Green Deal Validation study Wattlab

PV-system on general cargo vessels

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Summary

The International Maritime Organization (IMO) and the Dutch Green Deal have set ambitious targets for reducing CO_2 emissions from shipping, aiming for a 70-100% reduction by 2050 compared to 2008 levels. This study focuses on the application of Solar Flatracks, which are modular PV systems installed on the deck of vessels to generate sustainable energy. In this study, conducted by TNO, the potential of Wattlab's Solar Flatrack photovoltaic (PV) system for reducing greenhouse gas (GHG) emissions on general cargo vessels is evaluated.

Key Findings:

1. **Environmental Impact:**
   - The Solar Flatrack system was piloted on the general cargo vessel Vertom Anette. Over seven months, the system generated 496 kWh of energy, leading to a fuel saving of 123 litres.
   - The study used a mixed methodology, combining data from the pilot with a modelling approach to assess the environmental impact on a broader scale. The average annual energy production was estimated at 866 kWh per kilowatt-peak (kWp) of installed PV capacity.
2. **Technical and Safety Aspects:**
   - The Solar Flatrack is designed to fit into the corner castings of vessels, making installation straightforward. Each panel is equipped with a microinverter for optimal power output.
   - The system complies with relevant safety standards, including SOLAS and IEC 60092, ensuring it does not interfere with the ship's main power supply or critical equipment.
3. **Economic Viability:**
   - The business case for the Solar Flatrack system appears promising, with a payback period of approximately 9,6 years based on fuel savings and CO_2 emission pricing under the EU Emission Trading System (ETS). This is based on a price of the Solar Flatrack system between €1,5/kWp-€1,9/kWp.
   - The system's cost-effectiveness improves when the FuelEU Maritime GHG intensity limits are taken into account. Compared to meeting these limits by blending HVO into the fuel mix, the Solar Flatrack becomes the more cost-effective option after 5,1 years.
   - The breakeven point between installing the Solar Flatrack and instead meeting the GHG limits by blending HVO into the fuel mix depends strongly on two factors: the PV system CAPEX and the assumed HVO price.
     To capture this uncertainty, a sensitivity analysis was carried out.
4. **Scalability and Future Proofing:**
   - The scalability of PV systems on vessels is primarily limited by available deck space. General cargo vessels, with their large deck areas, offer significant potential for PV deployment.
   - The long-term supply of materials for PV module production, such as silicon, glass, and aluminium, is not a major concern

Conclusion: The Wattlab Solar Flatrack system is a suitable and effective option for reducing GHG and pollutant emissions on general cargo vessels. The system's energy yield and resulting fuel and emission reductions depend on the vessel's operational area. The study concludes that the Solar Flatrack can provide both a positive financial return and a meaningful contribution to reducing CO_2 emissions in the maritime sector.

Contents

1 Introduction

1.1 General

1.1.1 Green Deal

Firm objectives have been set by the International Maritime Organization (IMO) for shipping and the Dutch Green Deal goes one step further. The IMO agreements mean that the transport performance by seagoing vessels must improve to such an extent that CO_2 emissions per tonne-kilometre will be reduced by an average of 40-60% by 2030.
The Green Deal aims for an absolute reduction of 70-100% in 2050 compared to 2008, regardless of market growth.

These ambitious goals call for solutions that can be applied today, because ships that are put into service today will most likely still be operational in 2050. The potential of available sustainable maritime solutions is great and is constantly expanding, but none of the available solutions is suitable for all ship types and in all operational conditions. The decision to opt for a sustainable solution also depends on the business case in which the ship must be able to operate. Currently, there is a lack of objective information on the match between sustainable solutions and type of business case.

In addition to direct CO_2 emissions, the emissions of greenhouse gases CH_4 and N_2O and air-polluting emissions such as NO_x, NH_3, SO_x and particulate matter are of great importance. The emissions of NO_x, SO_x and particulate matter from shipping are relatively high and are decreasing slowly due to insufficiently effective emission legislation and slow fleet renewal.

The diversity of available sustainable maritime solutions makes it difficult to determine which solution is most suitable for application on a ship as this depends on many factors. For example, each solution differs in the required space on board, the layout of the ship and integration with other systems, as well as for the costs and earning capacity of the ship itself. There is a large array of available sustainable solutions for various ship types, for various operational conditions and lengths of shipping routes. It is therefore important that the effects of these solutions are made transparent in an independent manner and that through validation reliable information is collected so that these solutions can be weighed against each other (ref. NL Green Deal art.12 paragraph 3: “Knowledge institutions will work with the industry to provide independent insight into and validate the effects of the sustainable maritime solutions so that comparison of these solutions is possible and it is easier for shipowners and financiers to compare.”).

The results of the performed validations provide reliable information for all parties in the maritime chain, making it easier to choose sustainable solutions.

1.1.2 Validation process

Transparency towards all parties in the maritime chain (from ship owners, ship operators and other logistics operators, shippers, financiers, suppliers, shipyards, to government) is important in the implementation of these validations.

The sector itself is investigating which sustainable maritime solutions have the greatest potential to accelerate the energy transition. The technologies with the greatest potential are then validated at independent knowledge institutions. We call this form a cluster study; the sector is represented in this by KVNR and NMT, the knowledge institutions involved are MARIN and TNO, possibly supplemented by an external party if this is necessary for the implementation of a concrete validation case.

Transparency is achieved by making the results public through reports that present an overview of how the various sustainable maritime solutions, grouped by theme, perform in terms of social impact, technical impact and economic impact.

1.1.3 Green Deal validation

The Green Deal validation program of the Ministry of Infrastructure and Water Management (I&W) offers the opportunity to independently review reduction measures. The marine sector, represented by KVNR and NMT, plays an important role in putting forward the key solutions for GHG reductions which can be implemented or scaled up in the near future. KVNR and NMT consult the sector (technology providers and ship owners) to identify the most important techniques to validate. Thereafter, the contacts are handed over to the knowledge institute that is most knowledgeable, which can also be both, making it a joint validation project.

The validation needs to include the following aspects:

- **Environmental impact**: impact on reduction of GHG and pollutant emissions
  This is the core of the validation: the provider claims an emission reduction technique, which is validated by an independent study;
- **Applicability** to the maritime fleet (categories);
  Related to the 6 reference ships identified in the Green Deal (See Table 1.1). Identifying possible opportunities and obstacles;
- **Technical impacts and safety aspects;**
- **Economic aspects;**
- **Scalability and future proofness** with respect to materials used and sustainability criteria.

Table 1.1: Green Deal Validation reference vessels and their mission profiles. For dredgers and yachts, the hotel-load is accounted for. For the transport vessels, the hotel-load is low and not included in these high-level mission profiles. (MARIN, 2020)

	Lengte m	Breedte m	Geinstal. vermogen kW	Waterver-plaatsing m³	DWT ton	Auto-nomie dagen	Operationele conditie	Snelheid kts	Tijdsdeel %	Vermogen kW	Huidig geïnstalleerd systeem Huidige brandstof
General Cargo											**4-stroke ICE-direct, medium speed MGO**
	112	18.2	4290	12800	9216	30	transit	13	55	3861	
							manoeuvreren	5	10	557.7	
							in haven	0	35	0	
Sleep boot											**Z-drive ICE-direct, high speed Diesel**
	32	12	5000	1140	285	15	transit	12.5	25	4275	
							slepen	4	25	4275	
							wachten/haven	0-2	50	500	
Offshore supply											**4-stroke ICE-electric, high speed MGO**
	82	17.5	6000	5800	2900	5	transit	14.5	45	5130	
							manoeuvreren	2	25	600	
							in haven	0	35	0	
Crew tender catamaran											**4-stroke ICE-direct, high speed Diesel**
	25	9	2100	90	20	3	transit	23.5	40	1850	
							manoeuvreren + on-/off loading	5	10	210	
							in haven	0	50	0	
Baggerschip											**4-stroke ICE-direct, medium speed MGO**
	125.00	28.00	12000	29750	21000	14	Transit	16	22	7814	
							baggeren	2	31	8730	
							Varen,dumpen door pomp	1	12	5567	
							varen, dumpen door deuren	1	14	6126	
							lossen aan kade	0	12	9948	
							in haven	0	10	0	
Superjacht											**4-stroke ICE-electric-hybrid, high speed Diesel**
	100	17.2	13000	4600	460	14	top snelheid	22	5	12300	
							cruise snelheid	18	10	6450	
							endurance snelheid	12	20	2550	
							manoeuvreren	4	10	1250	
							voor anker	0	20	600	
							in haven	0	35	0	

1.2 Technology specific introduction

1.2.1 Wattlab: PV-systems on seagoing vessels

Wattlab is a Dutch start-up based in Rotterdam, the Netherlands. After the development of solar hatches for inland shipping vessels, Wattlab has introduced a new system for the application on seagoing vessels. They are developing the “Solar Flatrack”, a modular photovoltaic (PV) system for installation on vessels to generate sustainable energy on board. The system consists of a relocatable, waterproof sandwich panel with integrated PV panels. Solar Flatracks can be positioned on a vessel, and the energy yield can be fed into the switchboard on the vessel. Figure 1.1 shows a Solar Flatrack as installed on a general cargo ship. Each Solar Flatrack contains five solar panels with a rated power of 375Wp each, adding to a total of 1.9kWp per Solar Flatrack. The total solar power potential of a vessel depends on how many Solar Flatracks are installed, which is primarily determined by the available deck space.

Figure 1.1: Single Solar Flatrack installed on the hatch of a general cargo vessel.

For this validation, a pilot project was conducted in which one Solar Flatrack was installed on a general cargo vessel to monitor its energy yield. In the pilot project, the yield of the PV-system is assessed.

1.2.2 Research questions (very brief)

The main research question is defined as follows:
Is solar power on ships, and in particular the Wattlab system, a suitable and effective option for GHG and pollutants emissions reduction for the Dutch reference ship categories? This research question will be answered by evaluating the five aspects that were mentioned in 1.1.3.

This study will only consider the application of the Solar Flatracks on general cargo vessels. The large flat surface area on the hatches of these vessels makes them suitable for placing Solar Flatracks on deck and thereby generating solar energy on board.

In this validation study, a mixed methodology will be used where the data from the validation period will be combined with a modelled approach. Data was collected from the PV-system and the vessel it is installed on. This data will be used to assess the environmental impact on this particular vessel. A modelling approach based on solar PV energy yield data from online sources in combination with operational profiles for the reference vessel General Cargo (as defined by (MARIN, 2020)) will be used to assess the environmental impact in more general terms.

The remaining aspects outlined in Section 1.1.3—namely applicability, technical and safety impacts, economic considerations, scalability, and future-proofing—are assessed through expert consultations with Wattlab and supplementary desk research.

2 Technical impacts and safety aspects

2.1 Technology types and standards

2.1.1 Mechanical installation

The Solar Flatrack is designed to fit into the corner castings on the vessel that would otherwise be used for placing containers. The Solar Flatrack is secured in place using twistlocks in the same manner as container securing. This is shown in Figure 2.1.

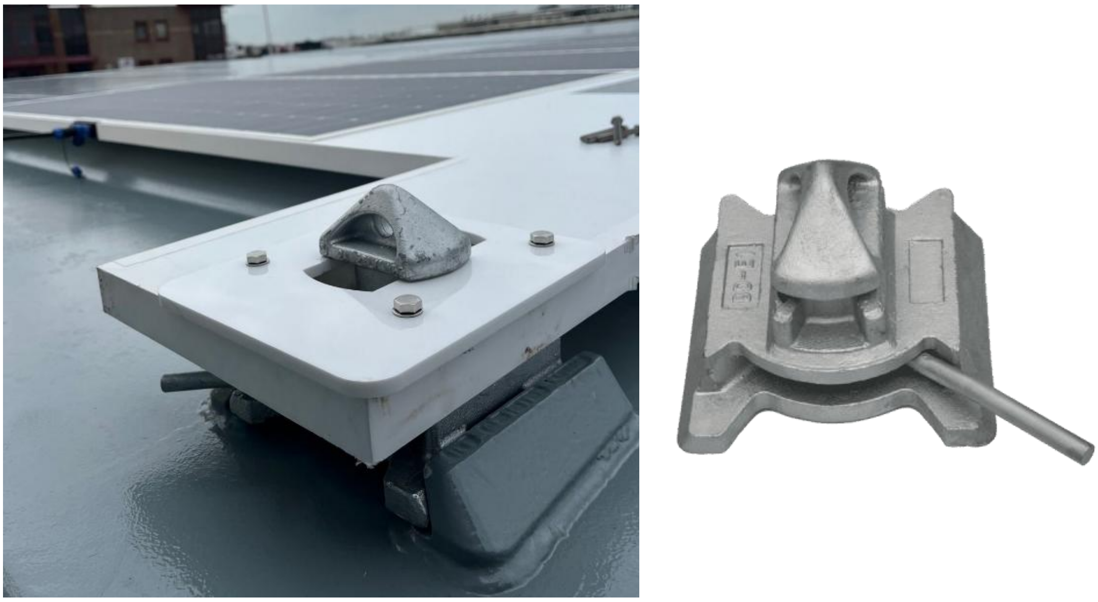

Figure 2.1: Attachment of the Solar Flatrack to the corner castings on the vessel using twistlock (left) and view of twistlock (right).

