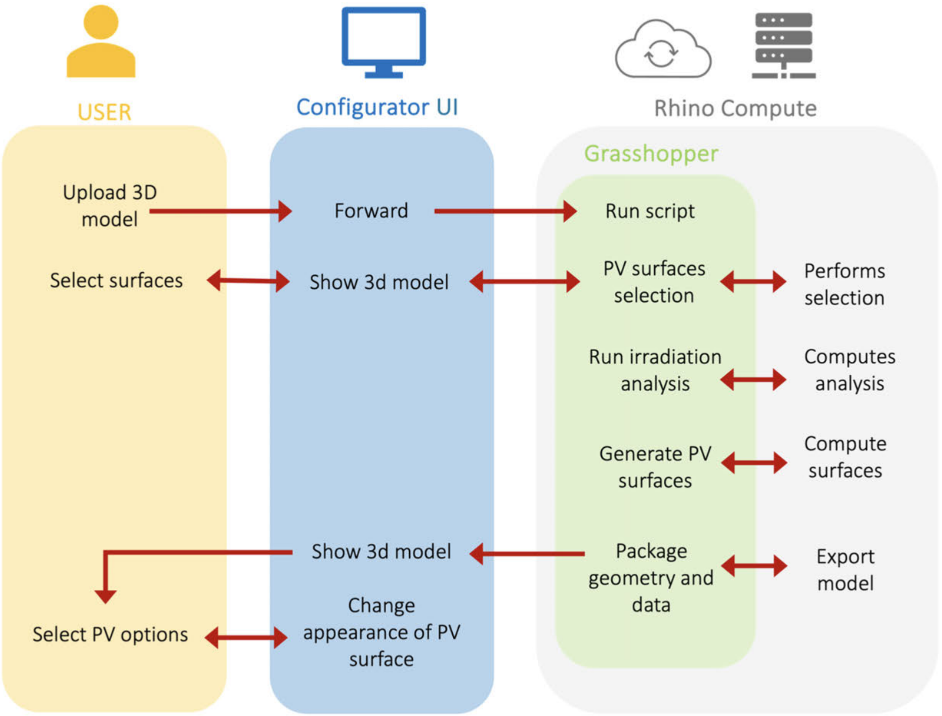


Figure 78: System diagram of the back-end of the design tool. Showing the interaction between the user, UI and Rhino Compute.

8.3 User testing

A user test was carried out to assess whether the design tool meets its intended purpose. A design tool prototype was developed and tested with yacht designers through an exploratory user test. The test focused on first impressions of the tool, users' expectations of how it should function, their navigation through the interface, identifying pain points, and discovering unmet needs or ideas for improvement. Observing how participants engaged with the prototype provided valuable insights into its strengths and limitations, forming the basis for further refinements and recommendations.

8.3.1 Prototype

A visual prototype of the Design Tool was developed in Figma, a web-based prototyping tool widely used in interface and interaction design. Figma allows designers to create interactive mock-ups that simulate the look and flow of a digital product without requiring software development.

The prototype included the following features and interaction:

Features:

- Home screen: Provides the starting point for accessing either the Shape Guide or the Visual Configurator
- Shape guide: Offers background information, including yacht type, integration strategies, constraints, and practical considerations.
- Design Analysis: To estimate solar potential, evaluate surfaces through curvature, shadow, and irradiation analysis.
- Visual configurator: The core module where users explore solar panel placement options and appearances.
- Surface customisation: Allows adjustment of solar panel type, layout, texture, and colour on specific yacht surfaces.
- Overview: Summarises all performance estimates of potential energy generation
- 3D viewer: Enables spatial exploration of the yacht and visual assessment

Interactions:

- Navigate from the home screen: Choose whether to begin with the Shape Guide or directly place panels in the configurator.
- Select yacht type and strategies: Exploring knowledge items on the kind of yacht, strategies, constraints and practical considerations, by selecting icons.
- Design analyses: start and stop analysis, and visually assess the results.
- Select a surface: Pick a yacht surface (e.g. Front dodger, hard top, etc.) for solar panel placement.

Modify panel options: change type, layout, texture, and colour of solar panels on each chosen surface and observe corresponding performance estimates. (visual feedback only with front dodger).

Switch between surfaces: Compare appearance and performance estimates per surface.

View results in overview: Examine the overall estimation of energy generation.

View yacht in 3d viewer: Rotate around yacht to assess visual appeal.

Iterate by returning to surfaces: Revisit earlier choices to adjust performance.

The prototype only simulates how these features and interactions are intended to work. Only the front dodger was elaborated with complete visual feedback, while for the other surfaces, the interaction remains limited to the performance estimates.

8.3.2 Test setup

An exploratory user test was conducted with potential users of the Design Tool. This test provides early insights into how the prototype was experienced in practice. The test plan and results can be found in Appendix I & J.

Goal

The exploratory user test aimed to evaluate how potential users perceive and interact with the Design Tool prototype. Specifically, the test aimed to gather insight into first impressions, ease of navigation, user expectations of how the tool should function, experienced pain points, unmet needs or ideas for improvements.

Method

An exploratory test approach was chosen, focusing on observation of how participants navigated and interacted with the prototype rather than on task performance.

Participants

The test was conducted with four participants who are yacht designers or closely involved in yacht design, representing the intended user group of the tool.

Test setup

The user test took place in person and through a video call, with the participants navigating the prototype in Figma. Screen recordings were made to capture their interaction, and participants were asked to speak aloud while using the tool. At the end of the session, a few follow-up questions were asked to clarify their experience.

Results

The user test showed that the visual configurator was perceived as the most valuable component and should be the tool's primary focus. The overall flow felt natural, and the visual design was attractive and professional. The shape guide was experienced as slow and of limited usefulness, especially the yacht type selection. Participants noted that most proportions and overall shapes are typically predetermined by the client, making this feature less relevant. It could be better as an optional educational feature rather than a central part of the tool.

Several participants said they would like more context at the beginning of the tool, including an explanation of why photovoltaic integration could be valuable for superyachts. Moreover, participants highlighted the need for transparency regarding the accuracy of performance calculations and were unwilling to rely on the results without understanding their reliability.

Across all interactions, participants valued the ability to upload their models and combine visual feedback with performance estimates. While the design analyses were considered of limited relevance, they were considered valuable when directly linked to energy yield calculations. Finally, three participants indicated that they would primarily use the tool for client communication, recognising its potential for supporting designers and presenting and validating design choices.

8.3.3 Iteration

Based on the test result, some changes were made to the design tool. These changes are mainly around the flow of the tool. Because the designers indicated that the primary focus should be around the visual configurator, the flows now go around the overview page of the configurator, and the user can navigate to all functions. Figure 91 shows the new workflow of the tool.

Figure 79: Addition of PV surface design button on overview page

Figure 80: Addition of Setup button on overview page

A few adjustments were required with the overview page now serving as the main page. Additional buttons were added to make all features easily accessible:

- **PV surface design:** This button opens the Shape Guide. This section is considered additional knowledge for users who wish to learn more about the surface design. (Figure 89)
- **Setup Manual:** This allows the user to change the model, operating area, and time of year, which influence the irradiation data.
 (Figure 90)

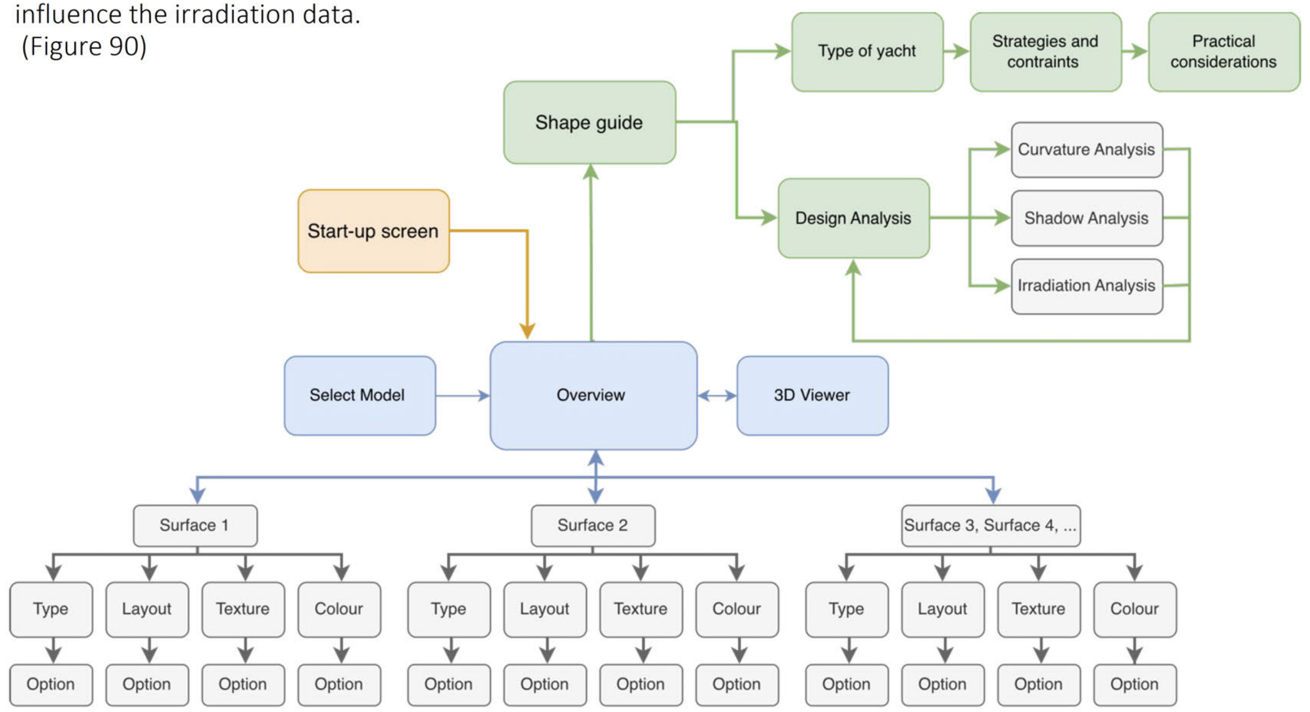


Figure 81: Overview of the new workflow of the design tool. Changes made based on the results of the user test

8.3.4 Further development

The tool is still a visual mock-up at this stage, meaning it only demonstrates the intended appearance and interaction flow. This mock-up can continue to be used for user testing and can be expanded with more detailed content. These iterations further refine the interactions and connection to the designers' workflow.

However, the next essential step is to explore the software implementation, determining how all functionalities can be integrated into a single working system. The software development can be divided into two main parts:

Front-end development: creating a web application that contains the user interface (UI) and manages user interactions.

Back-end development: developing the Rhino Grasshopper scripts that perform all computational tasks and linking Rhino Compute to the user interface.

The front end of this tool is comparable to a standard 3D product configurator commonly used in web applications. Many online configurators are built using templates, significantly reducing development costs and limiting flexibility and functionality. Because this configurator requires integration with additional software, it is assumed that the front end must be developed from scratch.

