Performance Evaluation of Photovoltaic Boats in an Early Design Stage

Numerical Simulations with Industrial Design Methods

Tim Gorter

PERFORMANCE EVALUATION OF PHOTOVOLTAIC BOATS IN AN EARLY DESIGN STAGE

NUMERICAL SIMULATIONS WITH INDUSTRIAL DESIGN ENGINEERING METHODS

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Summary

In order to reduce the need for fossil fuels for transport, alternative ways of meeting the energy demand for transport are required. Renewable energy sources such as solar energy can generate electrical energy with negligible production of local sound and CO_2 emissions. Therefore, the Province of Friesland in The Netherlands has developed into a niche sector for Photovoltaic (PV) boats among others to also reduce CO_2 emissions in transport.

Examples of the design of PV boats show different configurations considering installed PV power in the range of 1 kilowatt to several tens of kilowatts and as such differences in performance. This situation has led to the starting point of my research that the development and design of PV boats has not matured well enough yet and for that reason designers may need support to create better performing PV boats. Most PV boats are not older than 20 years and their performance is relatively poor which indicates that little is known about their design features. Opportunities exist to improve these boats regarding their energy efficiency, cost, usability and aesthetics. This dissertation demonstrates a tool which could be an aid for boat designers to design better performing PV boats.

This approach results from the fact that these factors need other approaches in order to quantify their impact on successful PV boat design and as such the other aspects, design&styling and use aspects are not part of this research. As a result it is proposed to describe PV boats with a specific set of mainly technical and financial design features.

In order to evaluate PV boats and their design features, a database has been created with 183 PV boats, which were found worldwide. These boats were categorized into various categories, such as purpose of use and hull type. Boats up to ten meters demonstrate good performance with respect to maximum speed. Larger boats are able to transport a relatively large amount of persons with solar power. In general most PV boats show a relatively low performance in the sense that their average speed is low. When looking at available surface area on PV boats, more area could be used for PV to increase solar power output and hence, increase their performance. If PV boats are designed to meet clearly specified criteria, the PV system design should be included early in the design stage as opposed to retrofitting during completion of the vessel.

Little to none is known about the real performance of PV boats during use of operation. Therefore, two PV systems at two different PV boats have been monitored with the aim to determine relevant performance indicators for PV boats, through analysis of the measurement data. By monitoring of PV boats with short time intervals, an accurate analysis of the boat's PV system data can be executed. The energetic performance of a PV boat is influenced by four factors: the available irradiance, the design of the PV system, the sort of drive train and

the hydrodynamics of the PV boat. A conventional indicator for PV system performance is the performance ratio R_P. However, because of its transport function, the performance of a PV boat should be described with two additional indicators, which are the power-speed relationship and the energy-distance relationship.

As a result from this research, a model has been developed to determine specific values for these performance indicators of PV boats, which has been implemented in a tool for Rhinoceros. The model is composed of a linear sequence of irradiation models, PV module models and battery models, and a hull resistance model. These models are integrated in a tool which is a plug-in for Rhinoceros. A next step would be to create a good Graphical User Interface (GUI) for the plug-in to allow boat designers to work with it.

To validate the models, a PV boat has been modeled and simulated with the tool. The comparison of monitoring and simulation data from one boat for five specific cases shows a distribution in the range of Root Mean Square Error (RMSE) and Maximum Average Error (MAE) values between 3.1% and 32.3% for a monitoring and simulation interval of 3 seconds. This may be due to the short interval which deviates from the hourly standard for many models for irradiance or energy components. When looking at hourly monitoring and simulation intervals, the RMSE and MAE values are also around 3%. Autonomous electric propulsion in boats by PV power sets specific requirements to the integration of Crystalline Silicon (c-Si) cells in boat surfaces. Light weight and flexibility of shape as well as endurance are required for successful PV-powered boat design. The weight of conventional PV modules was identified as a bottleneck for good performing PV boats. Conventional PV modules consist out of an aluminum frame which holds a laminate containing a glass front sheet and a backsheet. To embed PV cells in polymers which might be suitable as replacement of glass sheets while still providing the protection PV cells require, 15 polymers have been evaluated.

Epoxy is an affordable polymer and has good Ultraviolet (UV) resistance and tensile strength. For cost per gained speed, polymers such as the fluorides, polyimides and silicones show good properties to be used in PV-powered boats. These polymers have excellent UV stability but have higher cost. Silicones are good candidates for encapsulation of PV cells but show very low tensile strength. UV stability varies a lot per polymer compared with glass. Fluorides and polyimides seem to be the best candidates considering UV stability. The polymers and Glass Fiber Reinforced (GFR) polymers evaluated which can be used to embed PV cells for PV boats reduce the total boat-weight significantly. For the energy conversion performance, Ethyltetrafluorethylene (ETFE) and Polyethylene naphthalate (PEN) seem good candidates with high UV stability and transmittance. This should ensure a long lifetime for the PV cells when these materials are used to embed PV cells.

Samenvatting

Om de groeiende vraag naar fossiele brandstoffen voor transport te verminderen zoekt men naar alternatieven om aan de energiebehoefte voor vervoersmiddelen te voldoen. Een eventuele optie is het gebruik van duurzame energiebronnen die elektrische energie kunnen leveren met verwaarloosbare CO_2 emissies en weinig tot geen geluidsvoortbrenging. Fotovoltaïsche (PV) zonne-energie is een dergelijke duurzame energiebron die een aanzienlijke potentie heeft voor toepassingen in boten. Een bijkomend voordeel is dat door deze duurzame vorm van aandrijving op het water, het milieu in recreatieve waterrijke gebieden minder belast wordt. Om deze redenen heeft de Provincie Friesland de ambitie om een niche-sector voor PV-boten te ontwikkelen.

Voorbeelden van PV-boten die in het verleden gerealizeerd zijn, laten verschillende configuraties van het ontwerp zien met betrekking tot de hoeveelheid geïnstalleerd PV-vermogen. Dit leidt tot aanzienlijke verschillen in de prestaties van deze boten, die bepaald worden door de gemiddelde snelheid van voortstuwing in relatie tot het geïnstalleerde PV-vermogen. De meeste PV-boten zijn niet ouder dan 20 jaar en hun prestaties zijn relatief slecht. Dit geeft aan dat er weinig bekend is over de ontwerpkarakteristieken van PV-boten. Dit onderzoek is daarom opgezet om de grote verschillen in prestaties te kunnen verklaren aan de hand van ontwerpkarakteristieken en om toekomstige ontwerpen van PV-boten te kunnen optimaliseren op basis van deze kennis. PV-boten zijn nog niet uitontwikkeld en de veronderstelling is dat ontwerpers hulp nodig hebben in het ontwerpprocess van deze boten met als doel dat die boten beter gaan presteren. Deze dissertatie demonstreert daarom een tool waarmee ontwerpers beter presterende PV-boten kunnen ontwikkelen.

Er bestaan voldoede kansen om PV-boten te verbeteren met betrekking tot de energieefficientie, kosten, gebruik en vormgeving. Dit onderzoek richt zich voornamelijk op de technologie en kosten van PV-boten. Andere factoren, zoals vormgeving en gebruikersaspecten krijgen minder aandacht in dit onderzoek, omdat deze factoren respectievelijk weinig tot geen invloed heeft op de prestaties en er andere niet-technische onderzoekmethodes vereist zijn om de impact in de prestaties van PV-boten te bepalen. Daarom is voor dit onderzoek in een vroeg stadium besloten om PV-boten met een bepaalde set ontwerpkarakteristieken te omschrijven die voornamelijk van technische aard zijn.

Om PV-boten en hun ontwerpkarakteristieken te evalueren, is er een database gecreëerd met data van 183 verschillende PV-boten. De boten zijn ingedeeld in verschillende categoriën die bepaald worden door het toepassingsdoel en de rompvorm. Over het algemeen vertonen de meeste PV-boten tegenvallende prestaties zoals een lage gemiddelde snelheid. Wanneer het oppervlak op een boot in beschouwing wordt genomen wat geschikt kan zijn voor PV,

dan wordt dat niet optimaal benut. Betere benutting van het oppervlak voor PV kan leiden tot betere prestaties. Het wordt daarom ook voorgesteld dat boten, zodra deze gebouwd worden, reeds worden voorbereid voor gebruik met PV, in plaats van achteraf de boot uit te rusten met zonnepanelen. Verder blijkt dat boten tot tien meter goed presteren met respect tot hun topsnelheid. Grotere boten presteren minder goed maar zijn daarentegen geschikt om meerdere personen te vervoeren.

Er is weinig bekend over de prestaties van PV-boten tijdens het gebruik, namelijk tijdens het varen. Om deze kennislacune in te vullen zijn er twee PV-boten gemonitord. Een hoog frequent monitoringinterval maakte een gedetailleerde analyse van deze twee boten mogelijk. Bij de bepaling van de energiebalans zijn vier factoren onderscheiden: de beschikbare hoeveelheid energie, het ontwerp van het PV-systeem, de aandrijflijn en de hydrodynamische eigenschappen van de boot. Een conventionele indicator voor de prestaties van een PV-systeem is de prestatie ratio R_P. Echter, deze indicator volstaat niet voor PV-boten en dient aangevuld te worden. Om de prestaties van een PV-boot in zijn geheel te beschrijven, zijn er twee nieuwe relaties geïntroduceerd: de vermogen-snelheid relatie en de energie-afstand relatie.

In het kader van dit onderzoek is er een model ontwikkeld om waarden voor prestatie-indicatoren van PV-boten te bepalen door middel van simulatie. Dit model is geïmplementeerd in een tool wat als plug-in in Rhinoceros gebruikt kan worden. Het model bestaat onder andere uit een aaneenschakeling van instralingsmodellen, een PV-module- en accumodel en een rompweerstand model. Een modulaire opbouw is de grondslag voor de tool. Het vernieuwende aan deze tool is dat bestaande modellen aan elkaar gekoppeld zijn in één ontwerpomgeving. De kennis die verkregen wordt over deze boten kan leiden tot andere, betere ontwerpen van boten, betere planning van het ontwerp of zelfs het al vroeger uitsluiten van niet-haalbare ontwerpen. Door de modulaire opbouw is het mogelijk snel en effectief modellen toe te voegen en te optimaliseren. Op die manier is het eenvoudig om de tool in de loop van de tijd te verbeteren.

Om het model te valideren is één van de twee PV-boten die gemonitord zijn, gemodelleerd. De monitoring- en simulatiedata zijn met elkaar vergeleken en leveren een Root Mean Square Error (RMSE) en Maximum Average Error (MAE) waarde op van respectievelijk 3.1% en 32.3% bij een monitoring- en simulatie-interval van 3 seconden. Het relatief grote verschil in deze waarden is te wijten aan het interval waarover vergelijkingswaarden geïntegreerd worden. Namelijk, normaliter worden gemiddelde waardes van simulatiedata en monitoringdata vergeleken op basis van uurlijkse intervallen. In dat geval zat de MAE waarde ook rond de 3% zijn.