Complying to the same standard dimensions and securing mechanism as containers makes the Solar Flatracks easy and quick to install on a vessel.

2.1.2 Electrical layout

As mentioned, each Solar Flatrack holds five solar panels. Each panel is equipped with its own microinverter, which takes care of Maximum Power Point Tracking (MPPT). By using MPPT, the solar panel operates at its optimal power output by continuously adjusting the voltage and current to match the panel's Maximum Power Point (the point where it generates the most power). The microinverter then converts the DC power generated by the panel into AC power.

By having one microinverter per panel, each panel's performance is optimized individually, ensuring that shading, dirt, or other issues affecting one panel do not reduce the overall efficiency of the system. This way, the energy harvest from the Solar Flatrack is maximized.

In the case of the pilot on the vessel Vertom Anette only one Solar Flatrack was used, so the solar power production of the PV system will almost never exceed the power consumption of the vessels systems that are powered by its low voltage (440V) line. The generated power feeds directly onto the low voltage line via a 32 Ampere **3P+N+E 6h socket**.

To understand the electrical integration of the system on board, a simplified schematic of the electronic layout of Vertom Anette shown in Figure 2.2. As can be seen in the schematic, the vessel is equipped with four generator sets that supply its electrical power. All of the generated power feeds a high voltage DC bus (3), from which power is further distributed either to the electric motors for propulsion or the low voltage AC bus (7) to power the other on board systems. As indicated in Figure 2.2, the Solar Flatrack feeds into the AC bus. Since in current design no power can be converted from the AC bus (7) to the DC bus (2) the power generated by the Solar Flatrack can only be used by appliances that are powered by the AC bus (mainly the hotel load) and not for the propulsion motors (5).

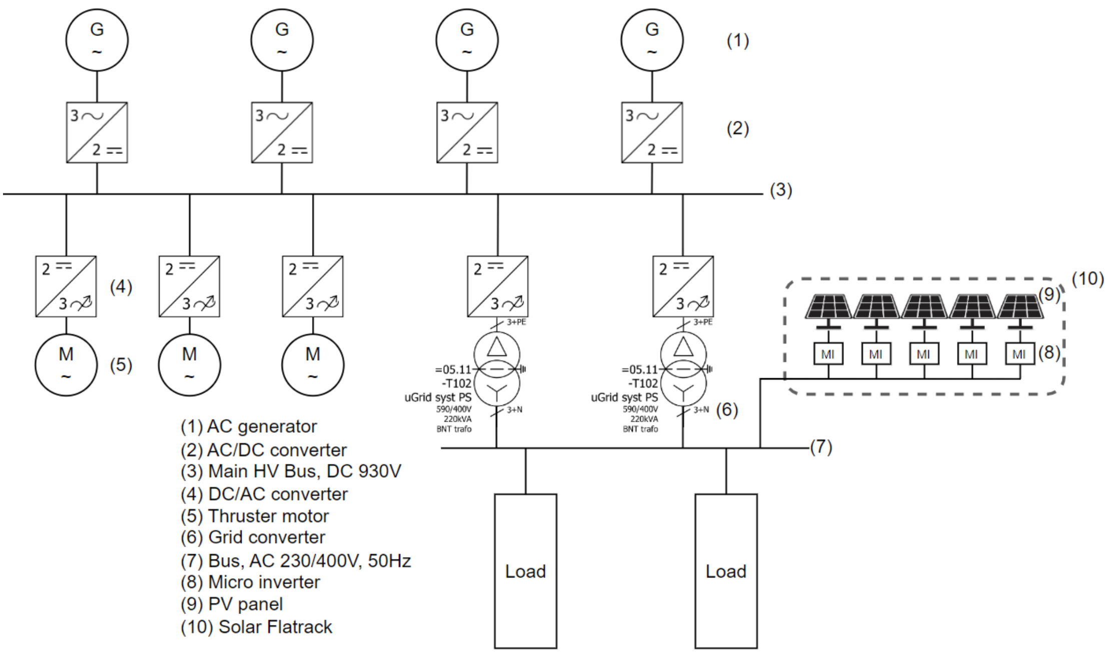

Figure 2.2: Simplified schematic of electrical layout of Vertom Anette.

When more PV capacity is installed, the generated solar power might exceed the power consumption on the low voltage line on some occasions when the energy production of the PV system is high relative to the load. In that case, excess solar energy is not utilized. The installation of a battery could be considered to buffer the excess solar energy for later use, instead of the excess solar energy being wasted. The inclusion of a battery is not within scope of the current project.

2.2 Regulatory framework (pollutants, safety) and effect on the technology

2.2.1 Emission reducing regulation

Several regulations and standards influence the implementation of PV systems in vessels. However, PV installations can contribute to compliance with emission-reduction regulations by reducing fuel consumption. The most relevant regulations (and the effect of PV systems on them) are summarised below.

FuelEU Maritime
Article 6 of FuelEU Maritime (European Parliament & Council, 2023a) specifies limits on well-to-wake GHG intensity (in gCO_2e/MJ) for energy generation on vessels. These targets gradually reduce over the coming years to incentivize ship operators to operate efficiently and reduce their CO_2-emissions. Generating solar energy on board reduces the amount of energy generation that is required from generator sets, and therefore can help ship operators to comply to the targets set out by FuelEU Maritime.

EU Emissions Trading System (ETS)
The ETS for shipping is a cap-and-trade system that requires ships above 5,000 GT operating in EU waters to monitor, report, and surrender allowances for their CO_2-emissions, effectively putting a price on carbon to incentivize emission reductions. PV systems on vessels help reduce emissions, which decreases the number of allowances a ship must surrender, which leads to cost savings for the owner or operator.

Alternative Fuels Infrastructure Regulation (AFIR)
Under AFIR Article 9 (European Parliament & Council, 2023b), the EU sets standards for ports to provide infrastructure for alternative fuels like electricity, hydrogen, and LNG to help decarbonize shipping. One of the main requirements is that, by 2030, EU ports must offer onshore power supply (OPS) to container and passenger ships over 5,000 GT. Future updates may expand OPS requirements to more ship types and sizes. Installing PV systems onboard could help reduce the electricity demand from the port, easing the strain on infrastructure and potentially lowering the costs and effort for ports to meet AFIR requirements.

Energy Efficiency Existing Ship Index (EEXI)
EEXI sets mandatory energy efficiency standards for existing ships to limit CO_2-emissions per transport work. EEXI is expressed in gCO_2 per ton-mile, and each ship type has a required reference line, usually based on its size or deadweight tonnage (DWT). If ships do not comply with the limits, measures must be taken (e.g., engine power limitation, hull modifications, or alternative fuels/energy solutions). PV systems on board of vessels can help reduce the gCO_2 per ton-mile of vessels. However, the is no consensus yet on how the yield of PV systems can be incorporated into the formula for EEXI, as solar yield depends strongly on the vessels location and time of year.

Carbon Intensity Indicator (CII)
CII is an operational measure introduced by the IMO to assess and reduce the annual carbon intensity of ships. It is expressed as grams of CO_2 emitted per cargo-carrying capacity and nautical mile, and applies to vessels above 5,000 GT. Ships are rated from A to E, with a D rating for three consecutive years or an E rating in a single year requiring a corrective action plan.

The rating depends strongly on how efficiently the ship is operated, including speed, routing, and fuel choice. PV systems can contribute by lowering fuel consumption and thereby improving a vessel's CII rating.

MARPOL Annex VI (Prevention of Air Pollution from Ships)
MARPOL Annex VI, adopted by the IMO, sets global limits on air pollutants from ships, including SO_x, NO_x, particulate matter, and ozone-depleting substances, and introduces measures to improve energy efficiency (such as EEXI and CII). These requirements establish the minimum international standards for shipping emissions and energy performance. While PV systems are not directly covered by MARPOL Annex VI, they can indirectly support compliance by reducing fuel consumption and CO_2-output, thereby improving a vessel's efficiency and helping operators meet the Annex VI performance requirements.

2.2.2 Safety

Several regulations address the electrical safety of systems on board vessels and are relevant for the installation of PV systems. These regulations focus on the vessel's electrical and electronic systems, while the PV panels themselves are subject to separate safety standards and certification requirements.

SOLAS (International Convention for the Safety of Life at Sea)
SOLAS sets international standards for ship safety, including electrical installations. Onboard **PV systems** must be integrated in a way that does not compromise the ship's main power supply, emergency systems, or stability. (Newly) installed systems should avoid interference with critical equipment such as navigation lights and radio systems, and all electrical components must be designed to withstand the marine environment.

Electrical installations in ships (IEC 60092)
The **IEC 60092 series** covers the design, installation, operation, and safety of electrical systems on all types of ships. It applies to high-voltage and low-voltage systems, AC and DC, and encompasses power generation, distribution, and utilization. The standard focuses on ensuring safe and reliable electrical installations in maritime environments. Any **onboard PV system** must be installed in accordance with IEC 60092, a special point of attention is the safe integration into the ship's power distribution network.

2.3 Additional potential risks of the technology (technical and operational and safety)

PV technology is a highly mature technology and has been widely deployed in stationary applications for decades. It has also been successfully applied in certain mobile contexts, such as vehicles and remote installations. The application of a PV system on a ship can still cause several risks.

Technical risks

- Mechanical failure of the Solar Flatrack due to unexpected mechanical loads or improper mounting. The Solar Flatracks remain in place when the ship hatches open and close, potentially causing increased mechanical loads. Extreme wind forces could also cause damage to the Solar Flatracks.

- Crew stepping on the PV panels or items being dropped on the Solar Flatracks could cause damage to the panels, leading to decrease in energy yield. However, the sandwich panel that makes up the structure of the Solar Flatracks is designed such that it can mechanically withstand the load of a person walking on it.

Operational risks

- Panels could limit available space for cargo operations, evacuation routes, or maintenance access. As mentioned, the Solar Flatracks are designed such that it can withstand the load of a person walking on it, but that might affect the electrical output of the panels.

Safety risks

- Errors during production or installation could lead to fire or other electrical hazards. While the likelihood is low if the system is installed in accordance with IEC 60092 and SOLAS requirements, the potential consequences are severe.
- Although PV technology is well-proven in stationary applications, on board vessels the system is exposed to dynamic mechanical loads and harsh maritime conditions (salt, humidity, vibration), which could damage the Solar Flatracks electrical or mechanical components and create safety hazards.

2.4 Impact on maintenance and reliability of operations

Impact on maintenance

- Placement of the PV system on the deck might limit access for maintenance. In case the PV system blocks access to certain parts of the deck, the panels can be temporarily removed to make space.
- Additional periodic cleaning required. PV modules on deck accumulate salt, dust and biological fouling that reduce yield; scheduled cleaning/inspection is therefore required to maintain optimal energy output.
- Extra crew training required. Crew needs instruction on inspection, safe cleaning, basic troubleshooting and updated emergency/firefighting procedures for PV systems.
- Extra work during maintenance/loading in case the Solar Flatrack(s) need to be disconnected and connected again.
- Deck-mounted panels can obstruct hatch operation and cargo/maintenance access.
- Extra inspection for corrosion. Salt spray accelerates corrosion of fasteners and connectors; select components tested to IEC corrosion standards and schedule corrosion inspections.