Combeenation, a company specialised in custom configurators, estimates that a self-built configurator typically costs around €85,000, but can increase to €150,000 depending on the required functionality (Burgstaller, n.d.). In this case, the software would need to be fully customised and adapted for use with Rhino Compute, meaning that a large part of the back-end system is included in this development effort.

However, the development of the Grasshopper scripts is less common and depends heavily on the complexity of the computational setup. While no exact cost estimation can be made without further research, it is safe to assume that the back end of this tool would be relatively complex due to the limited number of software developers experienced with Rhino Compute.

8.4 Link to YIPV Design Tool

The tool is available online and can be found at this hyperlink:

https://www.figma.com/proto/p8EB4m7HyCNsgetxXL5LiV/YIPV-Design-Tool?page-id=1099%3A5720&node-id=1099-5721&p=f&viewport=212%2C-78%2C0.19&t=efivT0L6tIiL7ZWa-1&scaling=scale-down&content-scaling=fixed&starting-point-node-id=1099%3A5721

Discussion

This thesis proposes a design tool that supports yacht designers in making informed decisions when integrating solar panels into yacht design. This section provides a broader interpretation of the findings, discussing their implications for design and industry and their validity and limitations.

Implications of findings

Estimating solar yield based on irradiation analysis and panel performance proved to be a practical way to assess energy potential. Including this function in the tool helps designers make trade-offs between appearance and expected output. However, the estimation is more of an indication than an accurate number, so that needs to be made clear for the tool user.

User testing showed that the tool works best when it gives immediate visual and numerical feedback. This allows the designers to quickly test, compare and understand the impact of different configurations. This also helped to understand the implications of ideas while seeing the direct effect of their choices. In this way, the tool supports analysis and creativity in the early design phase.

For the superyacht industry, this project and design tool serves as inspiration for what is technically and aesthetically possible. It is not intended to suggest that all yachts should include solar panels, but rather to act as a conversation starter, encouraging interest in renewable technologies and more sustainable yacht design.

Validity

The results rely on the choice for monocrystalline PV technology, which currently offers the best balance between efficiency, durability, and appearance, as confirmed by expert consultation. (Solbian). However, this focus excludes emerging alternatives that may become relevant. The conclusions, therefore, reflect current practice but remain valid within this scope.

The performance calculations are based on average irradiation data from a representative location and the efficiency of high-end solar panels, corrected with data from Feadship Project 713. These assumptions ensure consistency but make the results suitable for general comparison rather than detailed prediction.

Exploratory testing with yacht designers showed that the tool helps explore integration options and understand the effect of design choices. Although the number of participants was limited, the tool was perceived as clear, relevant, and supportive during early design stages.

The tool is in the early prototype phase. The test is therefore conducted with a visual mock-up focusing on the basic concept of the tool and the designer's first impression. The results show how the designers perceive the tool and think they would use it, rather than how they actually use it during a design process. The outcomes, therefore, validate the tool's concept but not its functionality.

The test included both freelance and shipyard designers. Some differences were observed in how they valued certain features, but with few participants, these differences cannot be linked confidently to background or preference.

Limitations

This project aimed to develop guidelines for solar integration in early yacht design and to translate these into an interactive design tool. Integrating solar panels on luxury yachts is a complex design challenge that involves many interrelated factors, but only those most relevant to early design stages were included. Not all aspects could be explored in depth within the available seven-month timeframe, and the limited time therefore required defining a clear scope and excluding certain factors from the process.

- The performance calculations in the tool are simplified and based on average yearly irradiation data for a representative location. Thermal losses, degradation over time, and variations in user behaviour were not included, making the results only suitable for general comparison but not for precise prediction.

- While the tool provides theoretical constraints and strategies, it lacks clear examples of well-designed surfaces, which limits its ability to illustrate what successful surface design looks like in practice.

- The tool does not consider the financial aspects, as this was outside this project's scope. Although cost is not always the main driver in the design, it ultimately influences the feasibility and adoption potential of solar integration on yachts.

- A 50-metre reference yacht was used for the analysis, serving as a representative case for large motor yachts. However, different vessel sizes and configurations were not studied in detail, so the results are mainly relevant for yachts with comparable dimensions and layouts.

- Choosing suitable PV technologies and appearance options was mainly based on literature, expert input, and references from other industries. The findings, therefore, reflect what is currently known and applied in related sectors, rather than results confirmed through real-world testing.

- The user test was exploratory and small in scale. It focused on how clear and relevant the tool felt to designers, rather than testing its actual use during a design process or evaluating the quality of the information it provides.

Conclusion

This thesis aimed to support yacht designers in early integrating photovoltaic (PV) systems on luxury yachts. As solar technology gains relevance in the super yacht industry, designers play a key role in translating its potential into feasible and visually coherent designs. However, the relatively low energy yield, aesthetic constraints and often lack of knowledge still make PV difficult to adopt. This led to the main research question.

How can design guidelines support yacht designers in the early-stage integration of photovoltaic systems on a luxury yacht, balancing aesthetics and performance?

To address this, two sub-questions were formulated. The first focused on identifying the factors that influence PV integration and how these relate to aesthetics and performance:

1. What factors influence the integration of photovoltaic systems on luxury yachts, and how do these relate to aesthetics and performance?

The integration of photovoltaic systems on luxury yachts is determined by several interrelated factors, including PV technology, surface geometry, irradiation, and the functional use of available surfaces (Chapters 2 and 3). The choice of PV technology determines appearance, integration method, surface finish, flexibility and durability. Among current options, Monocrystalline silicon cells offer the best balance between efficiency, durability, flexibility, and aesthetic adaptability for marine use.

Three primary integration methods were identified: flexible semi-custom panels and full custom composite- and glass-integrated panels. The full custom panels provide a higher visual quality but are more complex and costly to produce, while no significant performance difference was found. The colouring of solar cells is possible and can improve aesthetics, but can result in a 7-30% reduction in efficiency.

Surface geometry and orientation strongly affect performance. As yacht surfaces are often curved, only areas with a single curvature and a radius of at least 1 metre are suitable for solar cells, to prevent cell damage. Irradiation analysis showed that horizontal surfaces perform best overall, while vertical panels mainly add value during morning and evening hours. Generally, one well-oriented PV area generates more energy than multiple less favourable ones.

Building on these insights, the second sub-question examines how this knowledge could be translated into practical design support through guidelines and an interactive tool:

2. How can insights on photovoltaic integration be made accessible to yacht designers in a way that supports exploration and informed decision-making?

The case study, user test, and performance calculations were used to explore how knowledge on PV integration can be made accessible to yacht designers.

The results showed that clear quantitative data helps designers understand how their choices affect energy yield. The calculation described in Section 6.2.2 provides a practical estimation method that supports this understanding. In contrast, the user test in Section 8.2.2 confirmed that numeric feedback of the energy yield supports informed early-stage decision-making.

While quantitative data supports rational evaluation, visual communication was equally crucial for understanding and aesthetic assessment. The case study (Section 7.3) showed that visual references of solar panels best support aesthetic integration, helping designers see how different panel types and layouts fit within a yacht's design.

The user test (Section 8.2.2) showed that the tool's strength is combining numeric and visual feedback. Designers appreciated trying out different configurations and instantly seeing the effect on appearance and performance. This configurator-style setup encouraged quick experimentation and helped them understand the solar potential. However, participants also mentioned that more realistic visuals and validated performance data would increase the tool's relevance.

Combining quantitative data and visual feedback in a configurable interface proved an effective way to make PV integration insights accessible.

Together, the answers to these sub-questions form the basis for addressing the main research question:

How can design guidelines support yacht designers in the early-stage integration of photovoltaic systems on a luxury yacht, balancing aesthetics and performance?

The results of the sub-questions showed that design guidelines can best support yacht designers when they combine visual and numeric feedback in the early design stages. Testing different surfaces quickly and immediately seeing how this affects energy yield and appearance was the most effective form of support.

Surface geometry and orientation guidelines help designers understand how these factors influence performance. Even though the client's design wishes often limit geometry, these insights help designers make the most of the available surfaces and spot realistic opportunities for solar integration.

Designers indicated that the representation of the guidelines through the design tool could also serve as a valuable communication aid towards clients. The configurator style of the tool makes it easier to explain the benefits of solar integration and justify design choices with aesthetic and technical arguments.

Presenting these guidelines through the interactive tool developed in Chapter 8 proved to be an effective way to apply them. The tool combines concrete examples with real-time performance feedback, allowing designers to explore options and make decisions that balance aesthetics and performance.

Recommendations

Data and context

- A cost analysis is needed to understand the financial implications of PV integration on superyachts. This should include custom manufacturing, installation processes, and key components such as controllers and battery storage to assess overall system feasibility.
- Clear user profiles per yacht and owner type should be established to link operational behaviour to PV performance better. This would allow a more accurate estimation of energy generation and overall system use.
- Improving the reliability of the tool requires more accurate input data. Incorporating industry data, such as detailed energy demands, electrical losses, and measurements from existing solar yachts discussed in Chapter 2.4, would enable more precise performance estimations.
- The tool's accuracy can be improved by refining the irradiation analysis using multiple data points within the operating area. These results can also be used to quantify temperature effects on PV efficiency and onboard climate.

Tool development

- Realising the tool requires developing the back end, including a Rhino plugin for model preparation and irradiation data acquisition, which could be developed in collaboration with a computational design engineer or Rhino specialist. The web application, serving as an interactive configurator, can be created by a web developer experienced in 3D visualisation and user interface design.
- The workflow can be improved by emphasising the configurator component while offering the shape guide as optional background material and enhancing the configurator with higher-quality visuals and more accurate performance estimations to improve both client communication and design evaluation.

Implementation opportunities

- **Development by a shipyard:** A large shipyard could further develop the tool using its access to industry and real-world performance data. With support from a software developer, the tool could serve as both an in-house design aid and a client communication platform during project development.
- **Development by a PV supplier:** For a PV supplier, the focus can be only on the configurator part. Using a few representative yacht models allows for showcasing their PV solutions and demonstrating integration potential for yachts.

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Appendices

A. Timeline

Figure 82: Timeline with typical superyacht designs from 1960 till present.

B. PV basics

Photovoltaic Effect

Solar panels, or photovoltaic (PV) panels, convert sunlight directly into electricity through the photovoltaic effect. This effect occurs in materials known as semiconductors, with silicon being the most used in commercial solar cells.

A typical solar cell consists of two layers of doped silicon, an n-type silicon doped with phosphorus and a p-type silicon doped with boron, which forms a p-n junction. The top, n-type silicon layer has excess electrons, while the bottom, p-type silicon layer has a deficit of electrons (holes). At the junction of these two layers, an exchange of electrons finds an equilibrium, forming the so-called depletion zone. Due to this charge difference, an electric field is created, which is essential to set the stage for generating electricity.

When sunlight strikes the solar cell, it sends photons (tiny packets of light energy) into the silicon. If a photon has enough energy, it can knock an electron loose from its atom within the silicon structure. This frees the electron, allowing it to move, simultaneously creating a hole where it used to be. The electric field at the p-n junction immediately acts on this pair, pushing the electron towards the n-type side and the hole towards the p-type side.