Energievoorziening met PV-cellen is een niet-conventionele toepassing in of op bootoppervlakken. Een laag gewicht, vormflexibileit en levensduur zijn belangrijke karakteristieken voor het succes van PV-boten. Met name het gebruik van conventionele PV-modules met glasplaten in PV-boten kan door hun relatief hoge gewicht een negatieve invloed op de prestaties van deze boten hebben. Omdat het glas het grootste aandeel in het gewicht heeft, is er een studie uitgevoerd naar de eigenschappen van lichtgewicht polymeren die het glas zouden kunnen vervangen.

Voor een toepassing in PV-boten lijkt epoxy in principe een geschikte kandidaat; het is betaalbaar, UV-bestendig en kan goed belast worden op trekkrachten. Als een polymeer iets duurder mag zijn, zijn alternatieven gebaseerd op fluorides, polyimiden en siliconen ook geschikt voor PV-boten. Met betrekking tot transparantie, zijn ethyltetrafluorethyleen (ETFE) en polyethyleennaftalaat (PEN) zeer goede kandidaten. Verder hebben deze polymeren een hoge levensduur en zijn daarom zeer geschikt als glas vervanging in PV-modules. Vezelversterkte polymeren zijn uitermate geschikte om geïntegreerd te worden in PV-modules om zo het gewicht te verminderen.

List of acronyms, abbreviations and symbols

Acronyms

a-Si	Amorphous Silicon
AC	Alternating Current
AUV	Autonomous Unmanned Vehicle
BMS	Battery Management System
BIPV	Building Integrated Photovoltaics
c-Si	Crystalline Silicon
CAD	Computer Aided Design
CdTe	Cadmium Telluride
CFD	Computational Fluid Dynamics
CIGS	Copper Indium Gallium Selenide
CLI	Command Line Interface
CPV	Concentrating Photovoltaics
DC	Direct Current
DSC	Dong Energy Solar Challenge
EM	Electro-magnetic
ETFE	Ethyltetrafluorethylene
EVA	Ethylenevinylacetate
FEP	Fluoroethylenepropylene
FSC	Frisian Solar Challenge

GaAs	Galliumarsenide
GFR	Glass Fiber Reinforced
GPRS	General Packet Radio Service
GPS	Global Positioning System
GUI	Graphical User Interface
HEP	Hotel Electric Power
IC	Internal Combustion
IDE	Industrial Design Engineering
IEA	International Energy Agency
InGaP	Indium Gallium Phosphor
LB	Length-to-beam
Li-Ion	Lithium-ion
LiPo	Lithium-polymer
MAE	Maximum Average Error
MCU	Motor Controller Unit
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
PB	Polybutene
PE	Polyethylene
PEN	Polyethylene naphthalate
PEI	Polyetherimide
PI	Polyimide
PMP	Polymethylpentene
PP	Polypropylene
PTFE	Polytetrafluorethylene
PV	Photovoltaic
PVB	Polyvinyl butyral

PVDF	Polyvinylideenfluoride
RMSE	Root Mean Square Error
SHS	Solar Home System
SOC	State Of Charge
TL	Linke turbidity
TPU	Thermoplastic Polyurethane
TRIZ	Theory of Inventive Problem Solving (translated from Russian)
UV	Ultraviolet
VOC	Volatile Organic Compound
VR	Virtual Reality

Symbols

β	Solar incidence angle [°]
γ_{PV}	Direction the PV module is facing [°]
γ_s	Position of the sun projected on a horizontal plane while facing north (clockwise) [°]
$\delta_{Rayleigh}$	The Rayleigh optical thickness due to molecular scattering [m]
δ_s	Angle of the sun with respect to the equatorial plane [°]
Δt	Sailtime [h]
η_{cell}	Efficiency of a bare PV cell [-]
η_{module}	Efficiency of the PV module [-]
ν	Kinematic viscosity [m^2/s]
ω_{PV}	Slope of the PV module with respect to horizontal [°]
ω_s	A representation of time in angular degrees (24 h = 360°) [°]
ω_t	Day and year dependency on solar time [°]
ρ	Polymer density [kg/m^3]
ρ_w	Albedo of water [-]
τ_{polymer}	Transmittance of a polymer [-]
τ_r	Monitoring interval [h]
ϕ	Longitude of the PV boat's position [°]
$\widetilde{a}$	PV boat autonomy [-]
C_f	Constant describing the hull resistance [-]
D	Distance [km]
$d(t_i)_{mon}$	Data sample from monitoring [-]
$d(t_i)_{sim}$	Data sample from simulation [-]
D_c	Diffuse irradiance from the celestial sphere [W/m^2]
DoY	Day of year
D_r	Diffuse reflected irradiance [W/m^2]
$E_{A,\tau}$	Energy yield of the PV system over a monitoring period τ [Wh]
$E_{d(t_i)}$	Energy out of power over time [Wh]
$E_{FSN,\tau}$	Energy from batteries [Wh]
$E_{in,\tau}$	Available energy [Wh]
E_L	Energy for loads [Wh]
E_{nom}	Nominal battery capacity [Wh]
F_1	Parameter for circumsolar irradiance [-]
F_2	Parameter for horizontal ribbon irradiance [-]
$F_d(hs)$	Correction factor for the diffuse zenith transmittance depending of hs [-]
F_n	Diode quality factor (Values between 1 and 2. Value used in model: 1.2) [-]
G_h	Global horizontal irradiation [W/m^2]

hs	Solar altitude angle [°]
i	Data index number for data set [-]
$I(t_i)_{bat_{in}}$	Monitored battery charge current [A]
$I(t_i)_{bat_{out}}$	Monitored battery discharge current [A]
I_0	Extraterrestrial irradiance [W/m^2] (I_0 = 1367 W/m^2)
I_β	Total irradiance [W/m^2]
$I_{b,\beta}$	Direct irradiance [W/m^2]
$I_{c,\beta}$	Circumsolar diffuse irradiance parameter [-]
I_d	Horizontal diffuse irradiance [W/m^2]
$I_{h,\beta}$	Horizontal diffuse irradiance parameter [-]
$I_{d,\beta}$	Diffuse irradiance [W/m^2]
$I_{i,\beta}$	Isotropic diffuse irradiance parameter [-]
I_L	Temperature dependence of the photo current
$I_{L,T1}$	Temperature dependence of the photo current of one cell [A]
$I_{r,\beta}$	Reflected irradiance [W/m^2]
I_S	Diode saturation current [A]
I_{sc}	Short circuit current [A]
I_{V_c}	Cell current with respect to cell Voltage [A]
k	Boltzman's constant ($1.380 \cdot 10^{-23}$) [J/K]
k_0	Temperature coefficient
k_{C_f}	Correction factor for hull resistance [-]
L_t	Laminate thickness [m]
L	The hull length at the water line [m]
m	Correction factor of the thickness of the atmosphere seen by the sun's rays [-]
n	Number of samples in data set [-]
n_c	Number of cells in series
n_s	Number of suns (1 sun = 1000 W/m^2)
n_w	Refraction index of water: $n_w = 1.33$
P	Cost per square meter [€/m^2]
p	Cost per kilogram [€/kg]
$P(t_i)_{bat_{in}}$	Monitored battery charge power [W]
$P(t_i)_{bat_{out}}$	Monitored battery discharge power [W]
P_c	A factor to correct the pressure p_h for increasing altitude [-]
p_h	Atmospheric pressure at altitude h [Pa]
p_0	Atmospheric pressure at sea level [Pa]
P_{HEP}	Hotel electric power [W]
P_L	Power for loads [W]
P_{PV}	Power from PV modules [W]
P_v	Power required to sustain the respective speed [W]

$RMS_{E,d}$	Total root-mean-square error for all monitoring data [-]
T_1	Cell temperature [K]
T_aC	Ambient temperature [°C]
T_aK	Ambient temperature [K]
T_L	Linke turbidity [-]
T_L^*	Linke turbidity correction for pressure at an altitude [-]
$T_{rd}(T_L^*)$	Diffuse transmittance function for transmittance with the sun at the zenith [-]
v	Speed over water of the PV boat [km/h]
$V(t_i)_{bat}$	Monitored battery voltage [V]
V_c	Cell Voltage as variable to determine cell current ($0 \leqq V_c \leqq V_{oc}$) [V]
V_g	Bandgap Voltage (*e.g 1.12 eV for c-Si, 1.75 eV for a-Si*) [V]
V_m	Module Voltage [V]
$V_{oc,T1}$	Open circuit voltage for one cell with temperature [V]
V_{oc}	Open circuit Voltage [V]
V_T	Thermal Voltage [V]
r	Refraction angle of water [°]
Re	The Reynolds number [-]
R_s	Module series resistance [Ω]
S	Wet hull surface area [m^2]
y	Year
Y_f	Final yield, i.e. energy yield of the PV system [Wh]
Y_r	Reference yield, i.e. energy yield of solar irradiation [Wh]
q	Electron charge constant ($1.602 \cdot 10^{-19}$) [C]

Contents

“*You might not feel the need to read this, however I feel the need to write it.*”

Jean-Jacques Rousseau (1712–1778)

Chapter 1

Introduction

1.1 Introduction

In modern society fossil fuels are the primary energy sources. Energy from fossil fuels is used for various applications, such as transport, lighting and heating. At least 70% of the electrical energy is generated using fossil fuels, of which coal is the most important one. In 2010, the International Energy Agency (IEA) stated that the need for fossil fuels to generate electrical energy has increased with 67% from 1990 to 2007 [1].

Transport in general is a large contributor to various emissions such as Volatile Organic Compounds (VOCs) and in particular CO_2 worldwide. In 2009, the IEA estimated that around 25% of global CO_2 emissions originated from transportation [2]. One of the key advantages of fossil fuels is their high energy density. In combination with good fuel storage systems, this is a very reliable energy source. Most transportation is powered by fossil fuels, for which a worldwide infrastructure has been established [3]. A disadvantage of fossil fuels is the combustion products. Depending on the type of fuel, possible contamination and the combustion process, VOCs, CO_2, NO_x and CH_4 are emitted [4]. Reducing VOCs and other emissions is beneficial to the environment and extends the lifespan of our resources.

In order to reduce the need for fossil fuels in transport, alternative ways of meeting our energy demand for transportation are required. Photovoltaic (PV) solar power, wind power, hydro power and other renewable energy sources can generate electrical energy that can provide for almost all of our energy needs with negligible CO_2 emissions.

The Province of Friesland in the Netherlands is making an effort to reduce CO_2 emissions in transport. In this framework, particular building and retrofitting boats with electric propulsion is a topic of interest for the province. Silence during operation and reduction of polluting fossil combustion fuels are considered advantages for keeping large lake areas green, silent and clean. One example is whether or not boats can be powered through renewable energy technologies, such as PV.

In this chapter, the research framework and the regional context of the project presented in this dissertation is described in Section 1.2. This dissertation explains what PV technology comprises and what PV boats are. This is described in Section 1.3. This chapter concludes with previous research and the research questions addressing bottlenecks of the integration of PV into boats.