Operational reliability

The energy yield from the Solar Flatracks are complementary to the existing energy generation via generator sets on board. Therefore, failure or malfunction of the PV system does not cause immediate operational impact on the vessels operations.

3 Environmental impact

3.1 Validation approach

Environmental impact on the pilot vessel
The environmental impact of the Solar Flatracks will be validated by assessing the data that was collected for this study. Over the course of seven months (February 2025 until August 2025) the energy yield of the Solar Flatrack as well as the vessels energy system is monitored. Wattlab provided monitored data of the energy and power output of the PV system. Vertom provided access to their data dashboard from which generator powers, operational modes, location, and many other signals could be obtained. Section 3.2.1 will describe the monitoring campaign and the resulting solar energy yield and resulting fuel savings. The fuel savings are estimated based on the reduction of the power that is needed from the generators on board.

Modelling approach for environmental impact on the reference vessel 'General Cargo'
In order to make a more general assessment on the expected benefit of the Solar Flatracks outside of the Vertom Anette, a modelling approach was used. Representative routes were defined based on which the expected solar energy production were calculated throughout the year. Based on the operational profiles from the reference vessel 'General Cargo' (MARIN, 2020) the fuel consumption savings were calculated, as well as the associated emissions. This is described in Section 3.2.2.

3.2 Energy efficiency

3.2.1 Energy efficiency on the pilot vessel

This section will describe the solar energy yield and associated fuel savings on the pilot vessel during the monitored period. The pilot vessel is the Vertom Anette, a general cargo vessel built in 2024. This vessel has a gross tonnage of 4766 GT, a total length of 119m and width of 14 m. The propulsion system of this vessel is diesel-electric, powered by four 400 kW generators. Figure 2.2. shows how the power from the generators is distributed to both the propulsion system and the low voltage grid from which the other systems are operated.

3.2.1.1 Power consumption and specific fuel consumption

As mentioned in Section 2.1.2, the PV system is connected to the low voltage AC bus of the vessel. To assess how much fuel is saved by every kWh of generated solar energy we have to assess how much litres of fuel would have been needed to generate that same amount of energy on the AC bus using the generators on board. Two aspects have to be considered to evaluate these fuel savings:

1. The energy conversion losses that are incurred by converting the output energy from the generators via the AC/DC converter (number 2 in Figure 2.2)) and the grid converters (number (6) in Figure 2.2). We assume a conversion efficiency of 98% based on product specification (Marpower).

2. There are some losses associated with getting the produced solar energy on board to the main switchboard of the vessel. An efficiency of 98% is assumed here.
3. The amount of fuel (in litres) needed to generate 1 kWh of electric energy at the output of the generator(s) (number 1 in Figure 2.2).

The efficiencies of aspect 1 and 2 cancel each other out: for every kWh generated by the PV system, only 0.98 kWh ends up on the main switchboard. To generate that same energy with the generators, 0.98 kWh / 98% = 1kWh needs to be generated by the generators.

For the third aspect: The amount of litres of fuel that a generator needs to generate 1 kWh of electricity depends on the operating point (or power output level) of the generator. Generators are generally less efficient at low power levels as compared to higher power levels. Therefore, we first identify how frequent each power level occurs in the operating modes of the vessel. The data dashboard of Vertom contains an indicator for operational mode. Figure 3.1 presents two different perspectives on generator operation across the three main operational modes of the vessel: harbour (left), manoeuvring (middle), and transit (right).

The first row of Figure 3.1 illustrates the distribution of power output levels for a single generator. Each bar represents the proportion of time that a generator operates within a given power range, providing insight into how heavily the generators are typically loaded in each mode. This shows, for example, whether a generator is predominantly running at low, medium, or high output during a particular mode of operation. The second row of Figure 3.1 shows the distribution of time with respect to the number of generators that are simultaneously in use. Since the vessel is equipped with four generators, this number can vary between zero (all generators off) and four (all generators running at the same time).

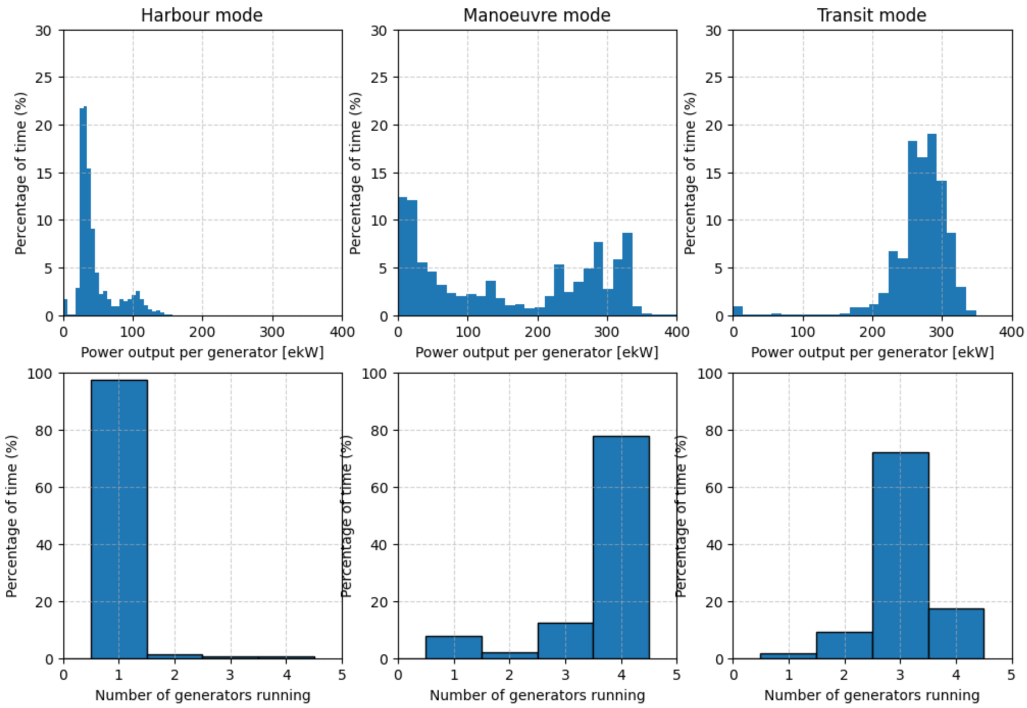

Figure 3.1: Top row: Distribution of power output level per generator as a percentage of time, per operational mode. Bottom row: Distribution of number of running generators as a percentage of time, per operational mode. All data was collected from Vertom Anette between July 2024 and January 2025.

As can be seen in Figure 3.1, the power level of a generator while the vessel is harbour mode is between 0 and 100 kW for the majority of the time, with an average of 46 kW. From the data dashboard of Vertom it becomes clear that in berthed condition, only one of the four generators is running. In manoeuvre mode, the power output varies strongly.

While the vessel is in transit, the power output per generator is roughly between 200 and 350 kW per generator, with an average of 269 kW. Most of the time during transit three of the four generators are running at these power levels, since the vessel uses about 800 kW to 900 kW in transit.

The power levels from Figure 3.1 can be used to identify the specific fuel consumption (SFC) in Figure 3.2. The SFC specifies how many litres of fuel are needed to generate 1 kWh. This figure shows the volume of fuel required to generate one electric kWh from the generator as a function of the generator output power. The figure, based on data from Vertoms data dashboard, shows that the SFC is higher at low power output, and lower for high power. In the figure the power levels while berthed in harbour mode are indicated by the orange box, and the power levels while in transit are indicated by the pink box. While berthed the SFC is between 0.26 to upwards of 0.60 l/kWh, and while in transit the SFC is relatively constant at around 0.23 l/kWh.

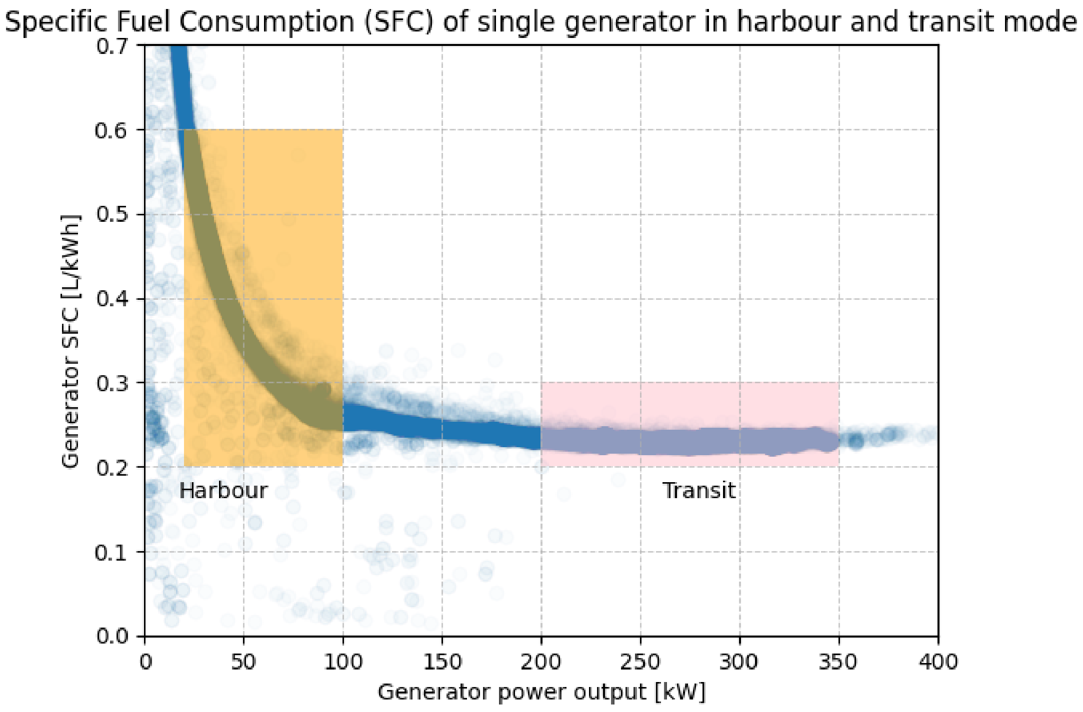

Figure 3.2: Specific Fuel Consumption [l/kWh] as a function of generator power for Vertom Anette between July 2024 and January 2025. The pinked dashed box indicates the generator power level while the vessel is berthed, and the red dashed box indicates the power levels while in transit.

As said, all the power that is generated by the Solar Flatrack does not have to be generated by the generators. During transit, the SFC is constant enough to estimate that approximately 0.23 litres of fuel are consumed for every kWh generated by the generators.

While the vessel is berthed, every kWh of generated solar energy saves 0.26 to about 0.60 l/kWh. As the average output power of a generator in harbour mode is 46 kW, an average SFC of 0.42 l/kWh.

It is however important to note that when the PV system takes over a significant part of the power production from the generator the power point of the generator drops, increasing the SFC as can be seen in Figure 3.2. For example: When the hotel load is 50 kW, and a potential large scale PV system would generate 20kW at the same time, the output power of the generator drops to approximately 30 kW. This increases the SFC from about 0.325 to about of 0.45 l/kWh.

Since the SFC curve is very steep in this pink indicated box, this reduces the fuel saving potential of the PV system quite significantly. Smart energy management and the addition of a battery to buffer generated solar energy could help improve the total fuel savings.

The power output in manoeuvring mode varies strongly (as shown Figure 3.1), and therefore also the SFC varies strongly. The generator operates in the efficient regime (>100 kW) for about half the time, while the other half of the time the generator operates in the more inefficient regime (<100 kW). Therefore, an average SFC of 0.3 l/kWh is assumed for manoeuvring mode.

Table 3.1 summarizes the SFC values per operational mode.

Table 3.1: Specific Fuel Consumption (SFC) values per mode based on data from Vertom.

Mode	SFC [l/kWh]
Harbour	0.42
Manoeuvre	0.30
Normal duty	0.23

3.2.1.2 Solar energy production

As mentioned, the solar energy production of the Solar Flatrack installed on Vertom Anette was monitored from February 2025 until August 2025. As a first rough indication of the energy production, the total daily energy yield over the course of the pilot is shown in Figure 3.3. This energy production is measured after the microinverters, so the losses associated with conversion from AC to DC by the inverters are already included in these numbers.