The solar cell has metal contacts on both the top and bottom layers to use this movement. These contacts collect the freed electrons and allow them to flow through an external circuit, from the n-side to the p-side, generating an electric current. This current can then power electrical devices or be stored in batteries. Figure 93 illustrates this working.

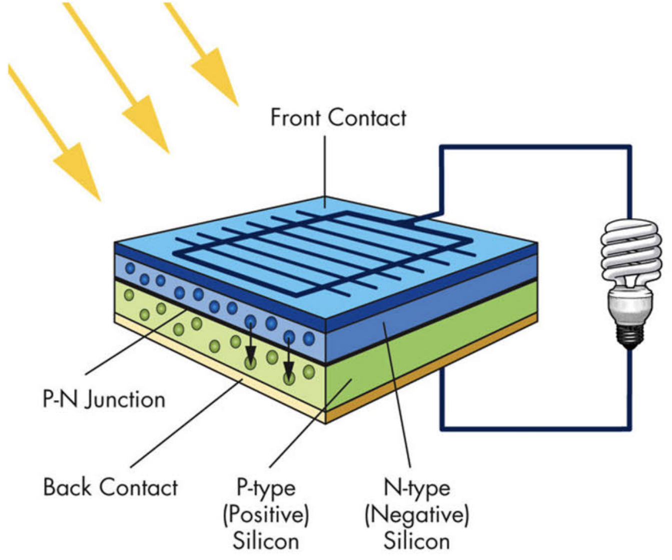


Figure 83: Illustration how sunlight is converted into electricity in a single junction silicon solar cell.

It's important to note that not all the light that hits a solar cell is converted into electricity. Some photons don't have enough energy to free an electron, while others may be reflected or pass straight through the cell. The overall efficiency of a solar cell depends on how well it can absorb sunlight and convert it into electrical energy.

Several factors limit solar panel efficiency:

- Spectral losses: Only a part of the light can be absorbed by the solar cell. This is primarily visible light, with wavelengths between 350nm and 1140nm.
- Thermal losses: the excess energy of high-energy photons is lost as heat. Also, de efficiency decreases if the panel heats up (often -0.25%/C°, when T>25C°). When the cell heats up, the atoms in the silicon increasingly vibrate and restrict the flow of electrons.
- Reflection losses: part of the light is reflected off the surface of the panel

PV glass

As photovoltaic technologies advance, the integration of solar cells into non-traditional surfaces is becoming increasingly relevant, particularly in context where both functionality and aesthetics are critical. One outcome of these innovations is PV glass, or Solar glass: glass panels with embedded photovoltaic cell that retain a degree of transparency. However, transparency comes at the cost of efficiency, as greater transparency reduces energy performance.

There are three main types of solar glass: crystalline silicon, Thin film and TLSC (Transparent Luminescent Solar Concentrators).

Crystalline Silicon glass is very similar to a standard mono- or polycrystalline solar panel. The cells are laminated between layers of tempered glass. It achieves its semi transparency through cell spacing or patterned layouts. The efficiency depends on the cell spacing but generally ranges between 10% and 18% efficiency.

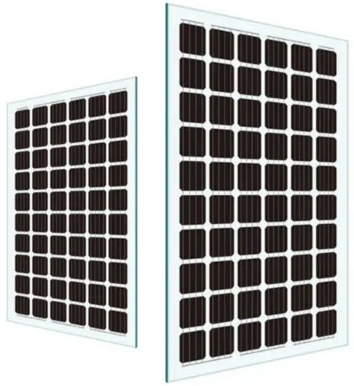


Figure 84: Crystalline silicon glass panel. The spaces between the solar cells allows light to pass through.

Thin film glass is achieved by depositing a very thin layer of a photovoltaic material, often amorphous silicon or cadmium telluride, on a glass substrate. The transparency depends on the thickness of the photovoltaic material. This method achieves a uniform transparency, maintaining an unobstructed view. However, this comes with a lower efficiency, ranging between 3% and 6%.

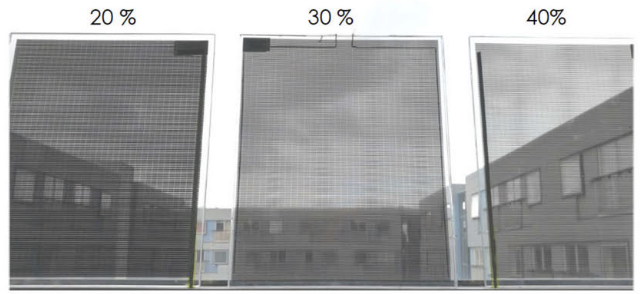


Figure 85: PV glass made with thin film. It can achieve a transparency ranging from 10%-50%. The numbers in this image indicate the transparency

In TLSC, the solar cells are not embedded in the glass itself but are located around the glass panel. The glass itself has a luminescent interlayer that absorbs mostly ultraviolet and infrared light, which is redirected to the hidden cells on the edges, where it is converted to electricity. It offers fully transparent energy-generating windows but has a very low efficiency below the 5%. Figure 96, illustrates shows this working principle.

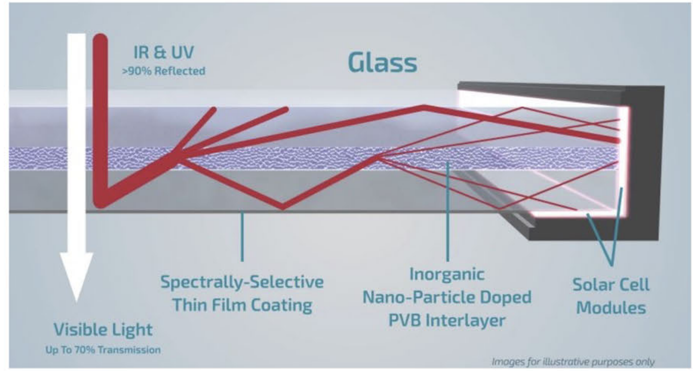


Figure 86: Illustrative image of the working principle of a Transparent Luminescent Solar Concentrators

Electrical basics

The performance of a solar power system depends not only on the type of photovoltaic (PV) cell used, but more importantly, on how modules are configured, controlled, and scaled. These design choices determine total power output, resilience to shading, and integration with the onboard electrical system.

Typical solar system

The diagram below illustrates a highly simplified solar power system onboard a yacht. Power from the solar array flows through a charge controller into a battery bank. An inverter supplies alternating current (AC) to the hotel load. A generator may provide backup power or serve as a stable power source.

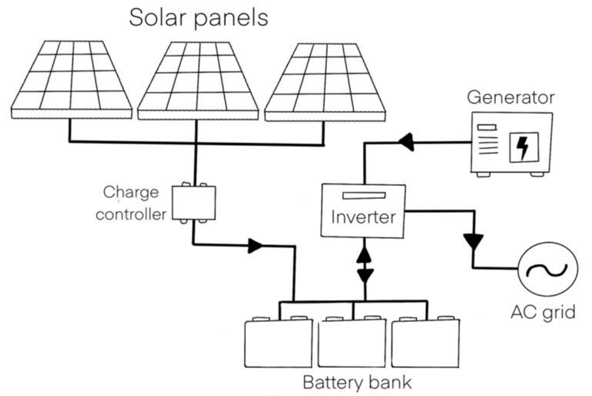


Figure 87: Illustration how sunlight is converted into electricity in a single junction silicon solar cell.

PV Arrays: configuration and shading sensitivity

A single solar panel typically does not provide enough voltage or power to charge a yacht's battery system. Multiple panels are therefore combined into an array. How these panels are interconnected, either in series, parallel, or both, significantly influences system performance, especially under shading.

- Connecting solar panels in **series** increases the voltage while keeping the current the same. This setup is ideal when you need higher voltage for charging large battery banks or using MPPT charge controllers. It also helps reduce energy losses over long cable distances. However, if one panel is shaded, it can affect the entire string, so bypass diodes are often used to limit this impact.
- In a **parallel** connection, the current adds up, but the voltage stays the same. This is useful for low-voltage systems like 12V setups or in situations with partial shading, as each panel operates more independently. It also increases resilience, since the system continues to function even if one panel underperforms. However, the higher current requires thicker cables, additional fuses, and increases safety risks if not properly managed.

On yachts, the vessel's movement frequently causes variations in panel orientations and shading. To make the system more resilient to this, charge controllers are used.

Controllers and system integration

Solar systems rely on control devices to manage energy flow and optimise performance:

- **MPPT (Maximum Power Point Tracking) controllers** continuously adjust the input voltage from the solar array to operate at its maximum power point, while efficiently converting this energy to match the battery's charging requirement via DC-DC conversion.
- **Microinverters** convert DC to AC at the module level. On larger superyachts with stable AC systems, maintained by constant generator operation, microinverters allow solar panels to feed directly into the onboard AC grid.

C. Grasshopper solar irradiation analysis

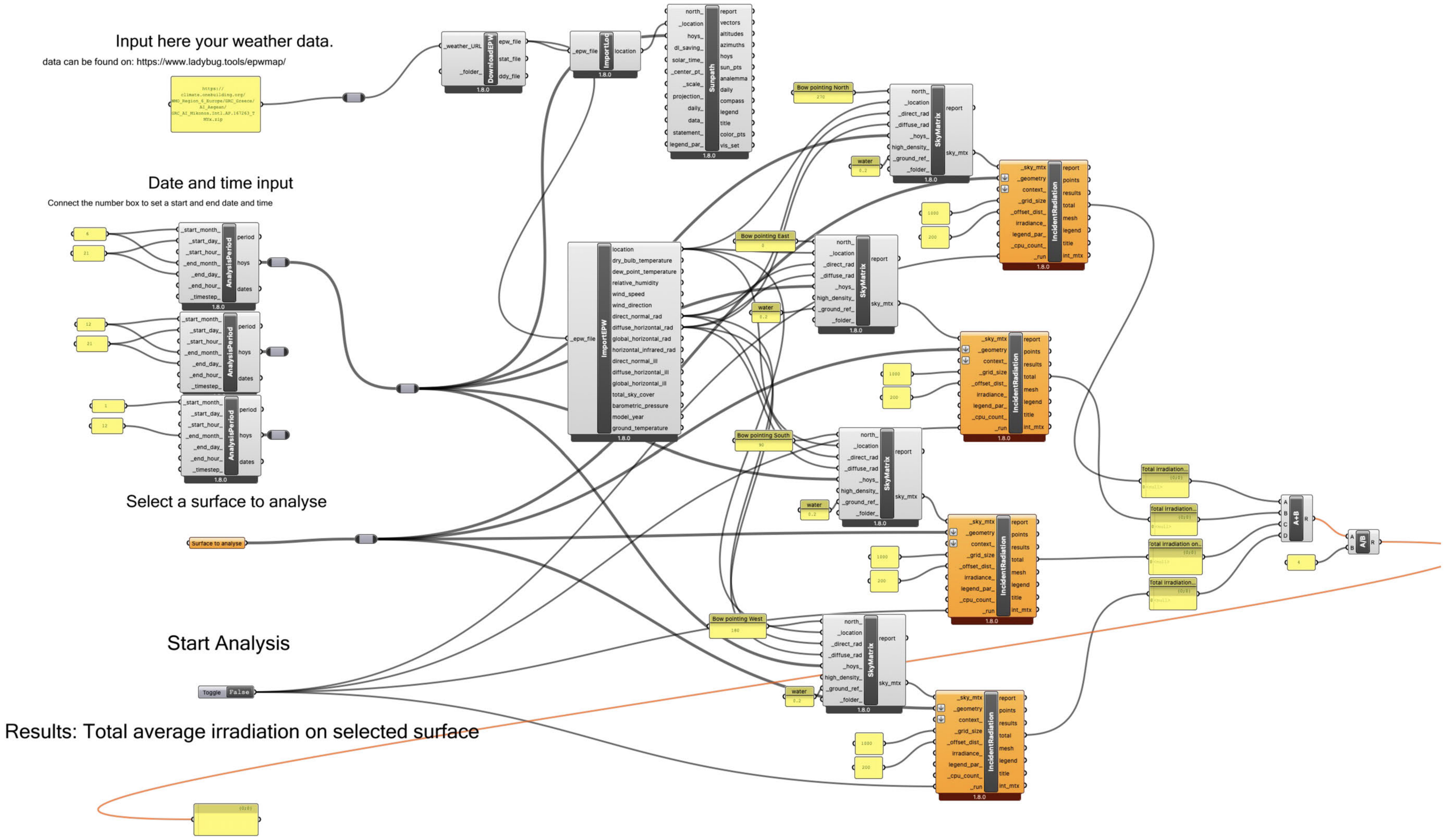


Figure 88: Grasshopper script for a solar irradiation analysis. The analysis is preformed four times in different directions