In this dissertation the term ‘boat’ is used to describe a floating vessel which is equipped with some form of propulsion.

1.2 Friesland as recreational watersports area

Friesland is a province in the northern part of the Netherlands. Friesland contains 2500 km^2 of lakes and open water ways: more than 40% of the total Frisian area. Because of the large water areal, many opportunities exist for water recreation. In 2012, CO_2 emissions in Friesland were 3.6 megatons. As a result, Friesland wants to generate at least 16% of its electricity through renewable means in 2020 (the Dutch national goal is 14% in 2020), in order to lower CO_2 and other emissions. Various key sources of CO_2 emissions such as transport, industry and agriculture were evaluated to explore the opportunities in using more renewable energy sources. This has lead to three conclusions. Firstly, energy demand in urban areas should be decreased. Secondly, more renewable energy sources should be

Figure 1.1: Friesland is located in the north and is one of the 12 provinces of the Netherlands.

installed in Friesland. And finally, more transportation should be powered by renewable energy sources [5]. The results from an inquiry amongst 400 tourists in Friesland in 2007 showed that enjoying nature and peace are the key reasons for tourists to visit Friesland [6]. Also, for animals which live on and around the water, silent propulsion can be beneficial.

One of the oldest examples of transport on the water is a sailing boat. Sailing boats use wind power for propulsion and wind power is a renewable energy source. However, sailing boats are not as reliable compared to motorized boats and only skilled users are able to maneuver sailing boats. This has lead to the development of steam-powered and later diesel-powered boats, which is the most used form of propulsion for boats in Friesland. Large cargo barges (diesel powered) ply the Frisian waters. Commercial transport is still important. For this study we distinguish four types of commercial boats:

1. Cargo barges (mainly carrying bulk products such as sand, coal or stone).
2. Passenger ships.
3. Working vessels (such as tugs).
4. Ferries.

In the second half of the previous century a new industry developed: yachting. This type of recreation has become very important to the Frisian economy. Hundreds of thousands of people spend leisure time on the Frisian waters during holidays and weekends. In 2005, it was estimated that 33 000 motorized boats were moored in Friesland of which 32 000 were equipped with Internal Combustion (IC) engines [7]. For this study we distinguish in the category ‘recreational’ boats or yachts:

1. Open sailing boats or rowing boats with no engine.
2. Sailing boats of about five to seven meters with an auxiliary engine (often a petrol outboard).
3. Motorized speedboats (able of reaching speeds over 40 km/h).
4. Open motorized runabouts (for example sloops) up to approximately 7 meters in length.
5. Motorized cabin cruisers (between 8 and 14 meters), mostly made out of steel equipped with relatively heavy engines.
6. Sailing yachts (with a cabin and a number of berths). All of these have auxiliary engines.

A large portion of these yachts (mostly the sailing boats, open motorized runabouts and the motorized cabin cruisers) can also be rented. This is very popular with tourists. Especially the larger motorized cabin cruisers are very dominant in the boat rental business. These boats also cover relatively large distances during a season, thus using quite some diesel.

For this study, sailing boats, open motorized runabouts, motorized cabin cruisers and sailing yachts are of most importance. Open sailing boats or rowing boats with no engine hardly have a need for energy and motorized speedboats are extremely power consuming and almost everywhere restricted in Friesland. Larger boats, such as cargo barges and working vessels, require so much power for propulsion, that PV-only is hardly an option.

The Dutch National Water Board estimated in 2006 the engine hours and fuel consumption of various boats in the Netherlands, which are shown in Table 1.1. On average from 1985 to 2005, the estimated emissions from recreational boats such as VOCs and CO_2 in the Netherlands were 2 megatons per year [8]. Friesland hosts most recreational boating of the Netherlands with 35% compared to the rest of the Netherlands [9]. From the numbers in Table 1.1 it follows that the open speedboats and cabin motorboats have the highest rate of fuel consumption compared to the other boats. Especially cabin motorboats are prevalent in Friesland [6].

Table 1.1: Operating hours and fuel consumption for various boat types in the Netherlands.

Boat type	**Engine hours [hours/year]**	**Consumption [kg/hour]**
Open boats	20	1.95
Open motorboats	70	1.52
Cabin motor cruisers	126	3.74
Cabin sailing boat	60	2.40

Recreational boat users hardly use their boats throughout the whole year. In general, boats are used on average 50 days per year, strictly during the summer period. Furthermore, boat users use their boats mostly during the weekends [6].

(a) Sailing boat [10]. (b) Steamboat [11]. (c) Dieselboat [12].

Figure 1.2: Development from sailing boat, to steamboat to diesel-powered boat.

Friesland had a strong position in the yacht building industry. In the Netherlands in 2007, around 1000 companies were involved in that industry with a total turnover of € 800 million. From all newbuilds, 75% were recreational boats [13]. However, since 2009 the boat industry has been declining in the Netherlands. The position of the boat industry is getting weaker and one of the reasons might be that boat designers and constructors are not united in the Netherlands and Friesland in particular. Several hundreds of different boat brands exist in Friesland alone, making it vulnerable for market changes [14, 15].

Now, with upcoming industries in third world countries, design and production of boats is shifting to other parts in the world where labor is cheaper and Friesland is losing its key position in the boat industry. In order to maintain a good position, Friesland is aiming at new technologies and strategies to design and construct boats. As a result, Friesland is stimulating research in more environmentally friendly boats for the recreational sector. Lightweight, electric boats powered with PV are opportunities for the boat industry in Friesland. Obviously, smaller boats such as those in the recreational sector of Friesland, are not the largest contributor to worldwide CO_2 and VOCs emissions. However, research in this niche sector can enable technologies which can be used in other transport sectors to reduce CO_2, VOCs and sound emissions. Furthermore, these emissions can be reduced locally in Friesland.

The retrofitting and building of boats with an electric motor has been promoted in Friesland since 2010. Their goal is to retrofit 3000 boats in Friesland with electric propulsion powered by battery banks onboard. For these boats, an infrastructure is currently being laid out to charge boats on shore. Furthermore, opportunities have been explored to create ‘electric only’ routes in the Frisian water areal [9]. A disadvantage of electric boats is their dependency on a charging infrastructure, which is not yet always available. Therefore, electric propulsion in combination with PV has some benefits compared to electric-only boats. The energy needed for propulsion is (partly) generated while on the water which leads to a higher degree of autonomy. The feasibility of PV boats is also increased since boat owners use motorized recreational boats mainly during summer periods, which makes PV even more attractive [6].

In Friesland, some pilot projects showed that sailing with PV boats is feasible. Educational institutions develop PV boats, which show better autonomy and higher top speeds compared to other PV powered boats [16–19]. A commercial spin-off of a racing boat, the PV-sportsboat, has been built by the partners of the PV-sportsboat consortium [20] in Friesland. This shows that Friesland is a niche sector for the development of PV boats [21, 22].

1.3 PV boats

A PV boat is a boat which sails solely on PV generated power under (favorable) daylight conditions. The energy on a PV boat is generated solely through solar means and is stored in batteries. This energy is then primarily used for propulsion. Navigation, safety, lighting and living [23] are the secondary loads or Hotel Electric Power (HEP) loads. According to Wachter [14], boats are much more feasible to sail with PV compared to for example cars, since at lower speeds PV boats are less energy demanding. However, with increasing size, boats with PV are becoming less feasible, even with lower speeds. Furthermore, PV boats which are equipped with a high variety of electrical appliances might not be suitable to be powered with PV only. In that case, combinations of PV with other sources of energy are an option.

1.3.1 PV for HEP on boats

PV on boats can also serve as energy supply for HEP loads. This is more likely the case for large steel cruisers. A combination of an IC engine for propulsion and a PV system to charge battery banks for HEP loads is realistic. Especially when these boats are relatively large. In the last case, the on board PV system functions as a Solar Home System (SHS). Larger sailing boats are also potential candidates for use of PV. Especially since sailing boats have different propulsion loads compared to larger steel cruisers. An autonomy of 100% is clearly not feasible for these type of boats, but on board PV can serve as an auxiliary energy source and possibly decrease the environmental impact locally.

1.3.2 PV energy

The average insolation in Friesland is 5.7 kWh/m^2/day in June (averaged over 22 years), with maximum variations between April and August of 25% [24], see Figure 1.3. These levels of insolation could provide for approximately 6.5 kWh/day of electrical energy during the summer period, when a boat's surface of 8 m^2 is equipped with 15% efficient Crystalline Silicon (c-Si) PV cells. Regions which are located closer to the equator, such as the south of Spain, show even higher levels of insolation in summer periods. Insolation values in July in the south of Spain are on average 7.8 kWh/m^2/day (averaged over 22 years). This could provide for approximately 8.9 kWh/day of electrical energy. Although Friesland is located farther north than Spain, the insolation in summer is relatively high. This makes it feasible to propel boats in the summer period between April and October with only PV power in the Province in Friesland.

PV systems do not contain moving parts, therefore their demand for maintenance is relatively low. PV systems can consist out of PV modules, one or several Maximum Power Point Trackers (MPPTs), a Battery Management System (BMS), energy storage, and typically DC/DC and/or DC/AC converters. An example is shown in Figure 1.4.

PV modules

PV modules convert solar irradiation into electrical power. Various PV module configurations exist and in general PV modules generate low voltage Direct Current (DC) power. Most

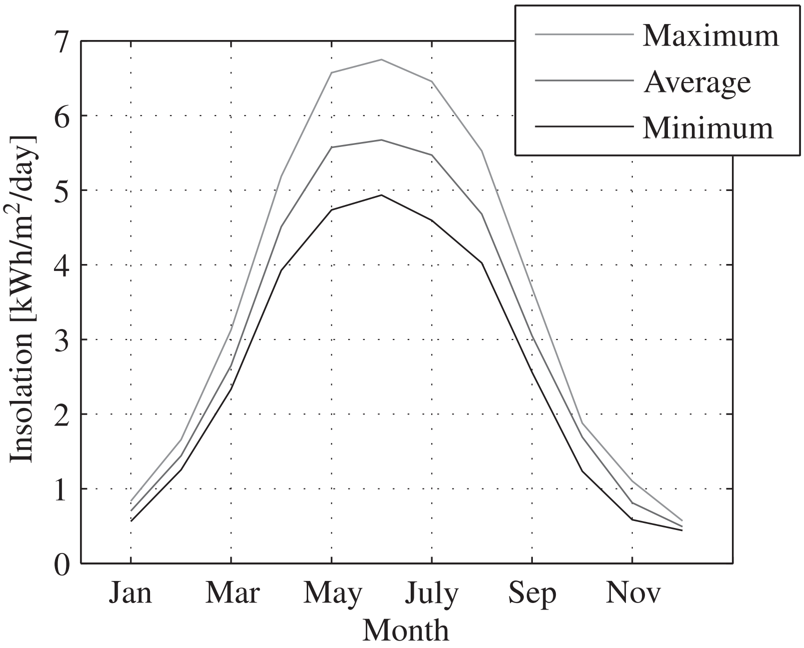


Figure 1.3: Minimum, average and maximum values for insolation in Friesland. The values are based on 22 year averages.