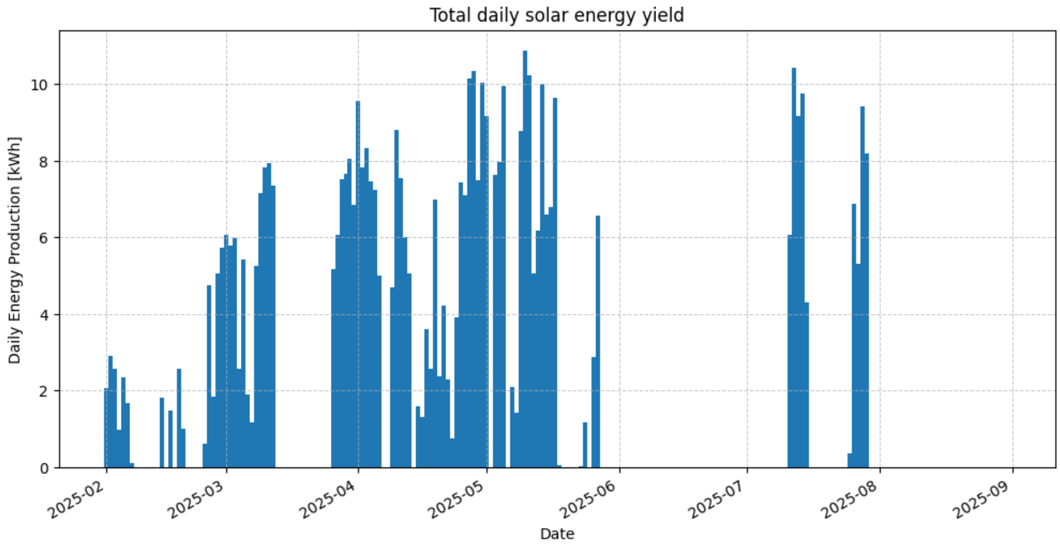

Figure 3.3: Daily solar energy yield monitored from February 2025 until August 2025 for the Solar Flatrack installed on Vertom Anette.

The image shows that on many occasions, the Solar Flatrack did not produce any solar energy. This is due to the system not being connected by the crew. On 91 days of the total 212 days the power output was nonzero, which is an uptime of 43%. This is because the system was disconnected and remained disconnected for long stretches of time, because it was a small pilot setup that was not top of mind for the crew. For the analysis, we will only consider the nonzero power outputs. Besides that, the image shows that the solar energy yield varies strongly over the days. Solar irradiance depends strongly on location and local weather effects, so it results in highly variable daily energy production.

The total energy generated by the Solar Flatrack on Vertom Anette during the monitored period is 496 kWh. Since the Solar Flatrack was not producing any energy on many occasions and those occasions are not distributed evenly throughout the monitoring period of February 2025 until August 2025, we first calculated the average daily solar energy production for each month. Considering only the days with nonzero yield, the system produced on average 5.45 kWh per day. Extrapolating this gives an expected yearly production of 1989 kWh per year when the days the system was disconnected are discarded. It is convenient to normalize the energy production to the installed power of the system in order to more easily compare it to our modelling approach later in this report. The installed power of the system is 1,875 kWp (as mentioned in Section 1.2.1), so the normalized annual energy production of 1061 kWh/kWp.

3.2.1.3 Fuel savings

Based on the signal 'operational mode' of the vessel during the monitoring period, we can assign an average SFC value for each day. This is done by calculating the timeshares of the different modes each day: "harbour", "manoeuvre" and "normal duty". For each mode we assign a SFC based on Table 3.1.

By multiplying the daily solar energy production by the corresponding average SFC for the day (depending on the shares of operational modes for that day), by the daily solar energy yields, a daily fuel saving can be found. These are presented in Figure 3.4.

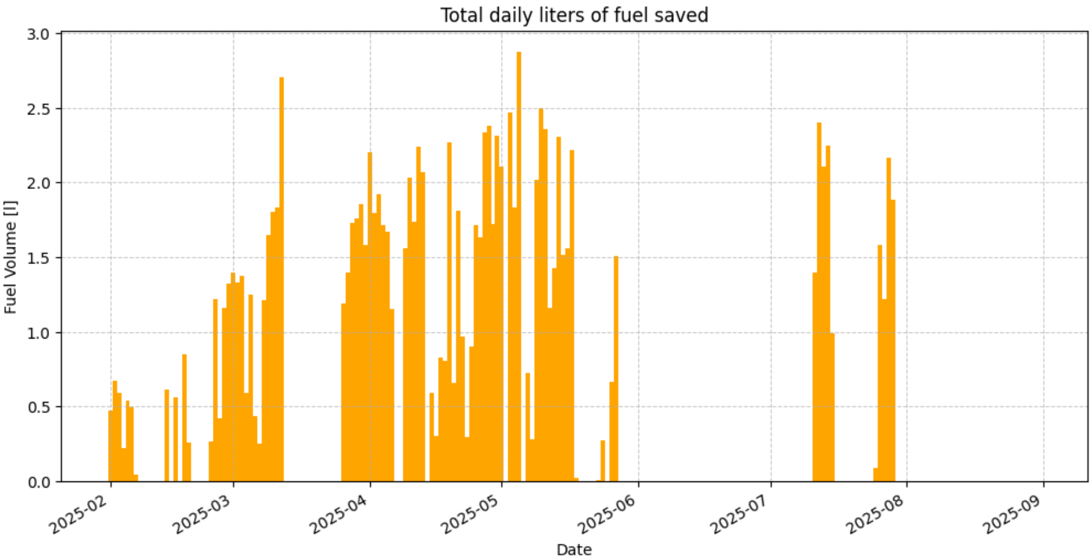

Figure 3.4: Daily fuel saved from February 2025 until August 2025 for the Solar Flatrack installed on Vertom Anette.

The total amount of fuel saved is 123 litres. On average, the single Solar Flatrack reduced the fuel consumption by 1.35 litres per day if only the days where the solar yield is nonzero are considered. This corresponds to 0.71 L/kWp per day, 262L/kWp per year when it is normalizing to the installed power of the solar system.

3.2.1.4 Location

As mentioned, the energy production and resulting fuel savings are directly linked to the geographic location. Regions closer to the equator typically receive more consistent solar radiation and more sun hours. Consequently, the routes sailed by the pilot vessel influenced the solar energy production. Figure 3.5 shows a heat map of the location of the pilot vessel: the more yellow the colour, the more time the vessel spent in that area.

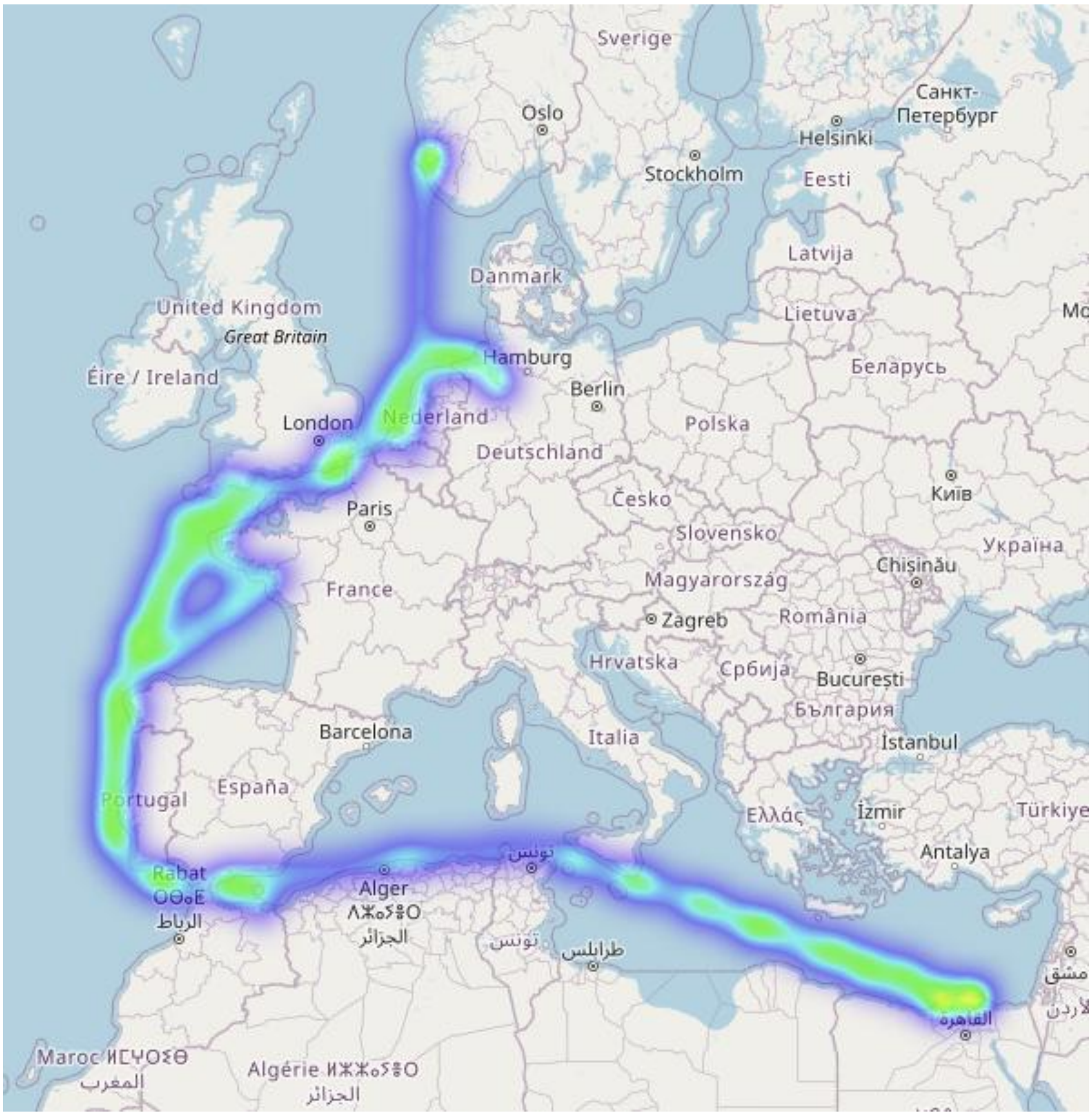

Figure 3.5: Heat map of the location of Vertom Anette during pilot period (February 2025 until August 2025).

The vessel frequently operated in the North Sea, along the Bay of Biscay, and towards the Strait of Gibraltar. Section 3.2.2 provides a more detailed discussion of how solar energy production varies with location.

3.2.1.5 Effect of shading and disconnection of the panels on the solar energy production

The Solar Flatrack consists of five panels (as described in Section 1.2.1. The output of the PV system is monitored per panel. That allows us to compare the energy output of the different panels amongst each other. This is shown in Figure 3.6. The order of the panels 1 to 5 does not correspond to their position in the Solar Flatrack.

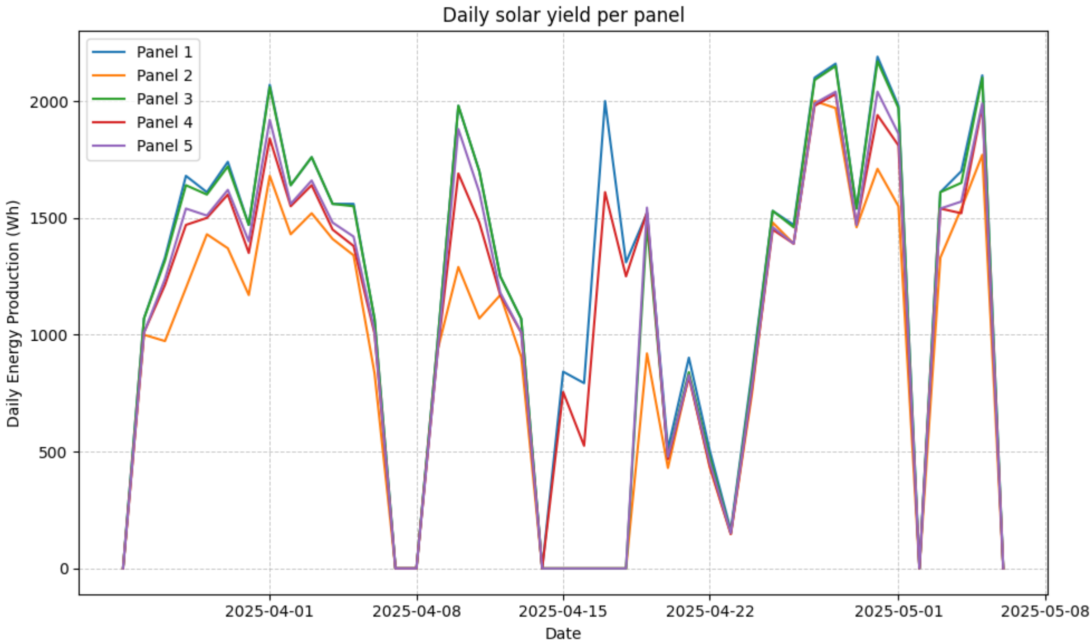

Figure 3.6: Daily solar energy production per panel (each of the 5 panels of the installed Solar Flatrack) over a selected period within the monitoring period.