D. Average solar irradiation per location

	Average Irradiation (kWh/m2/year)	
Operating area	**Horizontal**	**Verticaal**
French Riviera	1420	887
Greek Islands	1797	957
Caribbean	2042	929
Arab Gulf	2150	1003
Malidives	2060	888
Florida	1816	879

Location: Mykonos		
direction	**irradiation**	
Horizontal	1797	kWh/m2/year
north	422	kWh/m2/year
east	1103	kWh/m2/year
south	1323	kWh/m2/year
west	980	kWh/m2/year
average	957	kWh/m2/year

Location: Oman		
direction	**irradiation**	
Horizontal	2150	kWh/m2/year
north	471	kWh/m2/year
east	1228	kWh/m2/year
south	1278	kWh/m2/year
west	1033	kWh/m2/year
average	1003	kWh/m2/year

Location: British Virgin Islands		
direction	**irradiation**	
Horizontal	2042	kWh/m2/year
north	500	kWh/m2/year
east	1070	kWh/m2/year
south	1080	kWh/m2/year
west	1065	kWh/m2/year
average	929	kWh/m2/year

Location: Malidives		
direction	**irradiation**	
Horizontal	2060	kWh/m2/year
north	651	kWh/m2/year
east	1145	kWh/m2/year
south	815	kWh/m2/year
west	942	kWh/m2/year
average	888	kWh/m2/year

Location: Monaco		
direction	**irradiation**	
Horizontal	1420	kWh/m2/year
north	398	kWh/m2/year
east	1216	kWh/m2/year
south	1272	kWh/m2/year
west	660	kWh/m2/year
average	887	kWh/m2/year

Location: Miami		
direction	**irradiation**	
Horizontal	1816	kWh/m2/year
north	435	kWh/m2/year
east	1027	kWh/m2/year
south	1115	kWh/m2/year
west	937	kWh/m2/year
average	879	kWh/m2/year

E. General solar energy estimation tool

Average energy usage per yacht size

Average energy usage			Annual total energy	Annual Hotel energy	Annual Sailing Energy
		GWh/GT	GWh	GWh	GWh
"small" yacht 40-50m	500GT	0,00216	1,08	0,48	0,60
"medium" yacht 70-80m	2000GT	0,00199	3,98	1,75	2,23
"large" yacht 100-140m	4500 GT	0,00164	7,38	3,54	3,84

Average energy usage per yacht size

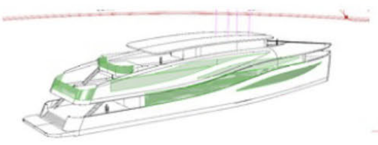
Solar energy assumptions			
Annual horizontal irradiation		1800	kWh/m2/year
Annual vertical irradiation		960	kWh/m2/year
Conversion efficiency		24%	
Performance factor		0,85	
Cell density		100%	
Loss due to colouring		0%	
	m2 solar area	GWh/year	kWh/year
Horizontal Solar energy harvest	0	0,000	0,000
Vertical Solar energy harvested	0	0,000	0,000
Total	0	0,000	

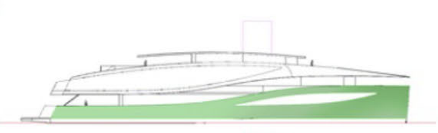
F. Detailed solar yield estimation – 50 metre concept yacht

scenario	total energy harvesting		hotel load covered
Highest day	524	kWh	58%
Lowest day	178	kWh	19%
Daily average	359	kWh	39%

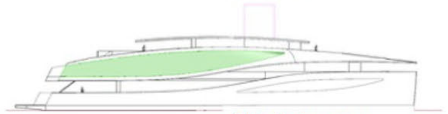
Surface	Area (m2)	Coverage	Colour loss
Hard top	192	73%	0%
Front dodger	103	75%	0%
Side dodger	140	40%	0%
Hull	280	75%	0%
Deck	90	0%	0%
Balustrates/windows	146	0%	0%

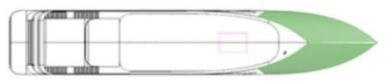
Average energy usage			Annual total ene	Annual Hotel energy	Annual Sailing Energy
	GT	GWh/GT	GWh	GWh	GWh
50m yacht	350	0,00216	0,756	0,33	0,42
			Daily average	Daily average Hotel energy	Daily average sailing energy
			kWh	kWh	kWh
			2071	911	1160

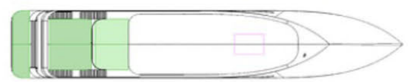

Windows and balustrates area


Hull area


Hard top


Side dodger area


Front dodger


Deck area

Scenario:
Location: Greek island, Mykonos
Date: full year

Annual yield scenario

Solar energy estimation:	Hard top	192m2
Average irradiation	350790	kWh
Conversion efficiency	24%	
Correction factor position	0,85	
cell coverage	73%	
Loss due to colouring	0%	
Solar energy harvesting	52240	kWh

Irradiation on hardtop		
direction bow	**irradiation**	
north	350544	kWh
east	350772	kWh
south	351036	kWh
west	350808	kWh
average	350790	kWh

Solar energy estimation:	Front dodger	103m2
Average irradiation	176153,75	kWh
Conversion efficiency	24%	
Correction factor position	0,85	
cell coverage	75%	
Loss due to colouring	0%	
Solar energy harvesting	26952	kWh

irradiation on front dodger		
direction bow	**irradiation**	
north	164079	kWh
east	173471	kWh
south	190529	kWh
west	176536	kWh
average	176154	kWh

Solar energy estimation:	Side dodger	140m2
Average irradiation	138314	kWh
Conversion efficiency	24%	
Correction factor position	0,85	
cell coverage	40%	
Loss due to colouring	0%	
Solar energy harvesting	11286	kWh

irradiation on side dodger		
direction bow	**irradiation**	
north	149704	kWh
east	126538	kWh
south	150052	kWh
west	126962	kWh
average	138314	kWh

Solar energy estimation:	Hull	280m2
Average irradiation	264776	kWh
Conversion efficiency	24%	
Correction factor position	0,85	
cell coverage	75%	
Loss due to colouring	0%	
Solar energy harvesting	40511	kWh

irradiation on hull		
direction bow	**irradiation**	
north	304691	kWh
east	254043	kWh
south	249848	kWh
west	250522	kWh
average	264776	kWh

Solar energy estimation:	Deck	
Average irradiation	83373,5	kWh
Conversion efficiency	24%	
Correction factor position	0,85	
cell coverage	0%	
Loss due to colouring	0%	
Solar energy harvesting	0	kWh

irradiation on hull		
direction bow	**irradiation**	
north	83376	kWh
east	83371	kWh
south	83376	kWh
west	83371	kWh
average	83374	kWh

Solar energy estimation:	Windows/balustrates	
Average irradiation	135364,25	kWh
Conversion efficiency	24%	
Correction factor position	0,85	
cell coverage	0%	
Loss due to colouring	0%	
Solar energy harvesting	0	kWh

irradiation on hull		
direction bow	**irradiation**	
north	146183	kWh
east	131112	kWh
south	140457	kWh
west	123705	kWh
average	135364	kWh

Total solar energy harvesting 130988 kWh

Scenario:
Location: Greek island, Mykonos
Date: 21 June (sunmer solstice)
Sun hours: 14h 45min

highest yield scenario

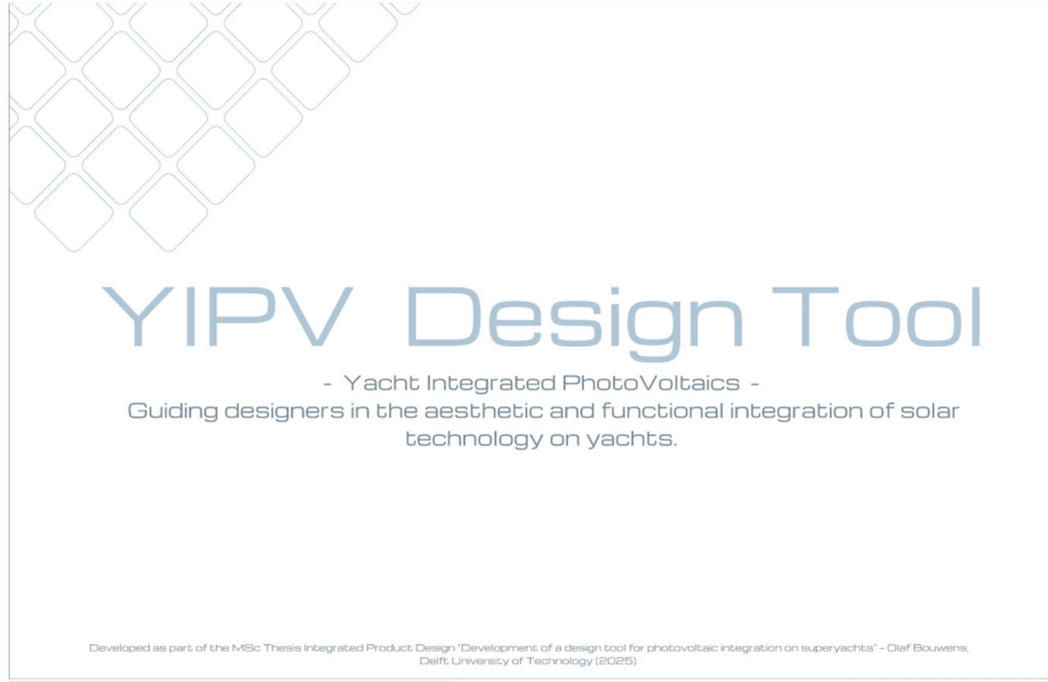
Solar energy estimation:	Hard top	192m2		Irradiation on hardtop		
Average irradiation		1534	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	1534	kWh
Correction factor position		0,85		east	1534	kWh
cell coverage		73%		south	1534	kWh
Loss due to colouring		0%		west	1534	kWh
Solar energy harvesting		228	kWh	average	1534	kWh
Solar energy estimation:	Front dodger			irradiation on front dodger		
Average irradiation		757,5	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	758	kWh
Correction factor position		0,85		east	741	kWh
cell coverage		75%		south	774	kWh
Loss due to colouring		0%		west	757	kWh
Solar energy harvesting		116	kWh	average	757,5	kWh
Solar energy estimation:	Side dodger			irradiation on side dodger		
Average irradiation		449	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	585	kWh
Correction factor position		0,85		east	313	kWh
cell coverage		40%		south	585	kWh
Loss due to colouring		0%		west	313	kWh
Solar energy harvesting		37	kWh	average	449	kWh
Solar energy estimation:	Hull			irradiation on hull		
Average irradiation		937	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	1133	kWh
Correction factor position		0,85		east	774	kWh
cell coverage		75%		south	1100	kWh
Loss due to colouring		0%		west	741	kWh
Solar energy harvesting		143	kWh	average	937	kWh
Solar energy estimation:	Deck			irradiation on hull		
Average irradiation		350	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	350	kWh
Correction factor position		0,85		east	350	kWh
cell coverage		0%		south	350	kWh
Loss due to colouring		0%		west	350	kWh
Solar energy harvesting		0	kWh	average	350	kWh
Solar energy estimation:	Windows/balustrates			irradiation on hull		
Average irradiation		446	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	547	kWh
Correction factor position		0,85		east	350	kWh
cell coverage		0%		south	542	kWh
Loss due to colouring		0%		west	345	kWh
Solar energy harvesting		0	kWh	average	446	kWh
Total solar energy harvesting		524	kWh			