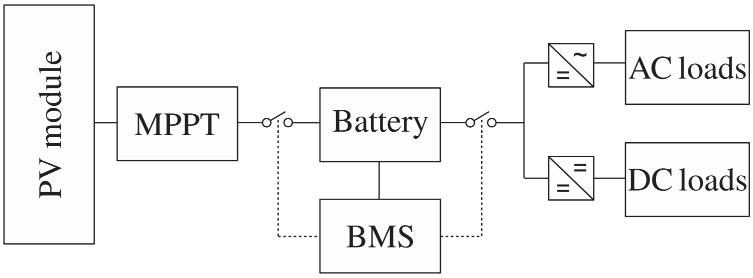


Figure 1.4: An example of a PV system with AC and DC loads.

PV modules have an efficiency in the range between 10% and 20%. As rule of thumb, the higher the efficiency of PV modules, the more expensive they are. A PV module consists of PV cells which are connected in parallel, in series or a combination of both.

Various PV cell technologies exist, of which c-Si is the most used. Other technologies are Amorphous Silicon (a-Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS) in thin-film PV modules and various combinations of materials such as Galliumarsenide (GaAs) and Indium Gallium Phosphor (InGaP) in multijunction cells [25]. In general, thin film PV modules, such as based on CdTe and CIGS are cheaper in the range of € 0.80/Wp to € 2.00/Wp [26]. However, their PV module efficiency is in the range of 7% to 13% [27]. Multijunction PV modules are the most expensive, but have module efficiencies in the range of 25% to 30%. Under concentrated irradiation, multijunction PV modules cost range is between € 2.50/Wp and € 4.50/Wp [26].

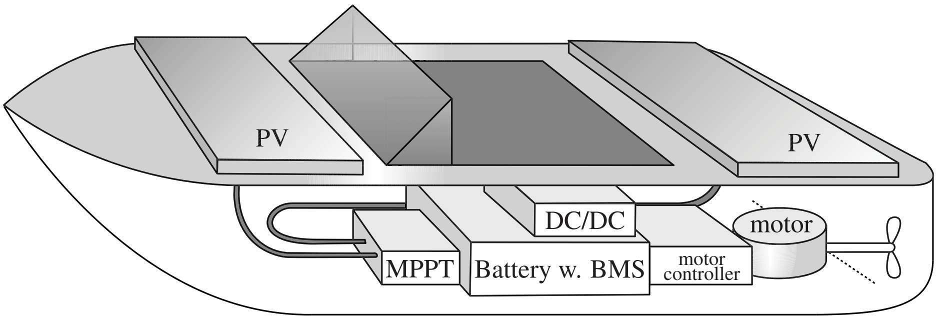


Figure 1.5: PV boat with PV system components.

Table 1.2: Overview of PV technologies with module cost and module efficiency ranges.

Technology	**PV module cost range [€/Wp]**	**PV module efficiency range [%]**
Wafer based silicon	1.00–3.00	14–20
Thin film	0.80–2.00	7–13
Multijunction (under concentration)	2.50–4.50	25–30

Some PV module technologies offer lifetimes over 25 years. Over this period of time, the output typically decreases between 10% and 20%. Table 1.2 shows and overview of the PV module cost and PV module efficiency ranges for common PV technologies.

Maximum powerpoint tracker MPPT

MPPTs let the PV module operate in its Maximum Power Point (MPP). Electronics in the MPPT vary the electrical load which is applied to the PV module. With search algorithms, the combination of voltage and current is found which delivers the most power.

Batteries

Batteries are chemical systems in which electric energy can be stored temporarily. Most cells from batteries work at a low voltage, in a range between 1.2 V and 3.7 V. By connecting these cells in series, more useful voltages can be achieved. Various rechargeable battery technologies exist, such as lead-acid, Lithium-ion (Li-Ion) or Nickel-Cadmium. Table 1.3 shows and overview of various rechargeable battery technologies.

Battery management system BMS

A BMS is used to protect the battery from under- and overcharging. The temperature of the battery will rise during (dis)charge due to it's internal resistance. Gases begin to form when the temperature of a cell pass a certain threshold. the result is a decrease in battery capacity or even permanent damage to the cells.

Table 1.3: Overview of battery technologies with various features.

Battery technology	**Specific energy [Wh/kg]**	**Energy density [Wh/l]**	**Charge/ discharge efficiency [%]**	**Nominal cell voltage [V]**	**Cost [Wh/€]**
Lead-acid	30–40	60–75	50–92	2.1	7–11
Alkaline	85	250	85	1.5	11
Nickel-Cadmium	40–60	50–150	70–90	1.2	1.7–3.5
Lithium-Ion	100–250	250–620	80–90	3.6–3.7	4–7

Figure 1.6: Solar Craft 1. A PV-powered boat built in 1975 by Alan Freeman [28].

1.4 Development of PV boats worldwide

The oldest PV boat found during this research is the Solar Craft, designed by Alan Freeman in 1975, see Figure 1.6. It is a catamaran type, with a PV module with adjustable orientation, a battery pack and a simple drive train for propulsion. Figure 1.6 clearly shows all the basic components of this PV boat.

From a collection of PV boats with known production years, about 10 were built between 1975 and 1995. But after 1995, the production of PV boats increased significantly, with over 120 known PV boats being built after 1995 [16], see Chapter 3. In the beginning, PV boats were conventional boats retrofitted with a PV system. As interest in PV boats began to increase, more purpose built PV boats were constructed. These developments are shown in more detail in Chapter 3.

Until 2013, PV boats can be distinguished into four categories. These categories are:

1. Recreation.
2. Private/research.
3. Racing.
4. Human transport.

(a) Solar Gajner, 1992 [29]. (b) Ra 66, 2000 [30].

(c) Aquabus 1050, 2000 [31]. (d) PV sportsboat, 2011 [20].

Figure 1.7: Development of PV boats over the years.

From every category, examples are shown in Figures 1.7 and 1.8. The boats in the various categories come in different form and sizes, so that these exist in a diversity of PV boat designs at present. for our study it is interesting to explore how the design of a PV boat can be optimized, for example financially, for a specific purpose. Chapter 5 goes into more detail in what way the design of PV boats can be optimized [17].

1.5 Practical value of PV boats

A PV boat uses solar energy to provide for the power which is consumed by onboard electrical systems, such as the propulsion system. PV boats have some benefits over conventional electric boats. Besides the shared advantage with electric boats of practically zero local emissions, PV boats carry their own PV power plant, providing for some or all of the energy needs on board. This can increase the autonomy of the PV boat significantly.

Research is being conducted in Friesland on how to design and build better performing PV-powered boats [21, 22]. As part of that research, the Dong Energy Solar Challenge (DSC)

(a) Sun21; research ship, 2010 [32].

(b) Passeur électro-solaire; human transport, 2009 [33].

(c) Sol 10; recreational PV boat, 2000 [30].

(d) Racing boats from NHL Solarboat Racing (picture taken by author).

Figure 1.8: PV boats in their four categories.

was initiated in 2006. The DSC is a race for PV-powered boats, held around June or July in Friesland every even year since 2006. Participants in the race have to sail a 220 km trajectory with solar energy only, divided over 5 days, in which speed and power management are the key challenges. Leg distances vary between 5 km and 56 km, showing the need for a fast boat, as well as an efficient one, to win the race. contenders can participate in 3 classes: A, B and TOP. A and B classes are equipped with provided c-Si PV-modules, whereas the TOP class may use whatever PV technology they prefer.

In 2012, the last DSC has been held and a high increase in top speeds as well as average speeds can be seen since 2006 [17–19, 34, 35]. Furthermore, commercial spin-offs such as commercial PV boats as well as PV boat components, such as batteries, are the result from this race. Research which now takes place in Friesland into flexible, high-efficient c-Si PV modules [36, 37] for boats is also a result from this race.

The DSC is different from the Solar Splash [38]: a race for PV-powered boats in the

United States of America. During the Solar Splash, the emphasis lies on the maximum speeds of the boats, but also maneuverability and endurance. However, these boats have larger battery packs and larger electrical motors compared with boats participating in the DSC. During sprints and slalom tests, the PV modules are allowed to be removed from the boats. Also, the PV modules on the boats participating in the Solar Splash have smaller PV modules and are thus less significant for the energy balance on these boats [38].

1.6 Previously conducted research

Designing boats with PV requires knowledge of two expert fields: PV and ship design. PV boat design depends on many interrelated design features. Examples of these features are shown in Figure 1.9. To increase the performance of PV boats, the design and production of these boats should be optimized. By installing only an optimal PV system or reducing the initial price of the boat at the cost of the maximum speed or usability, the user satisfaction of the PV boat might be low. These examples of design features as shown in Figure 1.9 are collected from different design fields such as ship building (boat geometry, structural integrity) and PV systems (regional context, PV lamination).

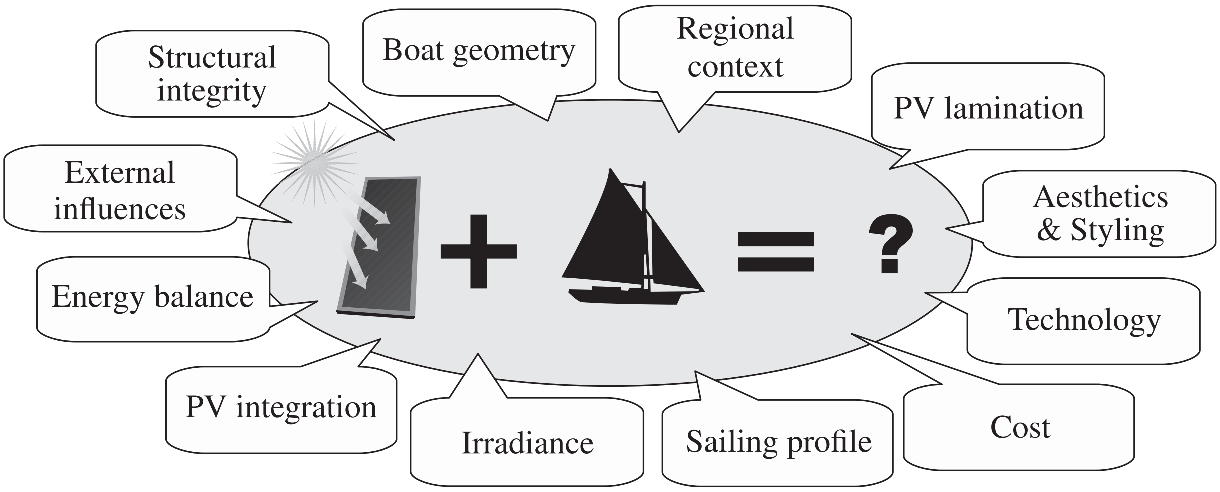


Figure 1.9: Example of design features of PV boats.