As can be seen in the image, the energy output of Panel 2 is on almost all days lower than the others. This can be explained by considering the positioning of the panels on the vessel as shown in Figure 3.7. Panel 2 in Figure 3.6 is most likely the panel closest to the structure on deck in Figure 3.7, which sometimes casts a shadow on a part of the Solar Flatrack.

Table 3.2 shows the total energy production per panel in the Solar Flatrack. From this it becomes clear that Panel 2 produced at least 10% less solar energy.

Table 3.2: Total energy production per panel during the pilot period (February 2025 until August 2025).

Panel	Total solar energy production
1	109 kWh
2	86 kWh
3	103 kWh
4	100 kWh
5	98 kWh

Based on conversations with Wattlab, there are only a limited number of structures on board of the vessel, and the positioning of the Solar Flatrack for this pilot is suboptimal.

Figure 3.7: Structure near the Solar Flatrack that can casts a shadow on a part of the PV system.

Since the on-board structure introduces substantial shading, the influence on the energy yield and the resulting fuel savings is evaluated. For this purpose, the computation is based on the average output of the three best-performing panels (Panels 3, 4, and 5). Based on that calculation, we find an average daily energy production of 5.51 kWh corresponding to 1.30 litres of fuel saved daily. Normalizing this to the installed power of the solar system gives an annual energy production of 1073 kWh/kWp and 265 L/kWp of fuel savings, both slightly higher than the numbers presented earlier in this section.

3.2.2 Reference vessel

To provide a broader evaluation of the potential benefits of the Solar Flatracks beyond Vertom Anette of the other Vertom vessels, a modelling approach is used. In this modelling approach, the reference vessel of “General Cargo” will be used as defined by MARIN (MARIN, 2020). On top of that, representative routes are defined for short-sea general cargo vessels, allowing the expected solar yield to be estimated over the course of a year.

3.2.2.1 Operational profile: power consumption

For the reference vessels within the Green Deal, certain average specifications and operational behaviour is specified by MARIN (MARIN, 2020). These specifications were already shown in Table 1.1, and the relevant part of the table is repeated in Table 3.3.
The most relevant specifications are the time shares in different operational conditions, and the associated propulsion power consumption. These can be used to evaluate the total fuel savings. The reference vessel assumes a 4-stroke ICE-direct medium speed propulsion system running on MGO.

Table 3.3: Snippet of the Green Deal Validation reference vessels and their mission profiles, only the General Cargo reference vessel is shown (MARIN, 2020).

Length m	Width m	Installed Power kW	Water displacement m³	DWT ton	Auto-nomy days	Operational condition	Speed Kts	Time share %	Propulsion power kW
General Cargo									
112	18.2	4290	12800	9216	30	transit	13	55	3861
						manoeuvring	5	10	557.7
						in port	0	35	0

Table 3.3 only specifies a “Propulsion power”, and not the hotel load. In the absence of a specified hotel load, the hotel load will be assumed to be a percentage of the transit Propulsion power in transit. The same percentage between propulsion power and hotel load will be used as for Vertom Anette, which is 6% as shown in Appendix C. The hotel load for the reference vessel then becomes 6% of 3861kW, which equals 234kW.

3.2.2.2 Representative routes

Representative routes for the reference vessel “General Cargo” are formulated and are shown in Table 3.4. These routes are based on common routes of this vessel type observed from operational data and literature taken as return routes from Rotterdam. These routes are used to analyse the energy yield from the PV system on board. The routes are visualized on the world map in Figure 3.8.

Table 3.4: Representative routes for reference vessel "General Cargo".

Route number	Origin	Destination	Distance [km]	Colour
1	Rotterdam	Hull	387	Dark blue
2	Rotterdam	Oslo	1012	Red
3	Rotterdam	Bergen	1011	Green
4	Rotterdam	Helsinki	1721	Orange
5	Rotterdam	Liepaja	1312	Purple
6	Rotterdam	Bilbao	1381	Black
7	Rotterdam	Lisbon	2023	(hidden below route 8)
8	Rotterdam	Venice	5611	Red/Brown
9	Rotterdam	Galway	1375	Grey
10	Galway	Aberdeen	1113	Turquoise
11	Aberdeen	Rotterdam	744	Magenta

Figure 3.8: Representative routes for reference vessel "General Cargo" on the map.

3.2.2.3 Solar energy production data

To validate the solar energy production on the sailed route, we compare the monitored daily solar energy production from the five panels on board with the expected solar yield for that specific location and month. The data source used for the solar irradiation along the route is Global Solar Atlas (World Bank Group, Solargis, 2022).

The Global Solar Atlas directly provides information about the expected PV system output in kilowatt-hours per installed kilowatt-peak capacity. This expected PV output is based on monthly averages, not on weather data (such as cloud coverage) of specific dates. Global Solar Atlas computes this based on a set of inputs about the orientation of the panels, the type of installed system and the location. Appendix A lists the assumed parameters (like operating temperature, efficiencies) that were used to get to the expected PV system output. Since the solar panels in the Solar Flatrack are mounted flat on deck, the heading of the vessel is not relevant for this energy production analysis.

Figure 3.9 shows an example of the used data for the location of Rotterdam. This figure shows the average daily energy output in watt-hours for each month of a year of the PV system per installed capacity in kilowatt-peak based on historic data. This image clearly shows the seasonal effect: daily energy production in summer is a multitude of that in winter. The shape of this curve varies depending on the location, and therefore it is important to consider both the location and time of year of a vessel when estimating the expected solar energy production on a route.

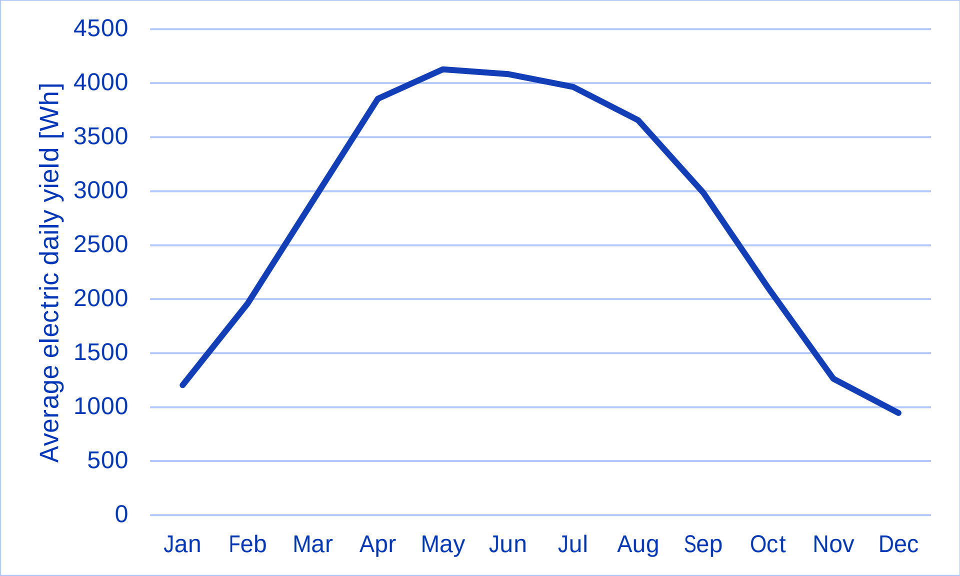

Figure 3.9: Daily solar energy yield in watt-hours per installed PV capacity in kilowatt-peak for the location of Rotterdam. (World Bank Group, Solargis, 2022)

3.2.2.4 Solar energy production along representative routes

Solar energy production data source

A model was created to estimate the expected solar energy production on the representative routes described in 0. This model uses the data from Global Solar Atlas (World Bank Group, Solargis, 2022), the expected electric energy output of a PV system per day for each month of the year. An example table of this data is shown in Appendix A. The energy production from Global Solar Atlas is expressed as Watthours per installed kilowatt-peak of PV capacity, which allows us to scale it to the capacity of the system we want to evaluate.

Time shares in each operational mode

The Green Deal Validation reference vessel (Table 3.3) specifies that the vessel spends approximately 15% of its time in harbour, 35% of its time in manoeuvring and the remaining 55% in transit. To estimate the energy production in the harbour, it is assumed that half of the 'harbour' time is spent in the origin port and the other half in the destination port. As manoeuvring often happens in/around ports, it is also assumed that half of the 35% is spent in the origin port, and the other half in the destination port.

Method of calculating solar energy production along representative routes

To estimate the expected solar energy in transit, the average daily energy production of the origin port and destination port is used. For most routes, this provides a reasonable estimate of energy production, since daily yield roughly varies with latitude (Figure 3.10), which along most routes changes in a relatively linear way. However, for some routes this is not the case. For example for route 8, Rotterdam to Venice, taking the average solar energy production of the origin and destination would not be representative because the route first has to travel south (passing through the Strait of Gibraltar) and then back up north once it passes Sicily. Therefore, two intermediate locations along the routes were added for which the latitude does not change relatively linearly along the routes: 8, 9 and 10.

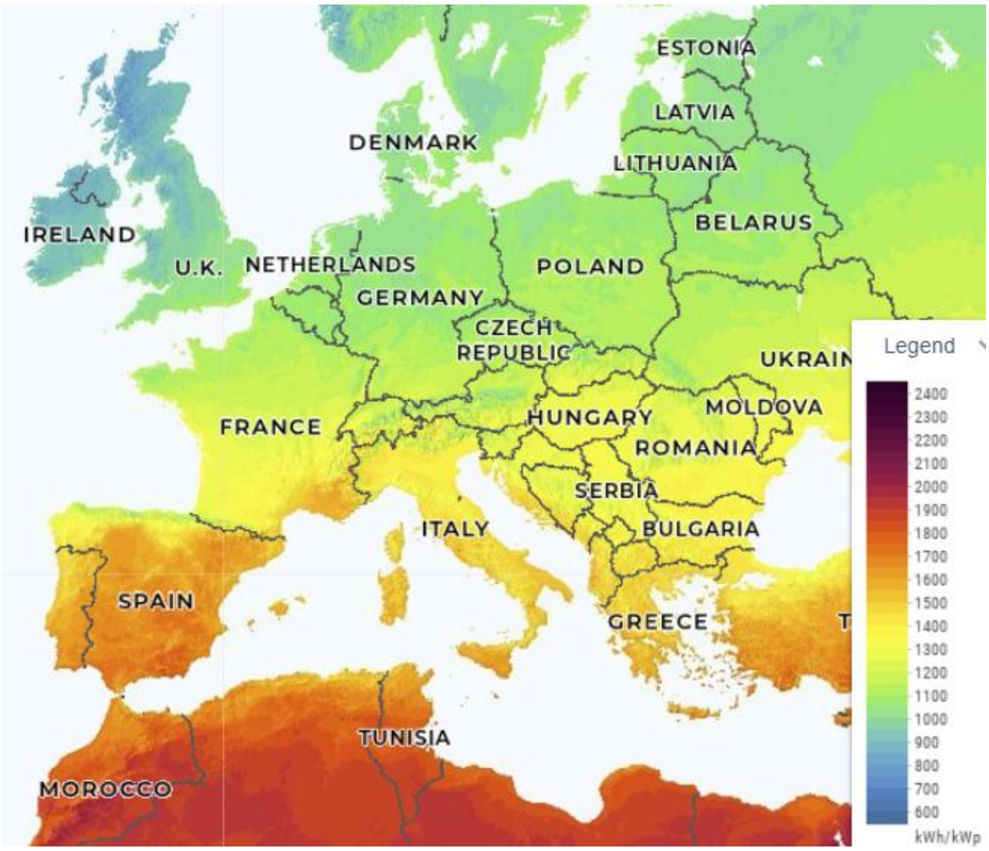

Figure 3.10: Map of yearly electric solar energy production per installed capacity in kWh/kWp (World Bank Group, Solargis, 2022).