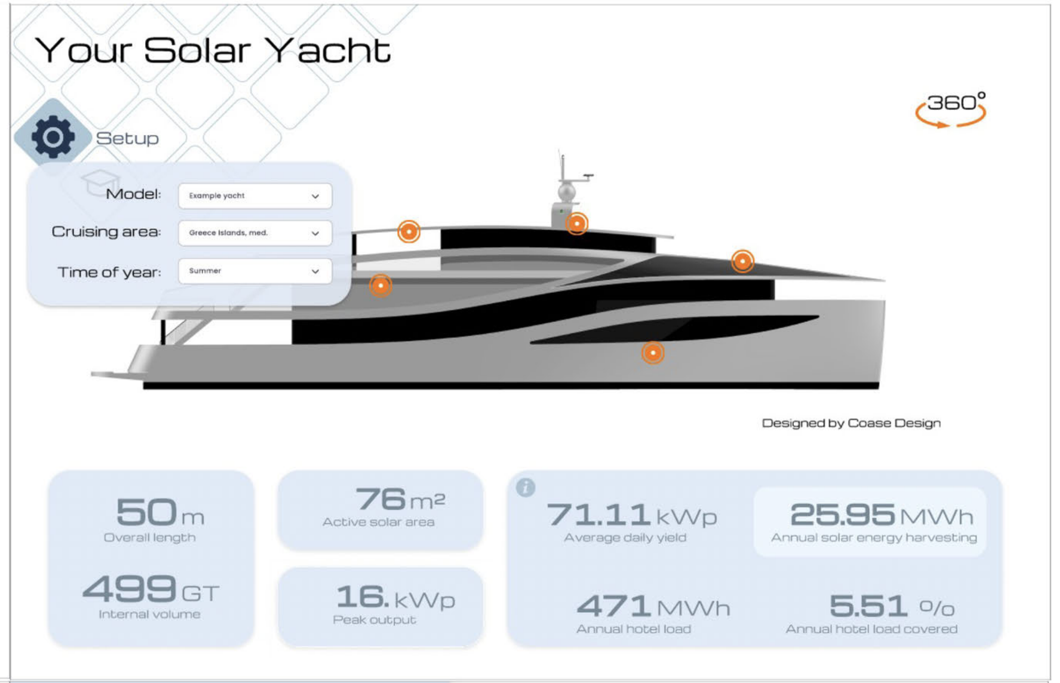
Scenario:
Location: Greek island, Mykonos
Date: 21 December (winter solstice)
Daylight: 9h 35min

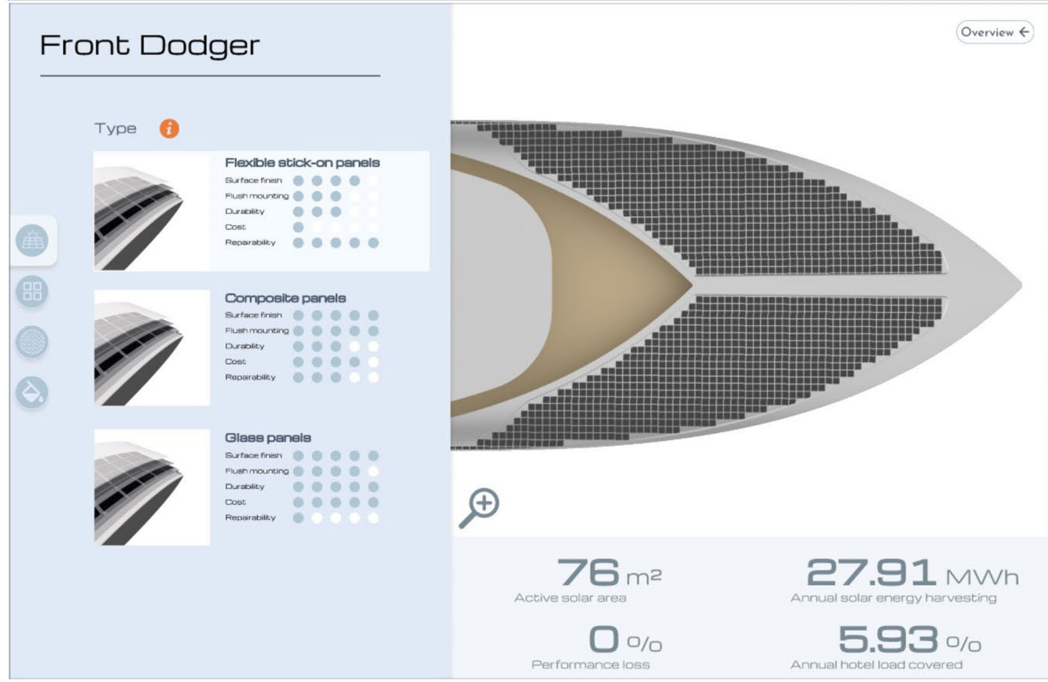
lowest yield scenario

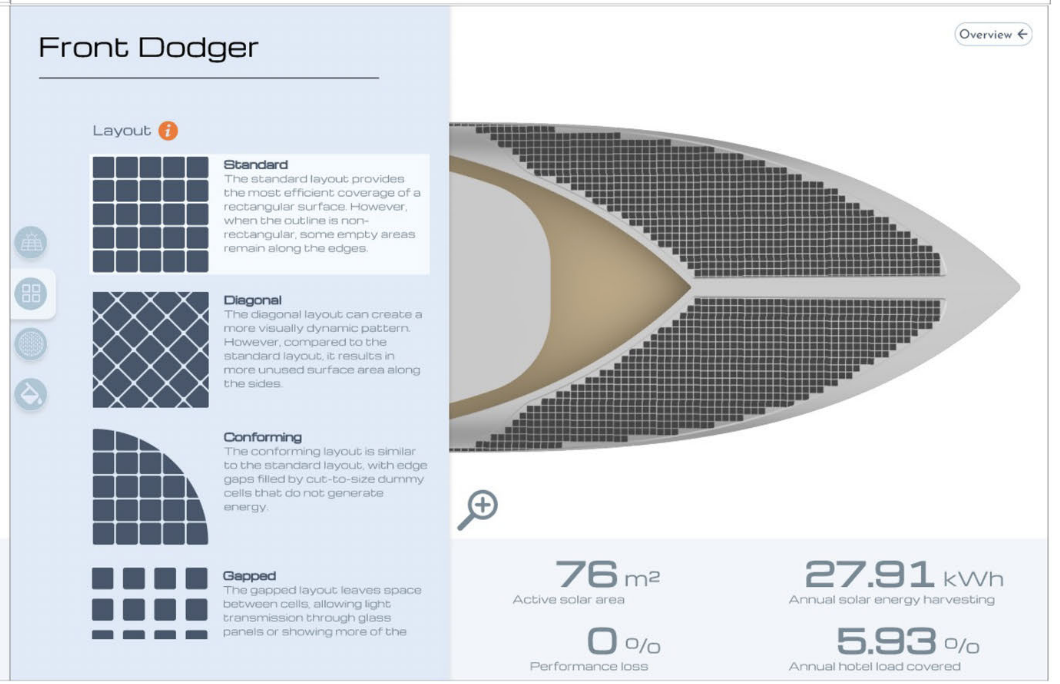
Solar energy estimation:	Hard top	192m2		Irradiation on hardtop		
Average irradiation		400,5	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	401	kWh
Correction factor position		0,85		east	400	kWh
cell coverage		73%		south	401	kWh
Loss due to colouring		0%		west	400	kWh
Solar energy harvesting		60	kWh	average	401	kWh
Solar energy estimation:	Front dodger	103m2		irradiation on front dodger		
Average irradiation		210,5	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	168	kWh
Correction factor position		0,85		east	217	kWh
cell coverage		75%		south	246	kWh
Loss due to colouring		0%		west	211	kWh
Solar energy harvesting		32	kWh	average	211	kWh
Solar energy estimation:	Side dodger	140m2		irradiation on side dodger		
Average irradiation		251,5	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	204	kWh
Correction factor position		0,85		east	298	kWh
cell coverage		40%		south	205	kWh
Loss due to colouring		0%		west	299	kWh
Solar energy harvesting		21	kWh	average	252	kWh
Solar energy estimation:	Hull	280m2		irradiation on hull		
Average irradiation		427	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	448	kWh
Correction factor position		0,85		east	477	kWh
cell coverage		75%		south	286	kWh
Loss due to colouring		0%		west	497	kWh
Solar energy harvesting		65	kWh	average	427	kWh
Solar energy estimation:	Deck			irradiation on hull		
Average irradiation		105	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	105	kWh
Correction factor position		0,85		east	105	kWh
cell coverage		0%		south	105	kWh
Loss due to colouring		0%		west	105	kWh
Solar energy harvesting		0	kWh	average	105	kWh
Solar energy estimation:	Windows/balustrates			irradiation on hull		
Average irradiation		244,75	kWh	**direction bow**	**irradiation**	
Conversion efficiency		24%		north	217	kWh
Correction factor position		0,85		east	290	kWh
cell coverage		0%		south	203	kWh
Loss due to colouring		0%		west	269	kWh
Solar energy harvesting		0	kWh	average	245	kWh
Total solar energy harvesting		178	kWh			