Up until now, little research has been conducted to integrate PV on boats. The research into PV boats in the last two decades shows fragmented results and data is not well organized. Research mostly focuses on individual components of PV boats, such as the PV system or the hull design. Some boats are retrofitted with PV and evaluated. However, none of those researches describe the choices between the design of the boat such that the boat performance is matched with the availability of PV energy. However, a PV boat is not guaranteed to perform well, if only the PV system is optimized, or if only the hydrodynamics are optimized. An optimal synergy between the individual components could lead to successful PV boat design. Furthermore, not much is said about successful PV boats and/or unsuccessful PV boats and which indicators describe the performance of PV boats.

Schaffrin et al. [39] described research in 1990 and 1991 about a PV boat. They claim that mechanical and electrical matching of their PV system on a boat resulted in good cruising performance. However, problems with PV modules and data acquisition were reported [39, 40]. A R_P has been identified between 0.1 and 0.4, which is relatively bad compared to more satisfactory values of 0.6 and 0.8 for rooftop installations.

In 1994, Loois et al. [41] reported monitoring data from PV systems installed on leisure boats in the Netherlands. The performance of these systems on these boats was monitored. The users recorded the readings of the ampere/hour-counters and the voltmeter on a monthly basis or more often. In selected systems the energy flows and ambient circumstances were monitored on an hourly basis by means of a datalogger. It is not clear from the paper how these boats look like and what their hydrodynamical performance is. Their results mainly focus on the performance of the PV system [41].

In 2000, Sousa et al. [42] conducted research to increase the efficiency of an induction Motor Controller Unit (MCU) used on a PV boat [42].

In 2007, Leiner [43] presented a research about the visualization on shore of the PV system data of a PV boat [43].

The Polish solarboat team Energa, which participated in the Frisian Solar Challenge (FSC) 2006 reported on their boats in the paper [44]. Their research mainly describes the lessons learned from the building of their boat and their result in the race.

Spagnolo [45] reported about a PV boat in 2012. As conclusion of their research, a new charge/discharge system for the batteries seemed an attractive way to make PV boats feasible. Furthermore, they demonstrated that it is possible to replace the standard combustion engine of their boat with an electric motor, by accepting a loss in power. The boat is more expensive in comparison to an equivalent boat equipped with traditional propulsion. Additional costs are partially compensated by reduction of operation costs. [45].

In 2000, Patch [46] wrote a paper on a PV-powered Autonomous Unmanned Vehicle (AUV). They have been investigating the feasibility of utilizing solar energy and proven AUV technology to provide long endurance, autonomous sampling systems. This paper mainly describes the development of an AUV as well as how it is powered by PV and considerations and choices in energy balance. The technical issue is the cost for energy efficient and system components which require low amounts of power to operate. [46].

Ju et al. [47] presented a paper in 2008 with considerations on the most efficient hull shape which was chosen to sail with PV and electric propulsion [47].

Joore and Wachter [22] describe in their research in 2009 the levels of innovation from commercial spin-offs from the DSC [22]. Furthermore, opportunities are described in Friesland, which is in their research designated as a niche market for PV-powered boats. These opportunities are:

1. The support of a clean and quiet environment with PV boats.
2. The support of innovative and recreational values for Friesland.
3. The development of rental solar boats for tourism in the Province.
4. The development of solar speedboats.
5. The development of low weight, high efficient and flexible PV modules.

1.7 Research questions

Given the experiences and framework described in this chapter, research questions are formulated which connect to the present stage of developments in the field of PV powered boats in Friesland. For instance, it is feasible to propel boats electrically with power generated with a PV system instead of with an IC engine, see Section 1.6. The integration of PV into boats is a new and innovative way to generate energy while being on the water.

Designing and building PV boats is a process which depends on many interrelated parameters as seen in Figure 1.9. In this figure, the problem of successful PV boat designs is illustrated: how to integrate PV into new boats? On one hand, boats can be retrofitted and on the other hand new boats can be built. Some of the design parameters which influence the outcomes of designed PV boats are positioned around the problem. For example, well performing PV boats exist, but the costs are relatively high. Other factors, such as the regional context or the aesthetics and styling can have influence on the end-result of new PV boat designs. Many opportunities can be explored to further develop these boats into more successful products. Up until now, building a PV boat is associated with high costs, long development times and on-board-systems failure [16, 18].

One of the key aspects in boat design, especially for smaller boats equipped with PV for propulsion, is the added weight of the PV system on board. Batteries are needed to store energy and PV modules are needed to generate electrical power. Therefore, a new design should not focus on the energy demands of existing boats, but instead the design should focus on the integral design of a complete PV boat. Therefore the new approach does not aim at meeting an existing energy demand with a new PV system. Instead, it focuses on the complete design of PV boats that show good performance in balance with the availability of energy from a PV system. Generally, the PV system installed on a boat is a retrofit and with these retrofit systems it is hard to meet the energy demands of conventional boats, once equipped with PV. PV systems can have negative impact on the performance of boats, depending on choice of the components. Especially for smaller boats which are equipped with a PV system to meet the energy needs on the boat. In an ideal world, a boat should be designed with its PV system fully integrated. The end-result should be a well-performing PV boat. Such a tool should be made available for boat designers in such a way that the integration of PV is with a low threshold.

‘How to aid boat designers to design well-performing PV boats, with the focus on choosing optimal PV system components?’

Boat design meets PV system design. These are two fields of expertise which are applied in PV boats. Furthermore, PV boats already exist. Some examples show boats which perform well, others seem low on performance. So what can we learn from previous experiences? How can we link boat design, PV system design and other design methods with each other to create a tool for boat-designers to create well-designed and well-performing PV boats? In order to answer these questions, five sub-questions have been formulated. By answering the sub-questions, the research question can be answered. Each chapter addresses one of these questions.

1.8 Research approach

Chapters 2 to 8 contain sub-questions to answer the research question. Chapter 9 holds the conclusions and discussions and the last chapter gives a personal note, describing the author's opinions about his involvement in two world championships of solar boat racing and his general experiences with PV boats.

An overview of the chapter structure is illustrated in Figure 1.10. Chapter 1 explains the framework of the research and the research questions. The following chapters contain the following five sub-research questions:

1. 'What are the design criteria of PV boats?'
   It is useful to know design criteria since faster design and development of PV boats will be made possible when the design criteria are known. With the right parameters which result from proper design criteria, it is most likely that faster and better performing PV boats can be developed. Various design methods are discussed in Chapter 2 which shows how these methods can be an aid in PV boat design. An overview of the resulting design criteria and how these criteria for PV boats can be evaluated is discussed in Chapter 3.

2. 'What are the design features of existing PV boats?'
   Design features from existing boats have been evaluated in order to determine important design criteria for PV boats. The results can be found in Chapter 3. The resulting design criteria are only practical when the performance indicators of PV boats are determined.

3. 'How is PV boat performance defined?'
   In a design process, the success of a design is determined by comparing the end-result with initial demands. By the determination of performance indicators for PV boats, measuring and comparing performance values can be enabled, see Chapter 4. Better integration of PV into boats as well as building low-weight PV boats is a pathway for better performing PV boats.

4. 'Which models and their algorithms are needed to simulate the behavior of a PV boat?'
   It is more effective to improve PV boats as a whole, instead of improving only subparts. Knowledge of the interrelationship between the individual components could lead to better performing PV boats. However, the different fields of expertise are not linked together yet. In order to model, simulate and determine the performance of PV boats, various models are linked together. The result is a tool with which boat designers can evaluate the performance of PV boats in an early design stage. This is shown in Chapter 5.

5. 'Which opportunities exist in developing better performing PV technology for PV boats?'
   In some areas of PV, opportunities exist to increase the performance of PV system components to increase the overall performance of PV boats. For example, from an

aesthetic and energetic point of view, conventional PV modules are not fit for use on smaller PV boats. This is discussed in Chapter 8.

With this research, five topics regarding the design of PV boats are addressed. This resulted in the development of a tool which comprises models to determine the performance of PV boats in an early design stage, see Chapter 5. This chapter is supported by the succeeding Chapters 6 and 7, which respectively describe the validation of the tool and a demonstration of the functionality. Furthermore, an overview of various polymers which might be fit to replace glass in conventional PV modules to reduce the weight of these modules is presented in Chapter 8.

Chapter 9 states the conclusions of this research and discusses the outlook of further research. The final chapter holds a personal note from the author with respect to solar boats and the experiences with two world championships of solar boat racing.

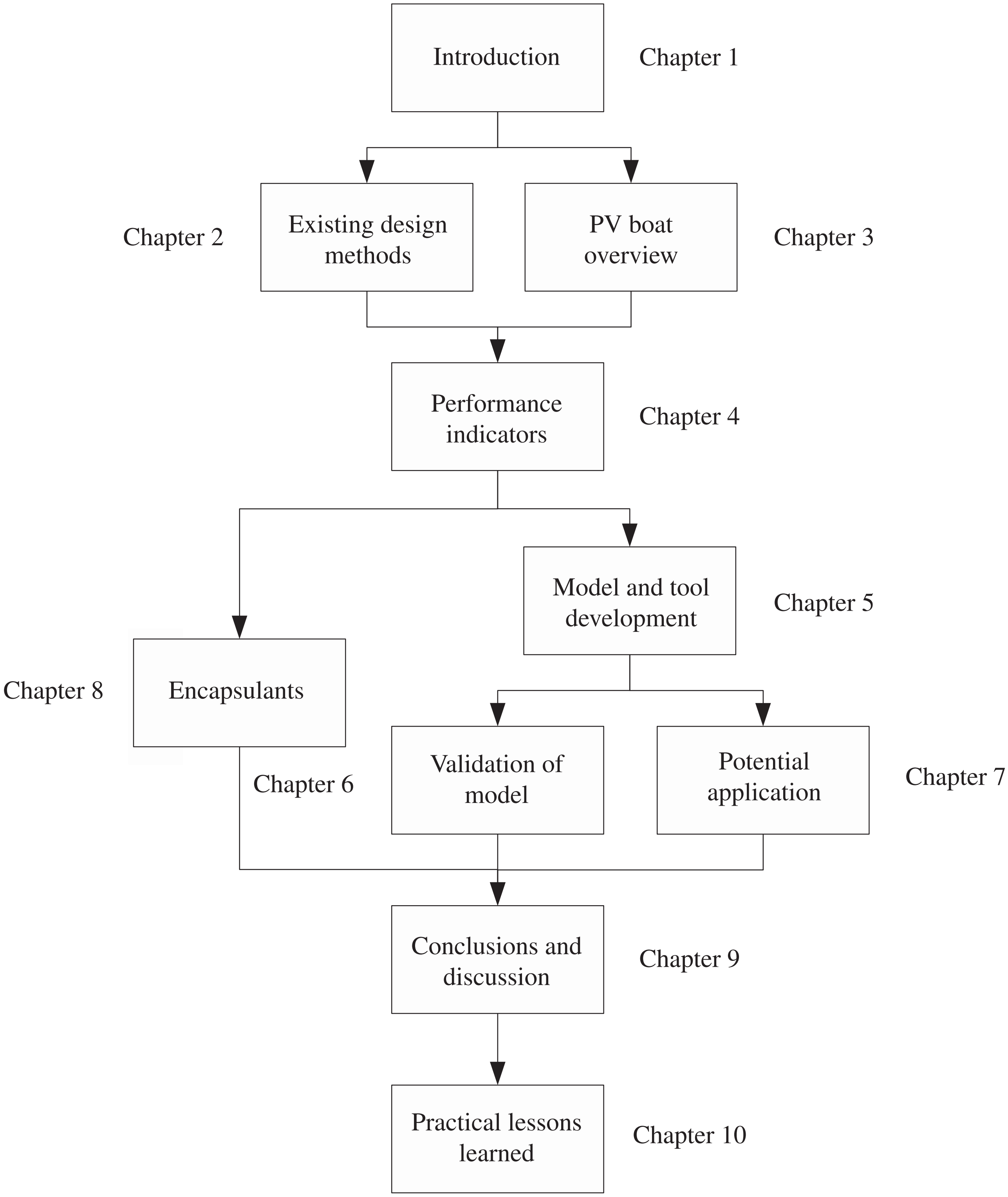


Figure 1.10: Research approach and chapter structure.