Table 3.5 shows the energy generation table for Route 1 (Rotterdam to Hull) per day on an average day for each month of the year. The "Port 1" row represents the expected daily energy production (in watt-hours per installed PV capacity in kilowatt-peak) in the origin port (Rotterdam in this case) multiplied by 7,5%, as half of the 15% port time as specified in Table 3.3 is spent in the origin port and the other half in the destination port. In a similar way "Manoeuvring 1" is calculated, under the assumption that half of the manoeuvring time is spent in or close to the origin port.

The "Transit" row represents the average daily energy production between the origin and destination, multiplied by a timeshare of 55% because the General Cargo vessel spends 55% of its time in Transit.

"Manoeuvring 2" and "Port 2" are calculated in a similar way as "Manoeuvring 1" and "Port 1", but for the destination port (Hull in this case). The "Daily total" sums all of the modes into a total.

Table 3.5: Solar energy generation estimate for Route 1 (Rotterdam to Hull) in watt-hours per installed power of the PV system per day on an average day for each month. All numbers are in expressed in watt-hours per installed PV capacity in kilowatt-peak.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Port 1	100	199	374	588	709	745	700	594	420	242	116	69
Manouvre 1	28	57	107	168	203	213	200	170	120	69	33	20
Transit	290	606	1137	1774	2166	2234	2130	1797	1277	736	351	207
Manouvre 2	24	53	100	154	191	194	187	157	112	65	31	18
Port 2	85	187	349	541	670	677	655	550	393	226	108	62
Daily total	527	1102	2068	3225	3939	4063	3873	3268	2323	1338	639	376

The assumption of equal time shares of transit, manoeuvring and port (55%, 35% and 15% respectively) regardless of the length of the route is not in all cases realistic. In reality it is likely that a route in which more distance is covered, a larger share of time is spent in 'transit' mode compared to a trip with a shorter distance. We acknowledge that these time shares are different based on trip length, but for the sake of simplicity, we use the specification as given by the specifications for the reference vessel in Table 3.3.

Results in energy, fuel savings and CO_2 savings for all 11 representative routes
Similar calculations as for Route 1 were performed for each route, resulting in estimates of energy savings. Table 3.6 summarises the results. The 'Min daily [kWh]' represents the month with the least amount of expected solar energy, and the 'Max daily [kWh]' represents the month with the highest expected amount of solar energy. For example, for Route 1 the least amount of solar energy is expected in December (Table 3.5): 376 Wh/kWp, so this number (although in kWh/kWp) appears as the "Min daily" for Route 1 in Table 3.6.

The yearly production values in column 6 of Table 3.6 show the total energy production per kilowatt-peak if the vessel operates exclusively on that given route. These totals are calculated by multiplying the daily values in Table 3.5 by the number of days in each month and summing the results. To obtain the absolute yearly energy production of the installed system in kilowatt-hours, the values must be multiplied by the system size in kilowatt-peak.

Table 3.6: Result table with energy, fuel and CO_2 savings for the representative routes for short-sea general cargo vessels.

Route	Origin	Destination	Min daily [kWh/kWp]	Max daily [kWh/kWp]	Yearly [kWh/kWp]	Litres fuel saved [l/kWp]	CO_2 saved [kgCO_2/kWp]
1	Port Rotterdam	Port Hull	0,376	4,063	**816**	200	579
2	Port Rotterdam	Port Oslo	0,247	4,341	**802**	197	569
3	Port Rotterdam	Port Bergen	0,235	4,187	**760**	186	539
4	Port Rotterdam	Port Helsinki	0,236	4,534	**821**	201	583
5	Port Rotterdam	Port Liepaja	0,291	4,576	**857**	210	608
6	Port Rotterdam	Port Bilbao	0,700	4,301	**946**	232	671
7	Port Rotterdam	Port Lisbon	0,964	4,972	**1104**	270	783
8	Port Rotterdam	Port Venice	0,835	4,979	**1071**	262	759
9	Port Rotterdam	Port Galway	0,393	4,190	**839**	206	595
10	Port Rotterdam	Port Aberdeen	0,268	4,001	**768**	188	545
11	Port Galway	Port Aberdeen	0,273	3,823	**737**	181	523

The average yearly production on all of these 11 routes combined is 866 kWh/kWp on a yearly basis based on 100% uptime of the system. This is slightly lower than the 1060 kWh/kWp during the monitoring period.

With the total energy production we can estimate the amount of fuel saved by assuming a specific fuel consumption value. For these calculations, an SFC of 0.25 l/kWh is assumed which is slightly lower than the average of the SFC values that were found for Vertom Anette in Table 3.1. The reference vessel is, as opposed to Vertom Anette, not diesel-electric. Therefore, it most likely has a separate auxiliary generator that is more fuel efficient at low loads. The seventh column in Table 3.6 shows the yearly fuel savings per installed kWp of PV. The efficiency of 98% to convert the generated solar energy to the main switchboard as mentioned in Section 3.2.1 is also applied here. The average annual fuel savings are 212 L/kWp.

The eighth column shows the yearly WtW CO_2 savings based on a TtW emission factor of 3,206 gCO_2 per gram MGO and WtT emission factor of 0.615 gCO_2 per gram MGO (European Parliament and the Council of the European Union, 2015) and a density of 900 kg/m^3 of MGO (IMO, 2014). This results in an annual WtW CO_2 emission reduction of 614 kg/kWp.

3.2.3 Comparison between model and monitored data from the pilot vessel

The model outputs are compared with actual routes from Vertom Anette to assess whether the modelled solar energy production matches what was. The origin and destination of these routes are not mentioned here for confidentiality reasons.

Comparison with collected data

The comparison was limited to solar energy production during transit, because the time shares of manoeuvring and harbour deviate from the 35% and 15% (respectively) assumed for the Reference Vessel. Table 3.7 shows the results of the comparison. The modelled daily PV energy production in transit is based on data from Global Solar Atlas in the months in which Vertom Anette executed the route. The monitored daily energy production is based on the data collected during this study. The energy productions are expressed in kWh/kWp, in order to make them comparable to Table 3.6.

Table 3.7: Comparison between model (modelled daily energy production) and monitored data (monitored daily energy production) during transit.

Route	Modelled daily energy production in transit [kWh/kWp]	Monitored daily energy production in transit [kWh/kWp]	Percentual difference
Route A	4.70	4.48	95%
Route B	4,39	3.50	80%
Route C	3.88	3.56	92%

Table 3.7 shows that the percentual differences between the modelled and monitored daily energy production are between 80% and 95%. Considering the fact that the monitored daily energy production numbers include significant shading effects (as shown in Table 3.2).

Comparison compensated for significant shading during pilot
Table 3.8 shows the comparison for the case in which the monitored daily energy production is calculated based on the average of the three panels in the Solar Flatrack that are least affected by shading, similar to what was done in Section 3.2.1.5. The modelled energy production and the monitored energy production match quite well. Based on this comparison, we are confident that the results of this modelling approach (Table 3.6) are a good approximation of the average solar energy production on the specified routes.

Table 3.8: Comparison between model (expected daily energy production) and monitored data (monitored daily energy production) during transit if the average of the three panels least affected by shading is used.

Route	Expected daily energy production in transit [kWh/kWp]	Monitored daily energy production in transit [kWh/kWp]	Percentual difference
Route A	4.70	4.6	2%
Route B	4,39	3.52	20%
Route C	3.88	3.61	7%

3.3 Tank to Wake emission

3.3.1 Pollutants (air, water)

Unlike combustion-based marine fuels, PV systems do not emit air pollutants (SO_x, NO_x, PM) or water pollutants during operation. Once installed, their energy production is emission-free. Potential risks are mainly indirect, such as leakage of cooling fluids from associated power electronics or waste from damaged panels, but these are minimal compared to fuel combustion.

3.3.2 Other (health, ...)

The main health and safety risks are electrical hazards and fire. These are covered by IEC 60092 and SOLAS requirements and have already been discussed in Section 2.

3.4 Well to Wake emission

3.4.1 Feedstock options

PV systems do not rely on a consumable fuel feedstock during operation; instead, their emissions are associated with manufacturing, transport, installation and end-of-life.
Key impacts come from silicon purification, wafer production, and module assembly, which are energy-intensive processes. At end-of-life, PV panels can be recycled to recover glass, aluminium, and some rare metals, but recycling infrastructure is still developing. Technological complexities resulting from different module compositions, different recycling processes and economic hurdles are significant barriers (Gerold & Antrekowitsch, 2024). Disposal without recycling could create environmental burdens due to heavy metals in some panel types.

3.4.2 GHG emissions

The greenhouse gas emissions of PV systems are largely concentrated in the production phase, with operational generation being virtually emission-free. Life-cycle assessments for different PV technologies indicate that emissions are about 44 gCO_2e/kWh for silicium-based panels (IEA PVPS, 2021) including manufacturing, transport, installation, use and end-of-life. As shown earlier in this section, the average annual production of solar energy by the Solar Flatrack is expected to be 866 kWh/kWp annually. Applying the life-cycle emission factor of 44 gCO_2e/kWh results in estimated emissions of about 0.038 tCO_2/kWp for the Solar Flatrack. This is negligible compared to the WtW CO_2 emission reductions due to the fuel reductions shown in 3.2.2.4.

3.5 Conclusion

Based on the representative route modelling, the expected average solar energy production is 866 kWh/kWp assuming 100% uptime of the system. The results from the modelling approach are well in line with the collected data from the Solar Flatrack on Vertom Anette, as shown in the comparison of three routes in Section 3.2.3. The average fuel savings based on the modelling approach is 212 l/kWp.

4 Applicability

4.1 Dutch fleet categories

The applicability of PV systems on vessels depends primarily on available deck or roof space and the level of solar exposure on the routes. From the reference vessels listed in Table 1.1, general cargo ships offer the greatest potential due to their relatively large deck areas. While the extent of deck space used for cargo varies between operators, vessels that frequently have unoccupied deck space over long voyages provide particularly favourable conditions for installing PV systems.

The other vessel types in Table 1.1 (tugboats, offshore-supply vessels, crew tender catamarans, dredgers and superyachts) generally have limited amount of unoccupied or unused deck space, resulting in lower potential for PV deployment.

5 Economic aspects

5.1 Market system and costs (CAPEX and OPEX) for end users

Wattlab has shared insights into business case calculations for users of their system under a non-disclosure agreement. Details of the business case will not be published here in order to protect sensitive business information. This section will first list the most important assumptions and then show the expected payback period. The business case is based on a PV system of a sized to occupy most of the deck space on a general cargo vessel, corresponding to the dimensions of the reference vessel (Table 3.3). This corresponds to an installed capacity of 150 kWp.

The following aspects that impact the payback period are considered in this section:

- CAPEX and OPEX
- Fuel consumption reductions
- EU Emission Trading System (ETS) savings
- Reduced need to blend in biofuel or take other measures to comply to FuelEU Maritime Green House Gas Intensity limits.

System CAPEX and OPEX

The scale on which the current products are produced is relatively small. The current CAPEX for which Wattlab currently offers its Solar Flatracks is between €1,90/kWp and €1,50/kWp. As they scale up further, Wattlab is aiming for further cost reductions. The necessary modifications to the vessel are added to the system CAPEX as well.

A discount based on the Energy Investment Allowance (EIA) of 10,32% is accounted for on the investment costs of the PV system. The Energy Investment Allowance (EIA) is a Dutch tax incentive for companies that invest in energy-saving technologies. Instead of a direct subsidy, it provides an additional tax deduction. In 2025, 40% of the qualifying investment can be deducted from the taxable profit. At the current Dutch corporate income tax rate of 25,8%, this results in an effective net benefit of approximately 10,32% of the investment amount.