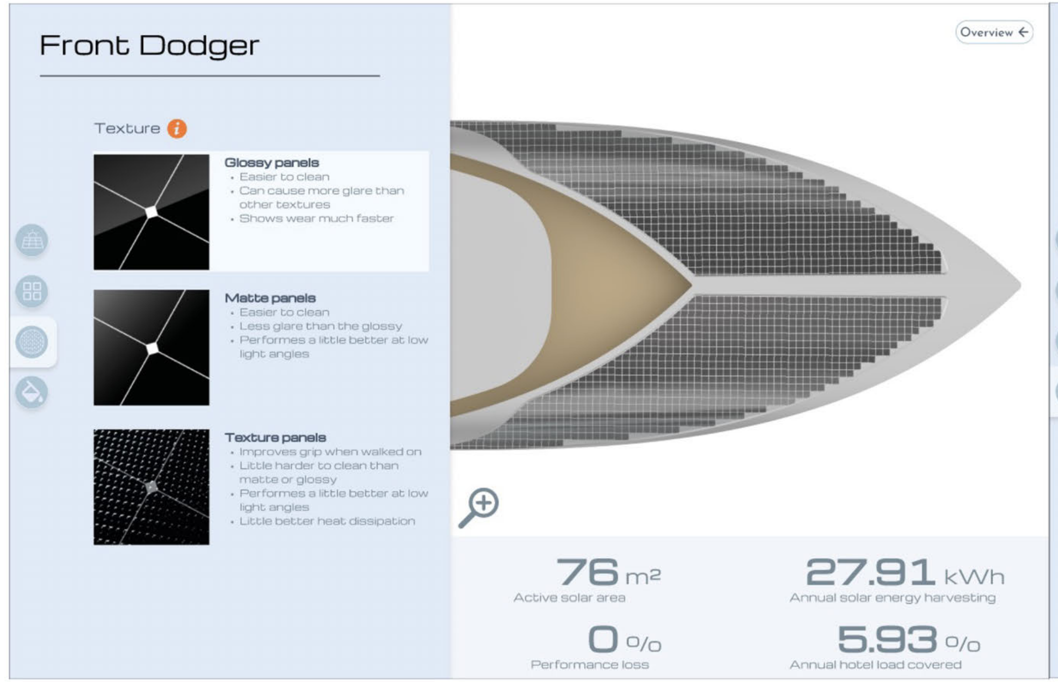
G. YIPV Design tool screenshots – Shape guide

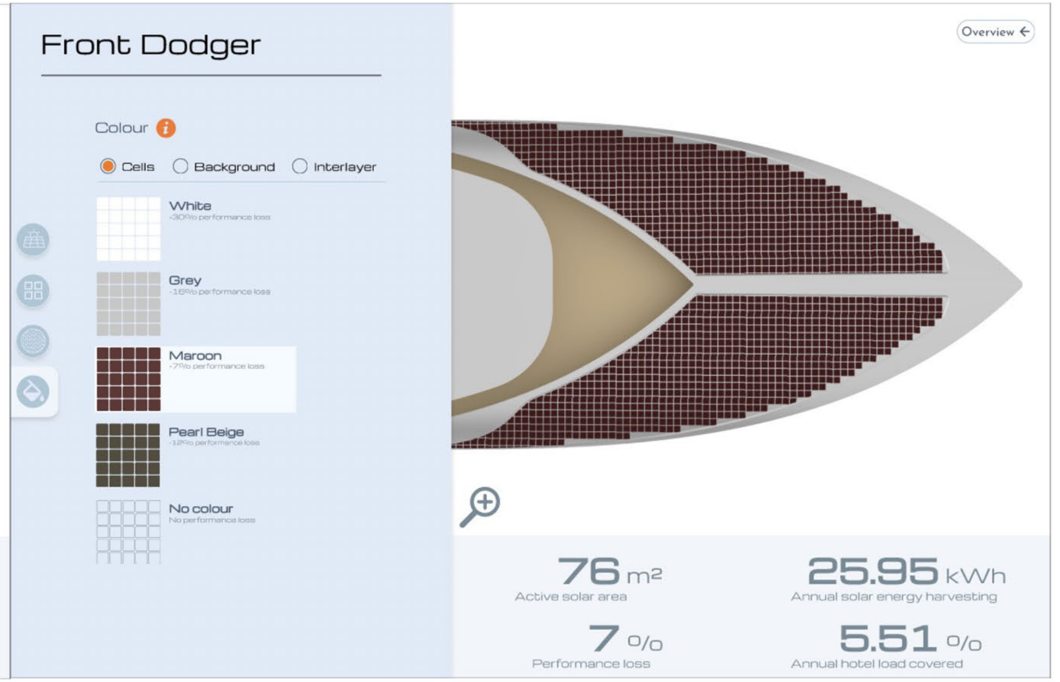




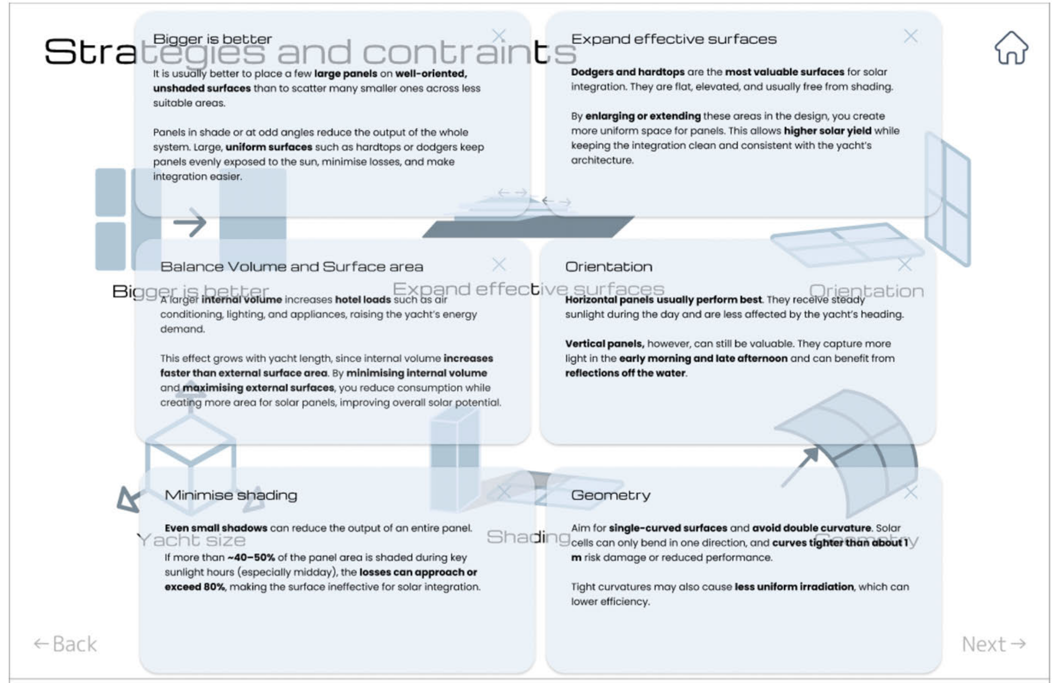


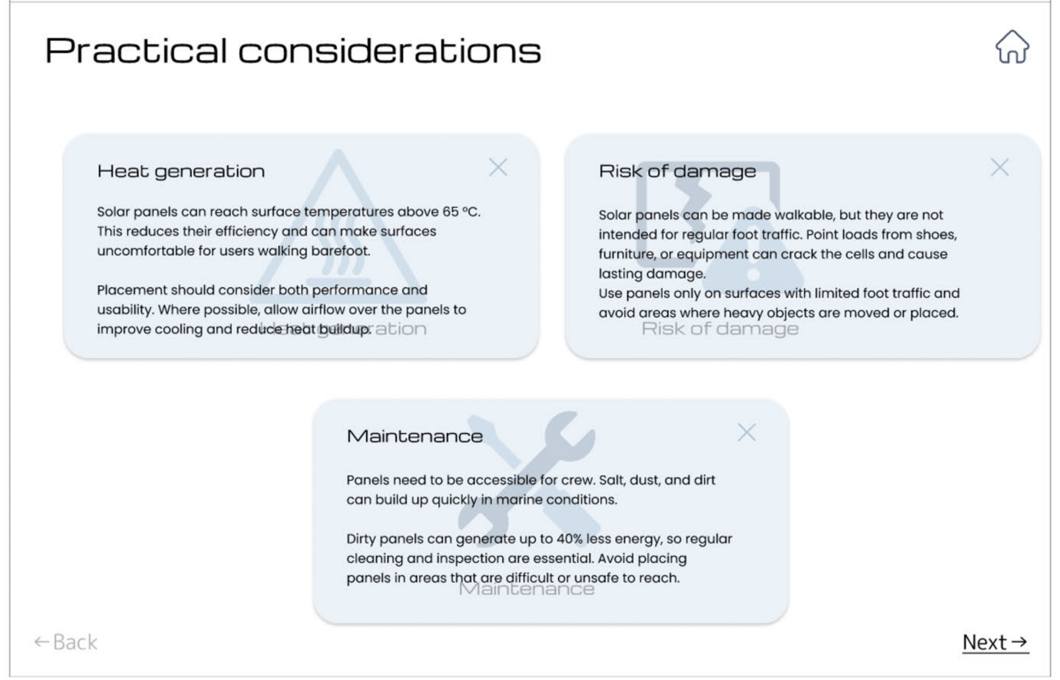


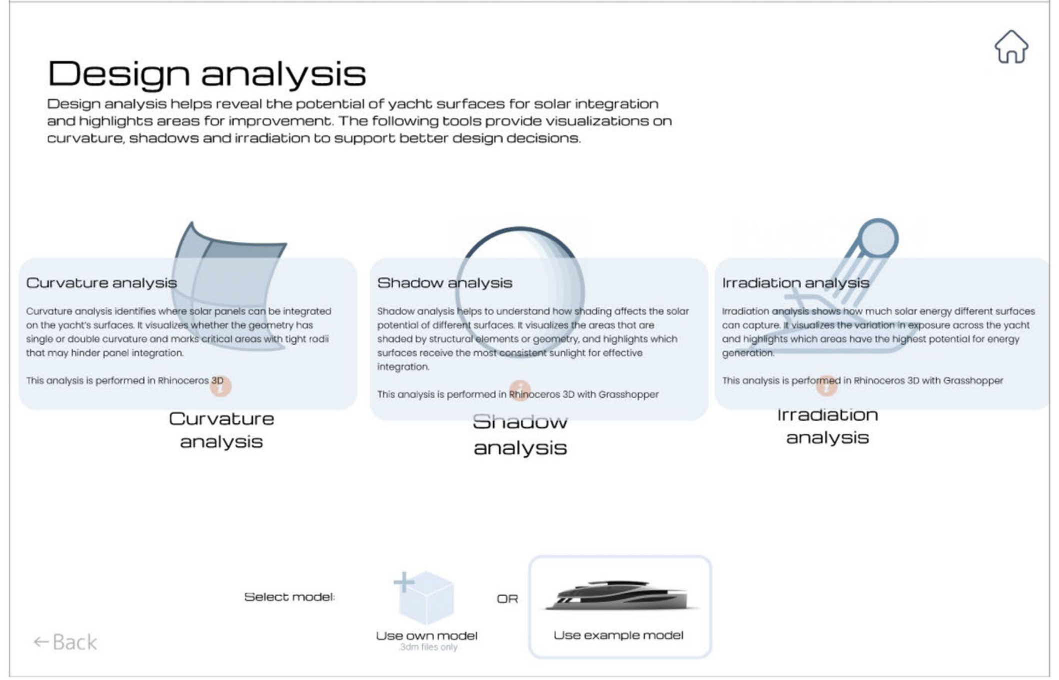




H. YIPV Design tool screenshots – Configurator







I. Exploratory user test - Plan

Objectives

What do I want to explore/understand?