Chapter 2

Design Criteria

2.1 Introduction

The aim of this chapter is to describe how Industrial Design Engineering (IDE) methods can help to design PV boats that perform better. PV boats are not a common good and most boats are not older than 20 years [16]. This indicates that PV boats are a relatively new development and not much is known about their design features. Although PV boats share sub-components with other PV products, such as PV-powered cars or SHSs, it is the question whether their integrated PV systems with their specific features can be directly adapted to PV boats' energy systems. Mainly, because other PV systems, such as seen in SHSs or rooftop mounted systems, are stationary and their designs are cost driven. However, for PV boats, other criteria such as maximum weight or dimensions are important variables. If the PV system is too heavy or covers a too large surface to fit on a PV boat, it is not feasible to propel the boat with energy generated with PV installed on the boat.

In order to answer the sub-research question 'What are the design criteria of PV boats?', this chapter describes links between different design methods which are applied to the different design areas which concern solar boats. We believe that methods which are used in IDE might be helpful to design PV boats, since IDE methods provide support to solve complex design problems. The design of PV boats has a multidisciplinary approach, see Section 1.3 and therefore optimizing one subcomponent can have negative impact on the other components [18, 48]. Other factors, such as societal aspects, human factors and design&styling, will not receive high attention in this dissertation, because PV boats are a relatively new development. Little to none is known yet about their technical issues and other design method approaches are required for research into user behavior. For example, design&styling is highly based on cultural and emotional values, which can not easily be validated, without doing intensive research under users.

In order to enhance the product efficiency and to minimize the design effort, processes have been formulated consisting of a number of sequences. One feature, common to all industries, is the identification of the design requirements as a first step and making the product available to the client as the last step [49].

2.2 Design methods

Various design methods exist which are developed for various kinds of industries. This section describes three common design methods which can be used as an aid to design better performing PV boats. First, the systematic engineering design method from Pahl and Beitz [50] is discussed in Section 2.2.1. Second, the theory of inventive problem solving is discussed in Section 2.2.3. Third, design methods for sustainable design is discussed in Section 2.2.4. Finally, the ship design spiral is discussed as a commonly used design method in boat design in Section 2.2.2.

2.2.1 The systematic engineering design process model of Pahl and Beitz

To describe the process of industrial design and development of new products, usually the model of Pahl and Beitz [50] is used. Their design engineering model is illustrated by Figure 2.1. The systematic engineering design process model of Pahl and Beitz is based on an intensive analysis of the fundamental design steps in development of technical systems [50, 51]. In the development and design model of Pahl and Beitz, four phases for product design and development can be distinguished. Firstly, planning and clarification of the task, which is the process of formulating design criteria for the product to be developed. Secondly, concept development, which aims at solving design problems and describing the working principles of the new product. The end of that phase should result in one or more solutions for the design problems. Thirdly, design, which is the process of the construction, formulated in a technical or fundamental structure of the active solution. Important aspects of the product, such as the technical and economic ones, are determined clearly and completely. And fourthly, detailing, which deals with complementing the building structure of a technical structure by final regulations for the form, design and finish of all components. All materials are set and the way of production and the final cost and the binding drawings and other documents for its material realization are created.

The model from Pahl and Beitz has three phases, which are:

1. Improve the functional principle.
2. Improve form and shape.
3. Improve production and assembly.

Within the first phase, the functional principle is developed. This results in a working principle, which worked out for a technical structure of the active structure or basic solution. Furthermore, the technical and economic barriers are cleared and completed. Then, the second phase can be entered, which deals with the part of construction that complements the building structure by governing the form, design and surface finish of all components. Materials and the production process are defined and the final cost and drawings and other documents are realized [50].

In the last phase, production and assembly are improved. When small batches of products are produced, a ‘prototype’ will be made to discover and correct any problems. These insights will be used to improve the final batch of products. However, the first product which was made in advance can also be marketed as well. According to Pahl and Beitz, especially when it comes to large machinery or systems, the end-consumer does not participate at all in the design process [50].

There is no clear boundary between these phases and sometimes they are (partly) merged. Although the model of Pahl and Beitz is abstract and not universally applicable in product design, the model can be used as a tool to aid designers in their design and development process [50–52]. One of the problems which is not fully addressed by the design model of Pahl and Beitz is that if a solution is found for a (sub-)problem, that solution can have a negative effect on another solution of a (sub-)problem or even increase the impact of another (sub-)problem negatively. This is illustrated with an example of a PV boat. A PV boat needs to be equipped with PV modules for power generation. As explained in Chapters 4 and 8, conventional PV modules are relatively heavy and their weight has impact on the performance of a PV boat. (When looking at the boat as described in Chapter 8, the PV modules comprise 75 kg of the total boat weight of 160 kg.) The extra weight is summed up with the weight of the boat and the boat needs a more rigid structure to support the PV modules. However, an

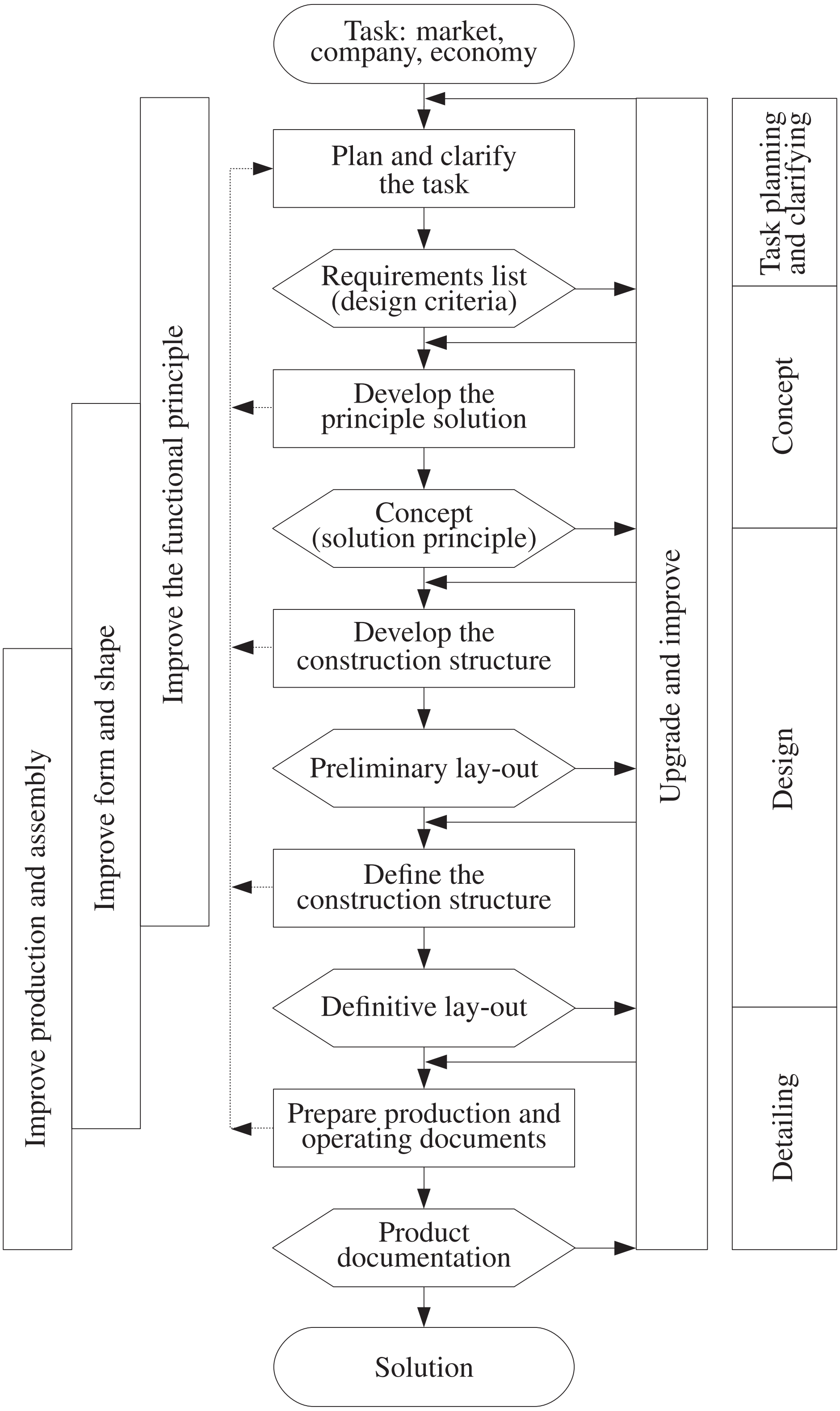


Figure 2.1: The systematic engineering design process model from Pahl and Beitz [50].

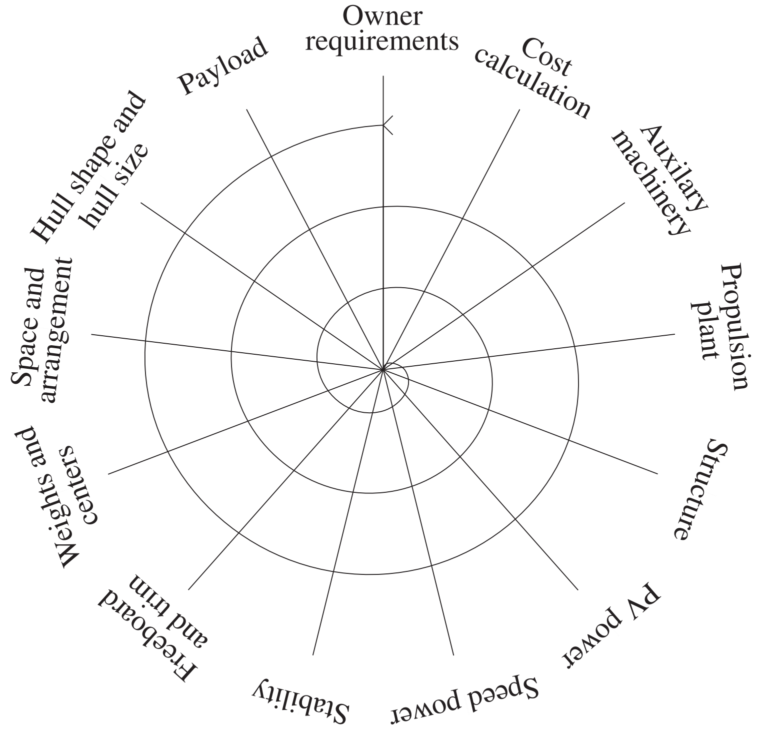


Figure 2.2: Design spiral of a ship design according to Hollister [53] and added to that; PV power.

increase of PV modules has a positive effect on the available energy on the PV boat. Therefore, to increase the available energy for propulsion of the PV boats, adding conventional PV modules comes with the cost of a decrease in performance caused by the added weight.