No OPEX are assumed. Once the Solar Flatracks are installed, no maintenance is needed besides occasional cleaning of the panels to guarantee their energy production.

Fuel consumption reductions

The main driver of the business case is the fuel savings that are achieved by installing the PV system on board. For these calculations, a specific fuel consumption of 0,25 l/kWh is assumed. The assumed price for MGO is €750 per ton, resulting in a total annual fuel savings of €3.434. For a vessel with the specifications of the reference vessel "General Cargo" (Table 3.3) and the assumed scale of the PV system, the fuel consumption on board of the vessel can be reduced by approximately 0,62% through the introducing of the PV system.

EU Emission Trading System (ETS)
The EU ETS effectively puts a cost on CO_2 emissions. Since fuel savings also reduce CO_2 emissions, a corresponding financial benefit can be applied to the PV system. The ETS-related savings are calculated by multiplying the CO_2 emission reduction (in metric tonnes) by the ETS price per tonne of CO_2. A price of €70 per tonne of CO_2 emissions is assumed based on the forecast of Enerdata (Enerdata, 2023), shown in Figure 5.1.

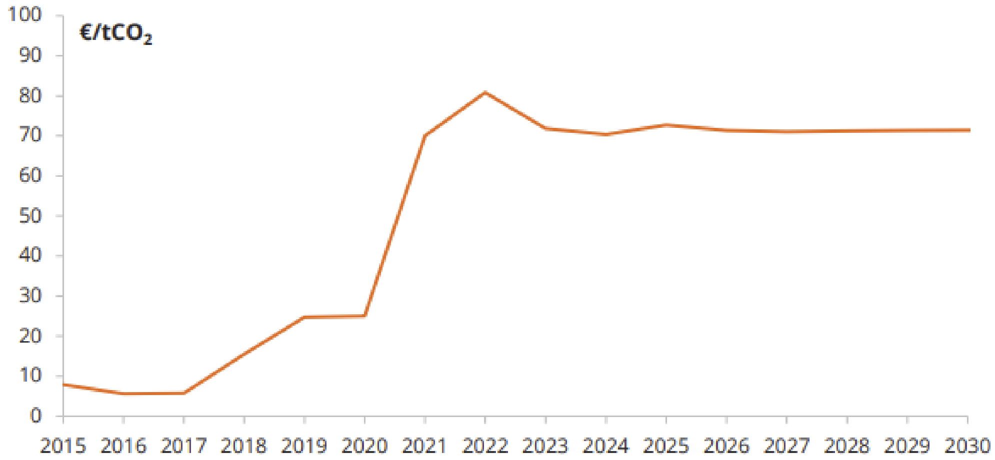

Figure 5.1: Forecast of the EU ETS carbon prince until 2030 (Enerdata, 2023).

FuelEU Maritime GHG intensity limits
FuelEU maritime introduced limits on the GHG intensity (GHGI) of on-board generated power expressed in gCO_2e/MJ in a well-to-wake perspective. The baseline value is set to 91,16 gCO_2e/MJ, and reduction targets are set for the years towards 2050, as shown in Table 5.1.

Table 5.1: FuelEU Maritime GHG reduction targets (European Comission)

Year	Target GHG intensity Reduction vs 2020 Baseline (%)	Target GHG intensity [gCO_2e/MJ]
2025	2%	89,34
2030	6%	85,69
2035	14,5%	77,94
2040	31%	62,90
2045	62%	34,64
2050	80%	18,23

Non-compliance with these reduction targets imposes a financial penalty. If a ship's actual well-to-wake GHG intensity is higher than the yearly target, the vessel owner must pay a penalty per unit of energy used. The GHG intensity is calculated using the following equation:

$$\text{GHGI} = \frac{\text{Total WTW GHG emissions [gCO2e]}}{\text{Total energy used [MJ]}}$$

A scenario study in Appendix B shows that that a full size PV system can reduce the GHGI by 0,24 gCO_2/MJ.

An alternative approach for achieving a comparable reduction in GHGI is adding HVO (Hydrotreated Vegetable Oil) to the MGO fuel. Due to the negative WtT emission factor of HVO, blending HVO into the fuel mix reduces the gCO_2/MJ. Appendix B shows that it would cost approximately €19.400 per year to achieve that same 0,24 gCO_2/MJ reduction in GHG intensity as the PV system.

Payback period

Figure 5.2 shows a scenario with a 150 kWp PV system (in blue) and a scenario using a blend of HVO and MGO (in orange) with equal reduction in GHG intensity. Only based on the fuel savings and CO_2 emission pricing due to ETS, the payback period of the PV system is 9,6 years, since the blue line crosses the x-axis between the years 2033 and 2034.

As described above, ship operators must meet the reducing GHG intensity targets set out by FuelEU Maritime. From the image it becomes clear that in the year 2029, after 5,1 years, the scenario for the solar Flatrack is more profitable than blending in HVO into the fuel mix. A 3% inflation rate and 10% discount rate are assumed for these calculations.

The scenario study in Appendix B assumes a certain size of the PV system, but the breakeven point between the scenario with a PV system and the scenario with HVO is not sensitive to the absolute size of the PV system (the number of Solar Flatracks), since the CO_2 emission reductions due to adding a PV system or blending in HVO scale linearly with the size of the PV system.

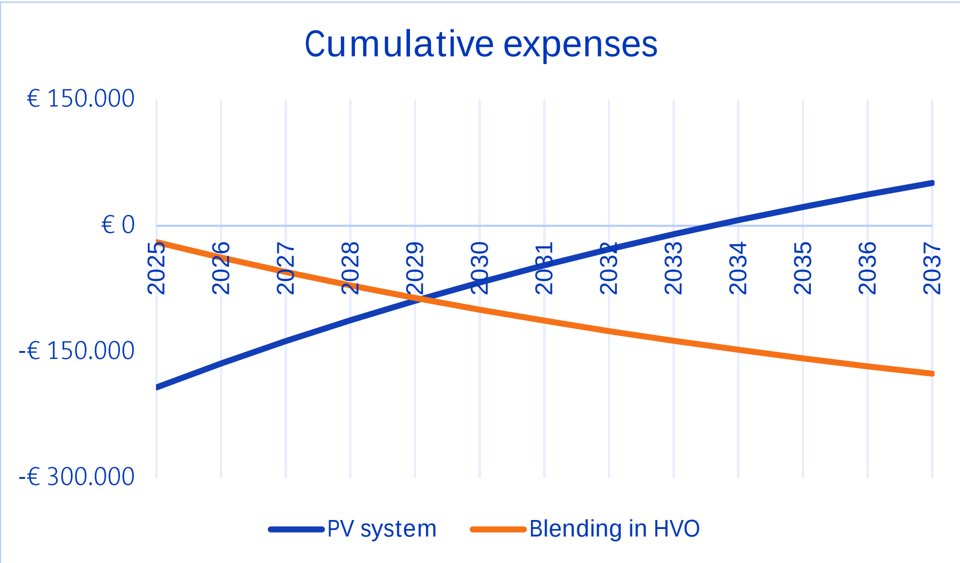

Figure 5.2: Cumulative expenses for a scenario using a 150 kWp PV system (blue) and a scenario using a blend of HVO and MGO (orange) with equal reduction in GHG intensity as set out by FuelEU Maritime (European Parliament & Council, 2023a).

The lifetime of silicon-based solar cells is about 25 years under normal land-based conditions. When applied on board a vessel, however, their lifetime is expected to be shorter due to exposure to harsh marine environments, including high humidity, salt spray, and constant vibration. At present, no conclusive data is available to validate the expected lifetime of the Solar Flatrack.

Sensitivity of PV system CAPEX and HVO price to breakeven point

The breakeven point between the scenario with a PV system and adding HVO to the fuel mix is sensitive to the PV system CAPEX as well as the HVO price. As Wattlab is developing their products and is scaling up, further price reductions to their system are expected. The price of HVO per ton is uncertain. The scenario of adding HVO into the fuel mix in Figure 5.2 assumes an HVO price €1.500/ton.

To assess the effect of the change in these two parameters (PV system CAPEX per installed kWp and HVO price), a sensitivity analysis was carried out to determine their impact on the breakeven point (in years). The results are shown in Table 5.2.

Table 5.2: Sensitivity of PV system CAPEX and HVO price to the breakeven point between the PV system scenario and the HVO blending scenario, both achieving the same GHG intensity reduction as required by FuelEU Maritime (European Parliament & Council, 2023a). The PV system CAPEX are excluding the EIA subsidy discount.

	HVO price €1.000/ton	HVO price €1.250/ton	HVO price €1.500/ton
PV system CAPEX: €1,90/kWp	8,26	7,52	6,91
PV system CAPEX: €1,50/kWp	6,35	5,82	5,37
PV system CAPEX: €1,10/kWp	4,65	4,28	3,96

6 Scalability and future proofness with respect to materials and sustainability criteria

The scalability of PV systems depends on the availability of raw materials required for module production. Crystalline silicon technology mainly uses abundant materials like silicon, glass, and aluminium, so long-term supply isn't a major concern. Some other parts, though—like silver for cell contacts or copper for wiring—have more limited supply chains, which could lead to shortages or price swings as global PV installation keeps growing.

Figure 6.1 illustrates the gradual decline in PV module prices over the past 15 years (IEA PVPS, 2024), reflecting ongoing cost reductions that make large-scale deployment increasingly feasible.

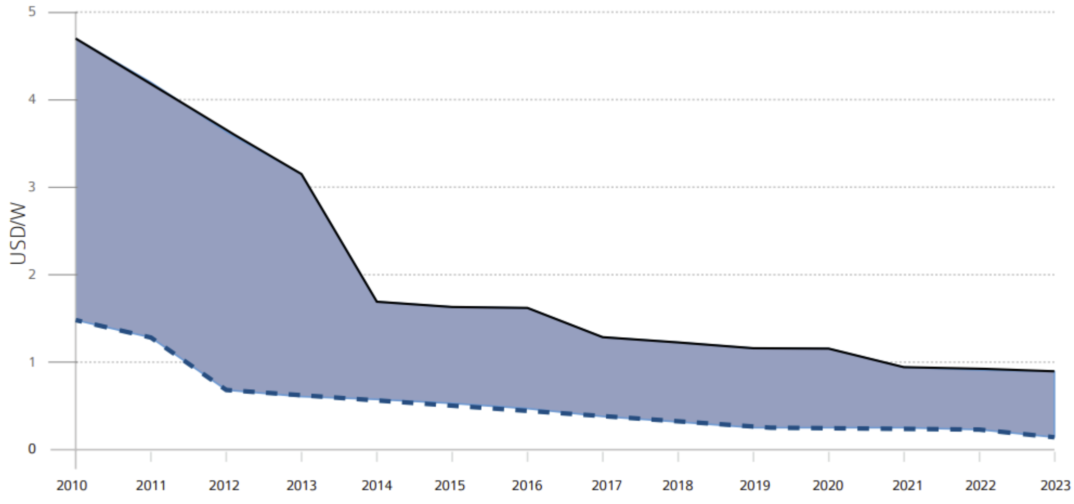

Figure 6.1: Evolution of PV module price range in US Dollars per watt (IEA PVPS, 2024).

With regard to scalability on vessels, the maximum system size and total energy output are constrained by the available deck space, which varies between individual ships.

7 Conclusion

The research question of this study as mentioned in Section 1.2.2 was:

Is solar power on ships, and in particular the Wattlab system, a suitable and effective option for GHG and pollutants emissions reduction for the Dutch reference ship categories?

Based on the findings of this study, the Solar Flatrack developed by Wattlab is considered a suitable and effective option for reducing GHG and pollutant emissions on general cargo vessels. This study shows that the energy yield, and the resulting fuel and emission reductions, strongly depend on the operational area of the vessel. Based on a representative set of routes for general cargo vessels, the expected average energy production per installed power of the PV system is 866 kWh/kWp annually. This results in an average annual fuel saving of 212 l/kWp, and an annual WtW CO_2 emission reduction of 61 kg/kWp based on a specific fuel consumption of 0,25 l/kWh.