I want to explore how yacht designers perceive and interact with the Design Tool prototype. What are their first impressions? Can they navigate the tool intuitively? What are their expectations of how the tool should function? Do they experience certain pain points, and are there unmet needs or ideas for improvements

Key research questions:

- *Which aspects of the tool are considered relevant and not relevant for the design process?*
- *Can yacht designers navigate the tool intuitively without much explanation?*
- *Do they understand the information, visuals, and outputs provided by the tool?*

Scope

Features/aspects to be tested:

- *First impression: Is it easy to understand what the tool does?*
- *Understanding visualisations and results*
- *Navigation between the pages*
- *Relevance to design practice*

What will not be included in this test:

- *The use of the tool in a real design scenario*

Methodology

Type of test: *Exploratory*
Format: *In-person*
Duration per session: *~ 30 minutes.*
Number of participants: *4*

Participants

Target user group: *Yacht designers/Naval architect or closely involved with yacht design.*

Recruitment criteria: *Working with superyachts >30m, at least 5 years of experience.*

Test Setup

Prototype/product version: *Figma visual prototype presented on a laptop*

Tools used: *recording and note-taking*

Location/platform: *on location or through video call*

Tasks & Scenarios

General scenarios to guide exploration:

Scenario 1: You want to start with a design for a solar yacht. Where do you start?

Scenario 2: You have a finished design and want to see what's possible with solar panels on your design.

On each page:

- *Explain your thought process.*
- *What does this page tell you in your own words?*
- *What do you like on this page, and what is missing or confusing*

Data Collection

What will be recorded: screen and audio

Observations to focus on: navigation, thought process and first impression.

Post-tests debrief questions:

- *What was your first impression?*
- *What part of the tool felt most clear or useful to you?*
- *What parts of the tool felt least clear or useful to you?*
- *In what situations would this tool not be useful for you? Or in which would you use it?*
- *If you could change just one thing to make it more useful, what would it be?*

J. Exploratory user test - Results

Pilot test

Participant #: 0 (Pilot)
Role: Freelance Yacht Designer / Naval Architect
Experience: 15 years
Test Date: 23-09-2025

General First Impression

First Impression: The tools are very user-friendly ("very, very easy"). The participant was instantly engaged by the configurator section. The tool is a brilliant, usable summary of extensive guidelines.

Relevance: Extremely high. The participant stated they would run every yacht they designed through this tool if it were this simple. It quickly provides a 'powerful number' regarding potential.

Understandability: Uncertainty about 'YIPV': The acronym is too cryptic and needs to be explained on the landing page (e.g., 'integration of solar power for YIP design').

Observations and Findings

Workflow & General Structure:

- The desired workflow is "Play first, Learn second".
- The current landing page (with 'Shape Guide' and 'Visual Configurator') is not ideal; the participant wants to be able to immediately 'play' with a model.
- The introductory and information pages need to be quickly traversable ('boring' but necessary).

Scenario 1 & 2 findings:

Navigation/Workflow: The educational pages ('Shape Guide' and 'Practical Considerations') would be better offered as a single, combined 'Information' section, hidden behind a button like 'Background Info' or 'Lessons Learned'.

Analysis Tools (Curvature, Shadow, Irradiation): These three should be merged into a single tool. By selecting a single surface, the tool should instantly provide all relevant data (curvature, shadow/irradiation, suitable products).

Most Useful Output: Maximizing power generation as a direct number after surface selection is the most valuable function.

Rhino Integration: A plugin would be useful, but as a standalone tool with the option to upload a 3DM file, it is acceptable in the early stage. Live feedback (on changes) is the ultimate goal.

Specific Page Feedback:

Shape Guide: Graphics are clear and concise. The visual explanation is effective. The information is very high level. Texts should be short and punchy (not 30 pages).

Practical Considerations: Valuable for understanding limitations. The page feels "a bit scary" due to the images (broken/overheating things), which might discourage starting with PV. The split with the previous page is not super organic.

Visual Configurator: This is the 'money shot'. The visual impact and linked numerical results are the powerful core of the tool.

When returning to the overview/other sections, a 'Done' or 'Save Changes' button should exist instead of 'Back to Overview' to avoid feeling like progress will be lost. A 'Discard' or 'Reset to Zero' button is also needed. Metrics (Hotel Load, etc.): The presented metrics are very good. The assumption of the Annual Hotel Load should be manually adjustable (or at least state 'Estimated').

Post-Test Debrief Questions

Most Clear/Useful: The Visual Configurator and the way numerical results are tied to visual choices. Being able to quickly generate a maximum power number.

Least Clear/Useful: The introduction pages (Shape Guide and Practical Considerations) are the least engaging. The split of the Analysis Tools (Curvature, Shadow, Irradiation). Use Cases: At the early concept stage. To quickly assess the viability of solar energy for a design. Before the first sketches are made.

Top Improvement: Combine the three analysis tools (curvature, shadow, irradiation) into one interface that directly shows the potential maximum power generation of a selected surface.

Conclusion

The pilot test validates the high relevance and significant potential of the tool. However, the participant clearly prefers a 'Design Workflow' (playing with the model) over a 'Research Workflow' (reading the guidelines). The tool must allow the yacht designer to immediately experiment with the model and generate numerical output. The educational components must be retained but should be hidden for the user who wants to start working immediately. The fusion of the three analysis tools into one is a crucial point.

User test 1

Participant #: 1
Role: Yacht & Marine Designer
Experience: 15+ years
Test Date: 24-09-2025

General First Impression

First Impression: The tool is deemed very useful as an early-stage assessment tool. The concept of translating complex technical issues into visual design choices is appreciated. The participant notes that the tool could save a lot of time by quickly eliminating unviable options.

Relevance: High. It fills a gap in the early concept phase, which is currently dominated by manual, time-consuming calculations.

Understandability: Clear. The participant immediately understands the tool's purpose: to support designers in making solar panel integration choices.

Observations and Findings

Workflow & General Structure:

- The flow of the tool seems logical, but the connection between the educational pages and the practical configuration is still a point of discussion.
- The participant wants to see a clearer link between the Shape Guide recommendations and the Visual Configurator results (e.g., 'This surface is X degrees, which corresponds to this efficiency loss from the guide').
- The participant explicitly mentions that the tool's output should be presented in a way that is credible to the client (e.g., "how much less autonomy" instead of just kWh/day).

Scenario 1:

Shape Guide: The participant finds the information useful but expresses the need for more detailed data than the high-level recommendations. Specifically: data on efficiency loss due to curvature.

Practical Considerations: Information about cooling and thermal management is found to be highly relevant and practical for the design process.

Scenario 2:

Visual Configurator: The core functionality (visualizing panel placement) is deemed useful.

Curvature Analysis: The idea of seeing efficiency loss due to curvature is the most desired feature. The participant confirms that this information is currently very difficult to obtain quickly.

Shadow Analysis: Understanding shadows is very important, especially for placement on deckhouses and near railings.

Rhino/CAD Integration: The participant notes that while Rhino is common for design, their large company uses Siemens NX connected to Teamcenter for traceability and version control. This means a direct plugin for Rhino might not be universally applicable in the superyacht industry. Uploading a .3DM file is a good

Specific Page Feedback:

Shape Guide: Good starting point, but requires more specific, quantified data on curvature efficiency.

Practical Considerations: Useful, especially the section on thermal management/cooling.

Configurator: The link between surface properties (like curvature) and the final efficiency loss number should be very explicit.

Post-Test Debrief Questions

Most Clear/Useful: The ability to quickly visualize the placement of PV panels on a 3D model and the potential for the Curvature Analysis feature to provide crucial data currently unavailable early in the design process.

Least Clear/Useful: The exact connection between the general recommendations in the Shape Guide and the specific numerical results in the Configurator.

Use Cases: Primarily in the early concept and feasibility phase (Phase 1-2). It is useful for quickly assessing whether the client's PV ambitions are technically viable with the hull form.

Top Improvement: Provide quantified data on how much efficiency is lost due to curvature to justify design decisions to both the client and the engineering team.

Conclusion

Participant 1 confirms the tool's value as an early design validator, particularly highlighting the potential of the Curvature Analysis to provide data that is currently a major bottleneck. The primary focus should be on quantification and traceability of data to ensure credibility within the professional engineering environment. The tool needs to clearly communicate why a shape is better or worse, using the data from the early educational sections to back up the numerical output in the configurator.

User test 2

Participant #: 2
Role: Project manager Design
Experience: 10+ years
Test Date: 07-10-2025

General First Impression

First Impression: The participant is initially sceptical about the real-world impact of PV on superyachts (noting that consumption is too high for a major contribution). However, the participant acknowledges that design support for PV is needed because the topic is becoming increasingly important for clients and for creating a 'green image'.

Relevance: Moderate to High. The tool is relevant not for technical necessity, but for client communication and initial concept validation (proof of concept).

Understandability: Clear. The participant immediately understands the goal: helping designers balance performance and aesthetics.

Observations and Findings

Workflow & General Structure:

- Initial Scepticism: The participant emphasizes that the tool's goal should be defined as: "If we really put effort into it, we can achieve 20% Hotel Load coverage, and this tool helps us get there." This frames the tool's value proposition against the typical low-impact view.
- Information Overload: Similar to other feedback, the participant notes that once the user understands the principles, the introductory pages become a hindrance. Direct access to the configurable 3D model is preferred.

Scenario 1:

Shape Guide: The basic information about angle/orientation is not news to an experienced designer, but it serves as a good reference and a structured approach.

Practical Considerations: The participant finds the information about cooling/ventilation to be the most critical piece of practical information, as thermal management is a significant practical and safety issue on yachts.

Scenario 2:

Aesthetics vs. Performance: The participant stresses that the aesthetic factor is paramount for superyachts. The tool needs to help the designer justify why a panel is placed in a non-optimal location for aesthetic reasons. The tool should help the designer argue for trade-offs.

3D Visualisation: The visual part of the tool (the Configurator) is the most valuable feature because aesthetics are visual. The ability to see the PV layout on the boat is key.

Curvature/Irradiation: The participant mentions that these analysis features are useful, but the main question is "How much power do I get out of it?" The individual analyses should clearly feed into a single, concrete number.