2.2.2 The ship design spiral

Product development regarding boats is different compared to automotive products, since most boats are produced in low numbers: usually batches from one to five, whereas automotive products are produced in numbers of hundreds of thousands up to a million. A significant difference between boat design and product design is that in product design, prototypes are built and evaluated. The results from the evaluation are feed back into the design process to optimize the design. However, in boat design, this is usually not the case [49], so that the final design is directly applied to a real boat that has been built. In that case, it is for example not a real problem when design flaws exist. These are easily corrected during or after building of the boat.

The design process of a boat is described by Hollister [53] in four phases, which are:

1. Design statement.
2. Conceptual design.
3. Preliminary design.

4. Detailed design.

This is illustrated in Figure 2.2, which shows all the phases and detailing in conventional ship design.

The design statement is made first. It defines the main functions of the boat and lists the major attributes. This is similar to clarification of the task from the model of Pahl and Beitz [50].

Secondly, the conceptual design phase is started. A preliminary estimate is done on the feasibility of the boat design. This feasibility study will include the principal dimensions, the general arrangements, weight distribution and the powering options.

Thirdly, the preliminary design phases is entered. It describes how the conceptual design will be implemented and what the hull shape will be. Furthermore, more exact calculations on the hydrodynamics are done. This fits with embodiment design from the model of Pahl and Beitz [50].

Finally, the detailed design phase is entered, which is the end stage before building the boat. All these phases are passed at least once during the design process of boats, as if it is a spiral. Within this spiral, the further the design reaches the middle point, the more detailed the design is [53].

The success of the performance based design is evaluated using a theoretical measure of merit starting at the very early design stages. Typically design optimization is used already during concept design as trade offs between the design elements which influence the ship's final performance, such as the cost, weight distribution or maximum speed.

As can be seen from Figures 2.1 and 2.2, the method from Pahl and Beitz [50] has close resemblance with the ship design spiral. As a conclusion, methods from ship design do not interfere with methods from IDE. Actually, IDE methods might have a positive influence on the design of PV boats, if these boats are not considered as 'boats' in the design process, but as automotive products at an industrial level.

2.2.3 The theory of inventive problem solving: TRIZ

In order to solve design problems such as aforementioned with PV modules and PV boats, other design methods than the model from Pahl and Beitz can be used, such as the Theory of Inventive Problem Solving (translated from Russian) (TRIZ)[48]. TRIZ is a methodology for the development of new systems and is a knowledge based methodology of inventive problem solving. It can be used to find solutions for technical problems with a systematic approach. TRIZ is based on the idea that 98% of all problems can be solved by using previous solutions for other or similar problems. Every inventive solution is the result of elimination of a contradiction in the design space. It is preferred that the new solution can perform at its maximum, without influencing other solutions negatively. TRIZ suggests to search for new principles by defining what function is needed and then finding which physical principle can deliver the function [48, 54, 55]. Where other methods aim at to identify the problems, TRIZ aims at identifying and solving these problems with the confidence that all possible solutions to the problems have been considered, see Figure 2.3. TRIZ consists out of three main concepts, which are:

1. Contradiction.

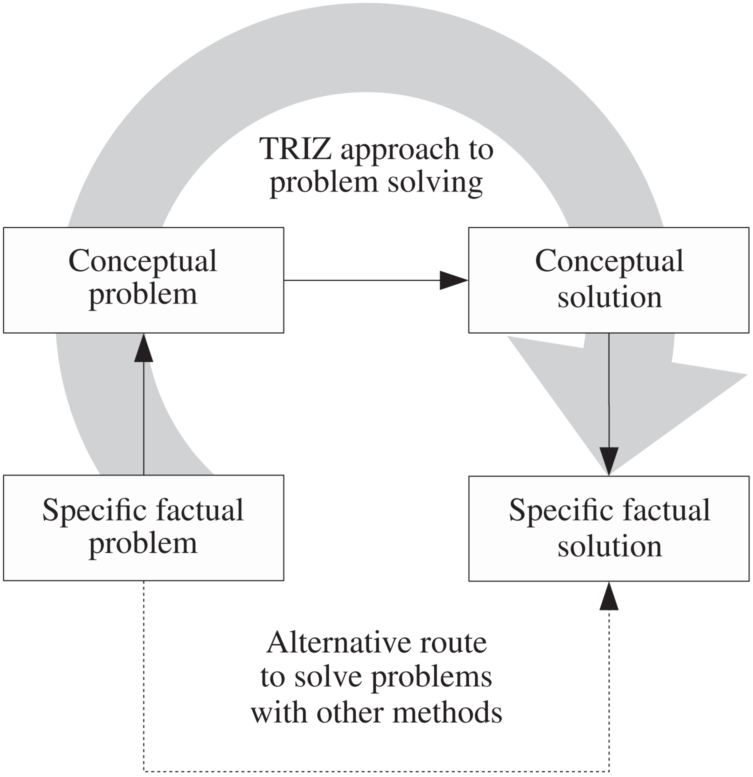


Figure 2.3: TRIZ systematics to problem solving by Altshuller [48].

2. Ideality.
3. Patterns of evolution.

Contradictions arise when solutions for one problem lead to problems in other solutions. A good example is the case of putting more PV modules on a PV boat. The ideality can be expressed as a function of the sum of the benefits divided by the sum of the cost and the sum of the harms of the solutions. Therefore, the aim of TRIZ is to increase the benefits while also reducing the costs and the harms of the solutions. Technical systems follow patterns of evolution in their development, which were identified by Altshuller [48] and can be used to develop good solutions to problems.

Like other design methods, TRIZ is not used stand alone, but best used in combination with other design methods [48, 55]. TRIZ can be a great support to the model from Pahl and Beitz in the principle phase, but in lesser degree in the clarification of task, the embodiment and elaboration phase [56].

To solve the aforementioned problem in the example of a PV boat with its PV modules, it is good practice to look at design features of the boat and the PV modules. The energy loss of a boat in the deformation of the hull while sailing, decreases with the increasing of the stiffness of the hull. The hull is continuously deforming by non-uniform and random forces of the surrounding water and more specifically, by waves. Therefore, by adding material in the hull and therefore increasing the stiffness, the hull's weight increases.

Conventional PV modules are stiff, because of the use of thick glass plates which are the protection for the PV cells during production, transport and usage of the modules. This is also the reason for the relatively high weight of PV modules, see Chapter 8. When considering the PV boat and the PV modules as two different designs and the PV boat has to support the rather heavy PV modules, the hull needs to be reinforced to support the heavy PV modules. However, using TRIZ, an alternative solution would be to integrate the PV modules into the PV boat as such that the PV modules are an integrated part of the PV boat. In that way, the stiffness of the PV modules can be used to increase the stiffness of the hull of the PV boat. Without PV modules, the hull would be less stiff and deform more easily while in the water. By integrating the PV modules in the hull, the result is a reduction in boat weight, a stiff hull and sufficient power from the PV modules. This practice has been used in the boat which was build in 2010 as described in Chapter 4. Other approaches to tackle this problem can be considered, which are described in Chapter 8. That chapter proposes to use other front sheet materials to replace glass in conventional PV modules to reduce the weight of PV modules.

2.2.4 Sustainable design methods

Opportunities can be identified with respect to increasing the energy efficiency of PV boats, reducing the cost and increasing the usability and aesthetics of PV boats. From a technical point of view, many opportunities for and applications of sustainable energy technologies exist. The success of sustainable energy solutions in products can be increased by applying IDE methods. Common practice up until the early 2000s was to design products with sustainable energy technologies from a technical point of view: the main focus was to increase the technology's energy yield [57]. This is also the case for PV boats, which show since 1975 advances in maximum speeds and sailing autonomy, see Chapters 1 and 3. However, advances in cost, usability and aesthetics stayed behind [34]. Reinders et al. [57] point out that not only advances in technology are key to the success of sustainable energy solutions.

They state that the success of an energy solution for PV boats is dependent on five key factors:

- Technical aspects.
- Financial aspects.
- Social aspects.
- User aspects.
- Design&styling.

Reinders et al. assume that interdisciplinary design methods can create better solutions compared to methods which focuses only on optimizing energy solutions. This is illustrated in Figure 1.9. Naturally, the end user plays an important role in the acceptance of new forms of energy and energy efficiency, also at the level of use of energy systems. User interaction with an energy system can effect the quality of the system's functions and the corresponding perception of usefulness and comfort by the end user.

The practical use of good technologies and also by using new technologies, opportunities exist in creating better performing PV boats. For example, recent developments in new battery technologies, such as Li-Ion made it possible to develop better performing PV boats. However, such technologies also find their way in other areas. Battery technology developed for PV boats in Friesland were used in solar cars which participated in the World Solar Challenge 2013. Two of these cars reached 1^{st} and 3^{rd} place as result.

In the case of PV boats, marketing can play an important role to emphasize on the benefits of PV boats over other, more common, forms of transport on the water with IC engines. The societal context needs to be identified to find opportunities in PV boat design and how these opportunities can be translated to successful PV boat design. Human factors play an important role in the design of PV boats. Design&styling can be a means to make PV boats more attractive, or distinctive compared with other more conventional boats. Therefore, in product development such as PV boats, IDE plays an important role. IDE can be seen as a crossover between industrial design and design engineering. Both fields try to solve design problems, however industrial designers tend to focus on the life styling features of a product, whereas design engineers focus on the technological features of PV boats [57].