The business case for deploying the PV system appears highly attractive, offering a relatively short payback period. However, profitability depends on several factors, including the operational routes (with higher returns on sunnier routes), the system price, and the availability of suitable installation space on deck. Under favourable conditions, the system can provide both a positive financial return and a meaningful contribution to reducing CO_2 emissions in the maritime sector.

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Signature

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Jan Hoegee Research manager	Tom van Beurden Author

Appendix A
Solar yield data

A.1 Solar system configuration

Figure A shows the assumptions applied in Global Solar Atlas uses to model the electrical output of the photovoltaic (PV) system. For the Wattlab Solar Flatrack application, the 'Medium-size commercial' system type was used, as its parameters best represented the installed system

		Theoretical (Site Data)	Small residential	Medium-size commercial	Ground-mounted large scale	Floating large scale
Installed power	[kWp]	1	Defined by user	Defined by user	Defined by user	Defined by user
PV module orientation	-	N/A	Portrait	Landscape	Landscape	Landscape
PV field self-shading*	-	2.0%	No	Yes	Yes	Yes
Relative row spacing	-	N/A	N/A	2.5	2.5	1.4
Nominal Operating Cell Temp.**	[°C]	46.2	51.2	49.2	46.2	46.2
Inverter EURO Efficiency***	[%]	98	95.9	96.4	97.8	96.4
DC losses: Soiling	[%]	3.5	4.5	4	3.5	6
DC losses: Cables	[%]	2	1	1	2	2.5
DC losses: Mismatch	[%]	0.3	0.8	0.5	0.3	6.5
AC losses: Transformer	[%]	0.9	0	1	0.9	1
AC losses: Cables	[%]	0.5	0.2	0.4	0.5	2
Availability	[%]	100	97	98	99.5	98

Figure A.A.1: Assumptions taken from Global Solar Atlas to model electric output of PV-system. The "Medium-size commercial" system type was used for the analysis in this document.

A.2 Solar data output format

Table A.1 shows an example of one of the possible outputs of Global Solar Atlas (World Bank Group, Solargis, 2022) for the location Rotterdam. The data represent the expected solar energy production of a PV system per installed capacity (in kWp) for each hour of an average day, for each month of the year. This type of data is used in the modelling approach described in Section 3 to estimate the energy production on a route.

Table A.1: Expected electric solar energy output in watt-hours per installed capacity (in kWp) in Rotterdam as obtained from Global Solar Atlas (World Bank Group, Solargis, 2022).

Day hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0	0	0	0	0	0	0	0	0	0	0	0
1 - 2	0	0	0	0	0	0	0	0	0	0	0	0
2 - 3	0	0	0	0	0	0	0	0	0	0	0	0
3 - 4	0	0	0	0	0	0	0	0	0	0	0	0
4 - 5	0	0	0	0	11	29	13	0	0	0	0	0
5 - 6	0	0	0	20	81	100	79	38	1	0	0	0
6 - 7	0	0	10	110	172	186	162	122	57	2	0	0
7 - 8	0	11	95	209	267	277	254	212	147	61	5	0
8 - 9	19	75	174	296	352	353	330	291	227	130	51	13
9 - 10	65	126	232	358	407	410	384	346	276	175	92	49
10 - 11	101	170	286	401	437	435	407	381	313	215	123	79
11 - 12	122	200	317	420	456	452	434	401	328	233	135	92
12 - 13	116	201	317	412	447	446	432	398	312	215	120	84
13 - 14	90	165	269	369	411	417	404	367	272	171	87	58
14 - 15	49	116	211	314	362	380	368	315	219	118	44	22
15 - 16	7	63	149	243	295	317	310	253	159	59	5	0
16 - 17	0	9	71	150	208	238	230	173	78	4	0	0
17 - 18	0	0	8	57	113	147	137	83	11	0	0	0
18 - 19	0	0	0	2	32	61	54	13	0	0	0	0
19 - 20	0	0	0	0	0	7	4	0	0	0	0	0
20 - 21	0	0	0	0	0	0	0	0	0	0	0	0
21 - 22	0	0	0	0	0	0	0	0	0	0	0	0
22 - 23	0	0	0	0	0	0	0	0	0	0	0	0
23 - 24	0	0	0	0	0	0	0	0	0	0	0	0
Sum	569	1136	2139	3361	4051	4255	4002	3393	2400	1383	662	397

Appendix B
FuelEU Maritime GHG Intensity

As mentioned in Section 5.1, FuelEU Maritime (European Parliament & Council, 2023a) has defined targets on GHG Intensity in gCO_2e/MJ for energy use on board of vessels. These targets reduce over the years towards 2050, so ship owners are strongly incentivised to reduce the CO_2 emissions from the energy they use on board. One way to reduce the fuel intensity is to add a PV system to a vessel reduces the GHG Intensity. One of the alternative ways to reduce the fuel intensity is blending HVO (biofuel) into the fuel mix.

In this Appendix, the following three scenarios will be assessed:

1. Baseline: Fuel intensity for a vessel that uses MGO,
2. Vessel running on MGO with a PV system,
3. Vessel running on a blend of MGO and HVO, with an equivalent fuel intensity reduction as Scenario 2.

By studying these scenarios it can be assesses how much HVO would have to be mixed into a fuel blend with MGO in order to reach the same effect in GHG Intensity as the PV system. This is used in Section 5.1 to put the cost of the PV system into context. This calculation is not sensitive to the absolute size of the PV system (the number of Solar Flatracks), since the CO_2 emission reductions due to adding a PV system or blending in HVO scale linearly with the size of the PV system. The PV system chosen in scenario 2 is a full-scale system, occupying most of the deck space on a general cargo vessel corresponding to the size of the reference vessel (Table 3.3). This corresponds to a PV system with a total installed power of 150 kWp.

General specifications and assumptions

The time shares and corresponding power levels for the Reference Vessel "General Cargo" were listed in Section 3.2.1.1, these can be used to come to an average power level of 2354 kW. This leads to a total yearly electric energy demand of 20618 MWh.

The GHG Intensity (GHGI) is defined as follows:

$$\mathrm{GHGI} = \frac{\text{Total WTW GHG emissions [gCO2e]}}{\text{Total energy used [MJ]}} = \frac{m_{fuel} \cdot LCV_{fuel} \cdot EF_{WtW} + m_{fuel} \cdot EF_{TtW}}{m_{fuel} \cdot LCV_{fuel} + E_{electric}}$$

In this equation:

- m_{fuel}: Fuel mass [g]
- LCV_{fuel}: Lower Calorific Value of fuel [MJ/g fuel]
- EF_{WtW}: Emission Factor Well-to-Wake (full life-cycle) [gCO_2e/MJ fuel]
- EF_{TtW}: Emission Factor Tank-to-Wake (combustion only) [gCO_2e/g fuel]

- $E_{electric}$: Electric energy used [MJ]. This factor was introduced in FuelEU Maritime to account for the use of shore power, but will be used here to account for on-board solar energy generation.

Scenario 1
Using the above equation with the specifications for a vessel running on MGO in Table B.1, the GHG Intensity becomes 89,48 gCO_2e/MJ. The total annual fuel cost in this scenario is €2,937 million.

Table B.1: Specifications for a vessel running on MGO.

Parameter	Value	Unit
SFC	190	g fuel/kWh
EF_{WtW}	14,4	gCO_2e/MJ fuel
EF_{TtW}	3,206	gCO_2e/g fuel
LCV	0,0427	MJ/g
Price	750	€/t

Scenario 2
Adding a PV system to this vessel reduces the energy need from the generators, as part of the energy is generated by the PV system. As concluded in Section 3.2.2, the Solar Flatracks are expected to generate on average 866 kWh/kWp on the representative routes per year. The annual energy generation of a PV system can be calculated by knowing its size in kWp. The annual energy generation can be calculated. Using the SFC from Table B.1 of 190 g fuel/kWh the solar energy production leads to a certain amount of fuel savings. With this scenario, the GHG Intensity becomes 89,24 gCO_2e/MJ. With respect to Scenario 1, the GHG Intensity has reduced by 0,24 gCO_2e/MJ.

Scenario 3
With the third scenario it is assessed how the same reduction in GHG Intensity as between Scenarios 1 and 2 can be reached by blending HVO into the fuel mix. With the specifications of Table B.1 and Table B.2 mixture of 99,67% MGO and 0,33% HVO leads to the same 0,24 gCO_2e/MJ reduction in GHG Intensity. The total fuel cost in this scenario is €2,957 million per year. Compared to Scenario 1, this is a €19.400 increase in fuel cost annually. The price point of HVO is uncertain. It is expected that demand will rise from different sectors to comply with emission reductions, driving up the price. In this calculation a price of €1.500 per metric ton is assumed, 200% of the price of MGO.

Table B.2: Specifications for a vessel running on HVO (European Sustainable Shipping Forum, 2025).

Parameter	Value	Unit
SFC	200	g fuel/kWh
EF_{WtW}	-54,79545	gCO_2e/MJ fuel
EF_{TtW}	3,16989	gCO_2e/g fuel
LCV	0,044	MJ/g
Price	1500	€/t

Appendix C
Hotel load as a percentage of propulsion power

Since no hotel load data are available for the reference vessel General Cargo (MARIN, 2020), the hotel load is estimated as a percentage of the total propulsion power during transit. To determine this percentage, operational data from the Vertom Anette were used. By comparing the total propulsion power (thruster power) with the total grid converter power (hotel load) during transit on the Vertom Anette, a representative ratio was derived.

Figure C.1 illustrates this approach: the top panel shows a histogram of the total thruster power, and the bottom panel shows a histogram of the grid converter power for the Vertom Anette during transit. This analysis provides a basis for estimating the hotel load as a percentage of propulsion power for the reference vessel.

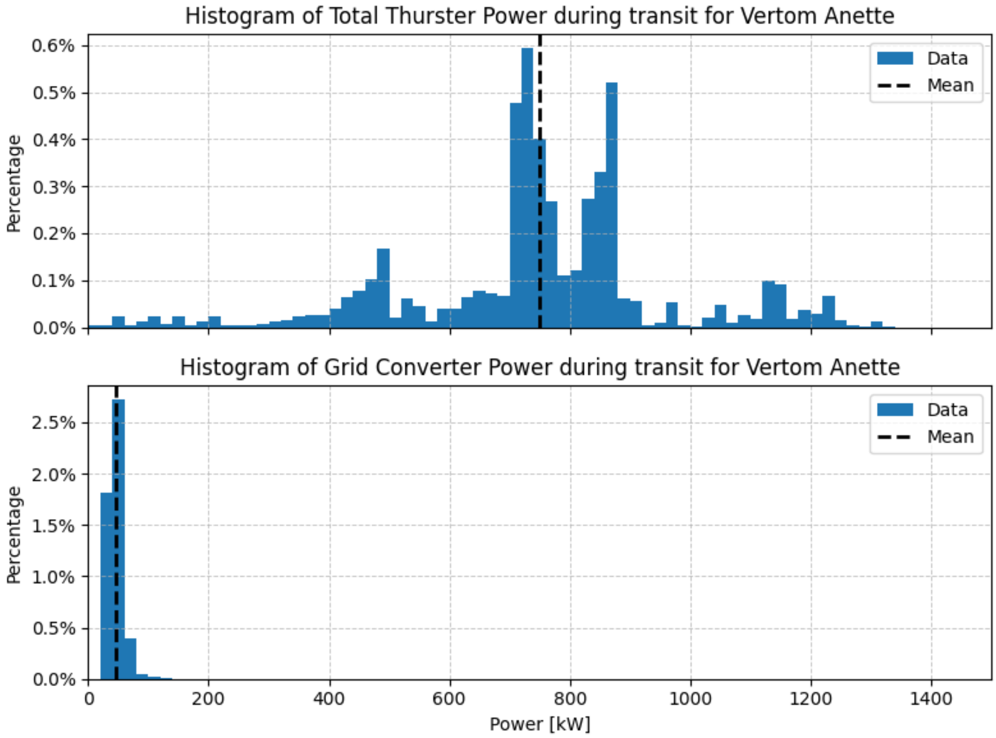

Figure C.1: Histogram of total Thruster Power (top image) and Grid Power (bottom image) for Vertom Anette during transit mode.

According to the data monitoring system of Vertom Anette, the average propulsion power is 750 kW, and the average grid converter power is 46 kW. That means that the hotel load is on average 6% of the propulsion power.

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