Specific Page Feedback:

Irradiation Page: Needs to clearly present the output as a 'Total Energy Output' number, not just a heat map, which is visually interesting but not actionable.

Visual Configurator: Should allow easy comparison between two options to facilitate client discussions about trade-offs.

Post-Test Debrief Questions

Most Clear/Useful: The Visual Configurator and its potential to facilitate the discussion of aesthetic trade-offs with the client by quantifying the performance loss of a visually preferred design choice. The Practical Considerations on cooling are also highly valued.

Least Clear/Useful: The sequential and mandatory flow through the introductory pages. The lack of a clear, single "Total Power" number on the analysis pages.

Use Cases: Primarily for concept sketches and client interaction. It serves as an internal check to ensure the team is not missing basic PV design rules and as a persuasion tool for clients.

Top Improvement: Focus on quantifying trade-offs (and provide a clear, numerical Total Power Output at the end of the configuration.

Conclusion

Participant 2 confirms the need for the tool as a way to structure the PV design process and manage client expectations, especially concerning the balance between aesthetics and performance. The tool's most significant value is its ability to quantify aesthetic compromises to make them justifiable to clients and internal stakeholders. The flow must be streamlined to prioritize the visual configuration/trade-off comparison.

User test 3

Participant #: 3
Role: Sales manager with yacht design background
Experience: 10+ years
Test Date: 07-10-2025

General First Impression

First Impression: The tool is considered cool and very useful as an early-stage assessment tool. The participant sees the potential for the tool to assist both the designer and the client in communication.

Relevance: High. It is highly relevant for initial concept development and for communicating the viability of solar PV to clients.

Understandability: Clear, but the Initial Page is confusing. The participant perceives 'Shape Guide' and 'Visual Configurator' as two separate, competing tools, forcing an immediate, unnecessary choice between aesthetics and function.

Observations and Findings

Workflow & General Structure:

- The Starting Page Problem: This participant strongly confirms the feedback from the Pilot test: the start page requires an immediate, difficult choice.
  Proposed Solution: The initial page should function as an explainer/promotional story, clearly stating the purpose of the tool ("This tool helps you maximize your design's solar output") before asking the user to start.
- Navigation: The participant initially chooses the 'Shape Guide' expecting to learn more about the functional form factors before moving to the visual configuration. This suggests that the flow should ideally guide the user from principles to practice, but not make the information pages mandatory.

Scenario 1:

Shape Guide: Found useful for concept designers. The information about the pros and cons of different yacht shapes (Multihull, Explorer, etc.) in relation to PV is seen as a good reference.

Relevance for Designer: The information is suitable for a designer who is new to the topic, providing a good foundation.

Scenario 2:

Visual Configurator (The Tool): This is identified as the main tool for exterior designers.

Use Case Split: The participant clearly defines the two parts of the tool for different use cases:

- Shape Guide: Informing the client/internal team about the initial feasibility and concept during the first design sketches.

- Configurator: Assisting the designer later in the process to check feasibility, efficiency, and aesthetics of the PV layout on the specific model.

Specific Page Feedback:

Shape Guide: Good content, but the pages should flow better. Visual Configurator: The ultimate goal is to see if the proposed design is feasible in terms of efficiency/performance while being aesthetically pleasing (neatly concealed).

Post-Test Debrief Questions

Most Clear/Useful: The concept of the Visual Configurator as an assistance tool for exterior designers, helping them determine if their aesthetic choices are efficient and feasible.

Least Clear/Useful: The current starting page, which creates a false choice between two seemingly independent tools, making the entry point confusing.

Use Cases: Split use: 1. Shape Guide: Informing the client and the concept design team in the very initial stages about sustainability goals. 2. Configurator: Assisting the designer with the detailed exterior design to check feasibility and integration aesthetics.

Top Improvement: Redesign the initial page as a promotional/explanatory splash screen that frames the tool's purpose and then guides the user into the main workflow.

Conclusion

Participant 3 reinforces the high utility of the tool for both design assistance and client communication. The most critical point is the confusing workflow entry, where the 'Shape Guide' and 'Visual Configurator' are presented as a choice instead of sequential or optional steps. The tool should begin with a clear Explainer/Goal Statement to onboard the user before directing them to the relevant section based on their current design stage.

User test 4

Participant #: 4
Role: Freelance Yacht Designer/Naval Architect
Experience: 6 years
Test Date: 08-10-2025

General First Impression

First Impression: The tool is deemed very good and productive for the current stage of the industry. The participant sees high value in a simple, dedicated tool.

Relevance: High. It is seen as a way to quickly integrate PV considerations, which is a growing necessity. The participant emphasises that if the tool makes small improvements (tricks), it can be highly productive.

Understandability: The participant immediately understands the concept. However, the initial page feels like it allows selection when it is only informational, leading to initial confusion about interactivity.

Observations and Findings

Workflow & General Structure:

- Start Page/Workflow: The participant recommends a pop-up screen similar to the startup screen in Rhino. This screen should ask if the user wants to start a Tutorial (all the information pages) or Start Design (go straight to the Configurator/Model). This echoes the 'Play first, Learn second' feedback from the Pilot.
- Information Pages: The Shape Guide and Practical Considerations are useful but should be an optional step for experienced users.
- Navigation: On the Curvature page, the participant missed the 'Back' button, indicating that the navigation flow needs to be clearer.

Scenario 1:

Shape Guide: The high-level information is useful for concept designers.

Irradiation Page: The participant expects to see numerical data corresponding to the irradiation visualization, such as a percentage or total kWh. A visual is not enough; the designer needs a number.

Scenario 2:

Visual Configurator: The ability to select surfaces is key.

Analysis Tools (Curvature, Shadow, Irradiation): The participant argues that the Shadow Analysis is the most crucial of the three for making practical design choices, especially with a well-developed model (near-final design).

Justification: The glass areas, canopies, and railings are already decided in later stages, and the shadow analysis provides strong, practical constraints for PV placement.

Model Context: The participant believes the tool is stronger when used with a detailed, well-based 3D design (near-final design) rather than in the earliest concept phase, as the later-stage design provides better data on available surface area and shadows.

Specific Page Feedback:

Irradiation Page: Needs a clear numerical output to validate the visual representation.

Overall Clarity: The participant was slightly confused by the difference between the 'Selection' and the 'Information' on the initial interactive elements.

Post-Test Debrief Questions

Most Clear/Useful: The ability to visualize the model and select surfaces, particularly the potential of the Shadow Analysis to give strong guidance for final PV placement on complex yacht geometries.

Least Clear/Useful: The lack of numerical output on the Irradiation page. The initial workflow that forces users through the information pages.

Use Cases: The participant sees the tool as being very useful later in the process, with a good, defined 3D model, rather than just the earliest concept phase.

Top Improvement: Implement a start-up screen/pop-up that allows experienced users to skip the information pages and go directly to the model configuration.

Conclusion

Participant 4 validates the necessity and potential of the tool but provides a different perspective on the optimal use phase: they find it stronger when used with a more detailed 3D model due to the importance of accurate Shadow Analysis. Crucially, the workflow needs an express route to the configurator for experienced users, and every visual analysis (like Irradiation) must be accompanied by explicit numerical data to be useful in a professional design context.

Personal Project Brief – IDE Master Graduation Project

Name student Olaf Bouwens **Student number** 4791703

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Exploring solar panel integration on luxury yachts: balancing energy output and design

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

As the maritime industry faces growing pressure to reduce its environmental impact, integrating solar power on luxury yachts presents both technical and design challenges. While photovoltaic technology offers a sustainable solution, its application on yachts is limited by two key issues. First, the limited availability of 'ideal' surfaces makes it difficult to install enough solar cells to cover the yacht's energy consumption. Second, high-efficiency solar panels often require large, flat surfaces which are often not that common in luxury yacht design. Their black appearance further clashes with the refined look of luxury yachts.
This project aims to explore the potential for integrating photovoltaic technology, answering the following questions: What if I use all surfaces to integrate solar cells? What is the performance on each surface and which technology will be used? How can I do it with minimal impact on the intended design and aesthetic? How feasible is it?
The primary stakeholders are yacht designers and shipbuilders, who need to find a balance between performance and aesthetics when using solar energy in their designs. Other stakeholders are yacht owners, that will be provided with an option to reduce the yacht's reliance on conventional energy sources and reduce the overall energy cost.
Factors as increasing cost and complexity of the yachts will also need to be evaluated to prove feasibility.

→ space available for images / figures on next page

introduction (continued): space for images

image / figure 1 illustrative example of used and potentials surfaces for solar cells. source: Adobe stock

image / figure 2 Impact on design and aesthetics. source: Sunreef Yacht

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Integrating solar power on luxury yachts is challenging because conventional solar panels need large, flat surfaces that are rare in yacht designs. Additionally, their typical black appearance often conflicts with the yacht's luxurious aesthetics. This makes it difficult for yacht designers and builders to maximize the use of solar technology to reduce dependency on fossil fuels. Currently, clear guidance on using alternative yacht surfaces or newer photovoltaic technologies without compromising aesthetics is missing.

This project addresses the need for practical guidelines that help designers and builders integrate solar panels onto various yacht surfaces, balancing energy performance, visual appeal, and build feasibility.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Create a design guideline to support yacht designers and shipbuilders in integrating photovoltaic cells on luxury yachts by identifying suitable surfaces, solar panel types, and integration methods while balancing performance with design and aesthetics.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The project will begin with a research phase, studying: photovoltaic (PV) technologies and efficiencies, shipbuilding techniques and materials and yacht design. This research will result in potential surfaces to integrate PV cells, what type of PV cells, potential ways of combining the PV cell in shipbuilding materials and key elements of a aesthetic yacht design. This research consist of both a literature study as interviewing experts in the industry.
The knowledge gained in this research phase will then be applied in a case sudy. In this case study I will take a concept design of a 50m yacht, provided by a yacht designer.
This case study has two goals. First, to integrate as many solar panels as possible, by balancing performance and the original design philosophy and aesthetics. Second, determine the feasibility of this integration.

The results will be formulated in a design guideline for yacht designers and shipbuilders that want to use solar energy in their designs.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	26-03-2025
Mid-term evaluation	19-06-2025
Green light meeting	02-10-2025
Graduation ceremony	31-10-2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

As a sailor, I have a strong passion for the maritime and shipbuilding industries, I am driven to make a meaningful impact by helping the industry become more sustainable. Studying Industrial Design Engineering has given me a strong interest in technology and innovation. Combined with my design skills, I aim to enhance how solar power is integrated into yachts, focusing on both design and aesthetics. I also hope to give the industry a fresh perspective on how solar cells can be used more effectively in yacht design.
Through this project, I aim to deepen my understanding of photovoltaic technologies and material science to find the best way to integrate solar power into yachts. It also allows me to strengthen my systems thinking skills by considering the many interconnected factors involved in integrating solar panels on unconventional surfaces, such as performance, aesthetics, structural integrity and the complexity of the building process. I also want to sharpen my critical thinking in evaluating the feasibility of the different intergration solutions

Besides the personal and acedemical growth, I also want to get more familiar with the yacht industry, seeing myself pursuing a career in shipbuilding.