2.3 Comparison of design methods

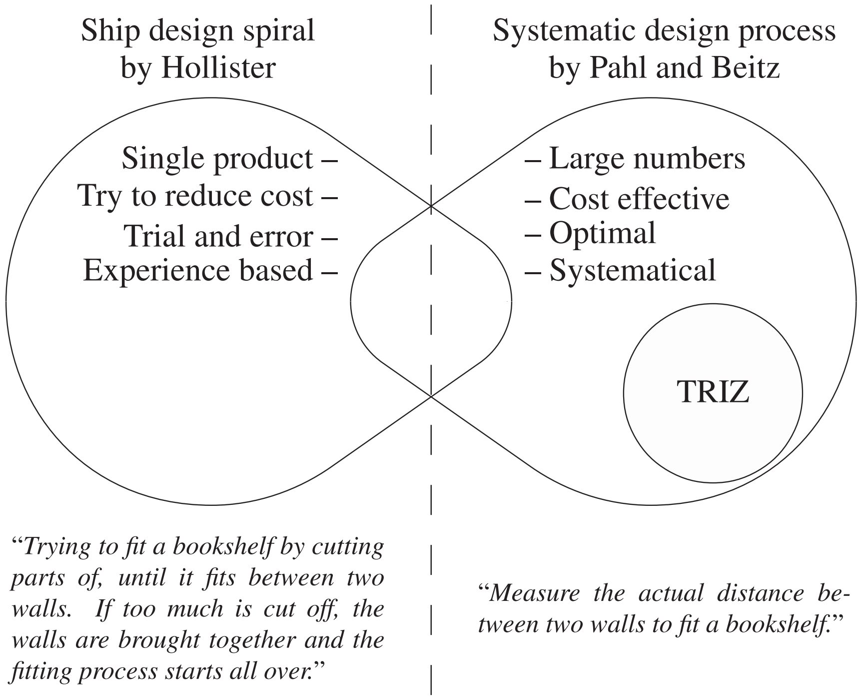
The two design methods, systematic engineering design process model from Pahl and Beitz and the ship design spiral from Hollister, have much in common, but also distinctive differences.

The model from Pahl and Beitz tries to find overall functions. The next step is to decompose these functions in sub-functions. By systematically trying to find solutions for these sub-functions, a large set of viable solutions can be achieved. The most promising structure for a sub-function is then chosen. These working principles for the sub-functions are then combined in principle solutions. From these solutions, the best one is chosen [51].

The model from Hollister can be considered as an ad hoc process. Especially when only one boat is being designed and built. The selection of the design concepts is usually guided primarily by experience, rules of thumb, preference and imagination. Generally, the design space in boat design is large, non linear and bounded by thresholds and constraints. It is therefore difficult to find optimal designs of selected concepts [58].

As described in Section 2.2.3, TRIZ is not used stand-alone, but best used in combination with other design methods. Therefore, it is not a design method in itself, but a means to improve an existing method. To illustrate the difference between these design methods and how TRIZ fits in these design methods, see Figure 2.4.

Although examples exist of boat designers and boat builders which do not follow the ad hoc approach such as described by Hollister, common yacht building industry is mainly based on producing one custom made yacht. This leaves more space for errors, which in return, are more easily solved compared to productions of severals hundreds of thousands of units, such as seen in the car industry. The ship design method which was based on one or several units, is slowly shifting towards more systematic design with as result more units. For every product, and PV boats in particular, such an approach can lead to better performance and more success.



“Trying to fit a bookshelf by cutting parts of, until it fits between two walls. If too much is cut off, the walls are brought together and the fitting process starts all over.”

“Measure the actual distance between two walls to fit a bookshelf.”

Figure 2.4: Design differences between the systematic design process by Pahl and Beitz and the ship design spiral from Hollister.

2.4 Design Criteria

The design of a product is good if it fulfills certain criteria. A good set of criteria is important to reach a good design. Testing of the criteria is determining which criteria are acceptable and which are not. In a design process of a complex product, such as a PV boat, different people with different disciplines work together. Their goal is to conceive a good design. Therefore, criteria are needed to make it clear for everybody what the design should be.

The design criteria formulated in this section are helpful to improve the technical performance of PV boats. Societal aspects are not considered in this dissertation, because clear indicators showed the need for a theoretical model with which PV boats’ performance could be evaluated in an early design stage. Performance related to a number of physical parameters such as speed and power are easily measurable and thus used as performance indicators in this dissertation, see Chapters 3 to 7. Zeisel [59] states that design criteria act more as directives or guidelines and should not be considered as design constraints. In that way, the design process of new products is more open for innovation, which is also needed in the design and development of PV boats.

A list of criteria is usually the result form a creative process, since this list of criteria is the first step in product design. One of the threats of design criteria is that the list of criteria can grow long. As a result, too much criteria can lead to difficulties in evaluation. First it is important to focus on the main items and not to get into much detail. In a later stage, such as the embodiment phase, the more detailed criteria will be evaluated [60, 61]. Furthermore, it is impossible to state all the design criteria in the first phase. Usually, design criteria are adapted as a result from findings in later phases of the design process.

Research in 2006 by Brezet and Fadeeva [23] described the developments of PV boats in Friesland. From this research, four key functions were identified where PV brings additional value to boats. These four functions are:

1. Propulsion.

2. Navigation, safety and lighting.

3. Living.

4. Battery charging.

More or less, these four functions can be merged into two functions for the PV system on a PV boat. First, the energy need for the propulsion (1) can be identified and secondly the energy need for other loads such as navigation (2) and living (3), which are called HEP loads. The last function, battery charging (4) can be neglected, since a (partially) charged battery is always needed to provide for the energy need for the propulsion and HEP loads on a PV boat. It is therefore not a function which brings additional value to a PV boat but it is mandatory on a PV boat, as shown in Figures 1.4 and 1.5.

In the research from Brezet and Fadeeva [23], some design criteria have been stated, which might lead to better design of PV boats. However, PV has been considered more as an add-on than being part of the boat. Their findings were that if PV boats should come successful, the relatively high capital cost of PV boats should be tackled. Secondly, aesthetic appearance of PV boats should be increased. Subsequently, more surface area for PV modules needs to be created. Furthermore, the energy density of batteries needs to increase. And finally, the energy efficiency of the PV boat needs to increase. A complete overview of design criteria for PV boats is shown in Chapter 3.

2.5 Discussion and conclusion

This dissertation mainly focuses on understanding the technological and financial aspects of PV boats, see Chapters 3, 4 and 5. From the perspective of Pahl and Beitz [50], this approach aims to 'improve the functional principle' phase. Other factors, such as society, human factors and design&styling, will not receive high attention in this dissertation, but only the working principle of PV boats. Two reasons can be named for that:

1. PV boats are a relatively new development and little to none is known about their technical issues.

2. Other design approaches are required for research into user behavior.

This is mainly the result that these factors need other approaches in order to quantify their impact on successful PV boat design. For example, design&styling is highly based on cultural and emotional values, which can not easily be validated, without doing intensive research under users.

In order to develop well-performing PV boats with design criteria, an overview is given of several design methods which can be applied in PV boat design. A complete overview of design criteria is formulated in Chapter 3. From this list follows an overview of performance indicators as presented in Chapter 4. Therefore as a result, Chapter 5 focuses on a tool with models to simulate the impact of the PV system on the technical and financial performance of PV boats. In that way, a boat designer can design a PV boat without having the need for expertise knowledge of PV systems and energy balance calculations. The boat designer, from which it is expected that she or he has a background in conventional ship design, is offered an aid which fills the gap with PV power in the ship design spiral from Hollister.

This chapter does not aim to provide for design methods with which the design of PV boats can be supported resulting in perfect PV boat designs. It is expected that the design and building of PV boats will be in low numbers (for now). Design errors can then be easily fixed. Therefore, these chapters can be seen as a guide on design methods which designers can use. Chapter 5 shows a solution to the design problem of PV boats to increase the success of PV boats and Chapter 8 tries to tackle a sub-solution of the design problems of PV boats.

Chapter 3

PV boat overview

This chapter has been submitted as manuscript in 2013 and has been conditionally accepted for the Journal of Renewable Energy.

Parts of this chapter have been published in the Proceedings of the 37th peer-reviewed IEEE Photovoltaic Specialists Conference, Seattle, Washington, USA, 2011. T. Gorter, E. Voerman, P. Joore, A. Reinders, and F. Van Houten, entitled ‘PV-powered boats: evaluation of design parameters’.

3.1 Introduction

This chapter explores the opportunities to design PV boats by summarizing design features of existing PV boats. This overview of design features helps to answer the sub-research question 'How is PV boat performance defined?' Design features have been identified from existing boats in Friesland and boats which were found worldwide. This resulted in an overview of 183 PV boats. As a result, the key design features of these boats have been evaluated. This resulted in an overview of design criteria for PV boats.

The successful use of PV modules on boats is influenced by various factors, such as appearance of the boat and the energy balance, see Figure 1.9 [34]. Gorter et al. showed that PV boats are under-performing with respect to sailing autonomy, top speed and reliability [17]. The sailing autonomy can be explained as the amount of time a boat can sail with a certain speed on PV and battery energy [62]. Another important factor for smaller boats is the weight of the PV modules, which is discussed in Chapter 8 in more detail. In Section 3.2 the research approach is discussed to find PV boats worldwide. This resulted in a categorization of PV boats. The PV boats which have been found are summed up in Section 3.3. This section also shows their categorization and other specific characteristics.

3.2 Methodology

In order to evaluate existing PV boats worldwide, a database has been created with 183 PV boats and their design features [16]. An Internet research has been conducted to find different types of PV boats in operation worldwide. The design features of these PV boats have been collected from datasheets and informative websites. A smaller part of PV boat data has been collected directly from PV boat builders. Another source of PV boat data was the DSC, see Section 1.5, in 2010 and 2012 from which various PV boats were evaluated [63]. During the DSC in 2010, participants filled out questionnaires and have been interviewed to gather data. A general overview of boats which participated in the DSC in 2010 and 2012 is shown in Table 3.1.

Table 3.1: Classes in the Dong Energy Solar Challenge 2012 with specifications per class.

Design feature	**Dimension**	**A**	**B**	**TOP**
Maximal length	[m]	6	8	8
Maximal width	[m]	2.4	2.6	2.6
Maximal PV power	[Wp]	952	1190	1750
Crew member(s)		1	2	1
PV technology		c-Si	c-Si	any
Battery capacity	[kWh]	1	1	1

The design features of all PV boats, including participants from the DSC, which were evaluated are shown in Table A.1 on page 159.

Since not all evaluated data was available for all boats, individual comparisons of features was done on PV boats which had sufficient data. For example, when the installed PV power is compared between different boats, boats of which this parameter is unknown, are left out.

Table 3.2: Design features of PV boats worldwide.

Design feature	**Dimension**	**Range**
Boat length	[m]	2.13 – 33
Boat width	[m]	0.91 – 22.83
Maximum draft	[m]	0.1 – 1.2
Empty weight	[kg]	98 – 115 000
Full weight	[kg]	190 – 185 000
PV surface	[m^2]	0.6 – 536
PV power	[kWp]	0.05 – 93.5
Motor power	[kW]	0.14 – 162
Number of motors		1 – 2
Battery capacity	[kWh]	0.076 – 1750
Cruise speed	[km/h]	3 – 20
Maximum speed	[km/h]	3 – 40
Person capacity		1 – 150
Price	[€]	2500 – 24 000 000

PV boats found worldwide exist with different design features and with different performance characteristics for all categories. The DSC however has strict guidelines for the design of PV boats to be allowed to participate in the race. Within a single category, this leads to boats with similar features. However, these boats perform differently when compared to each other with respect to speed and sailing autonomy and especially compared to PV boats operating worldwide. The details per boat are shown in Appendix A.2.

3.3 Results

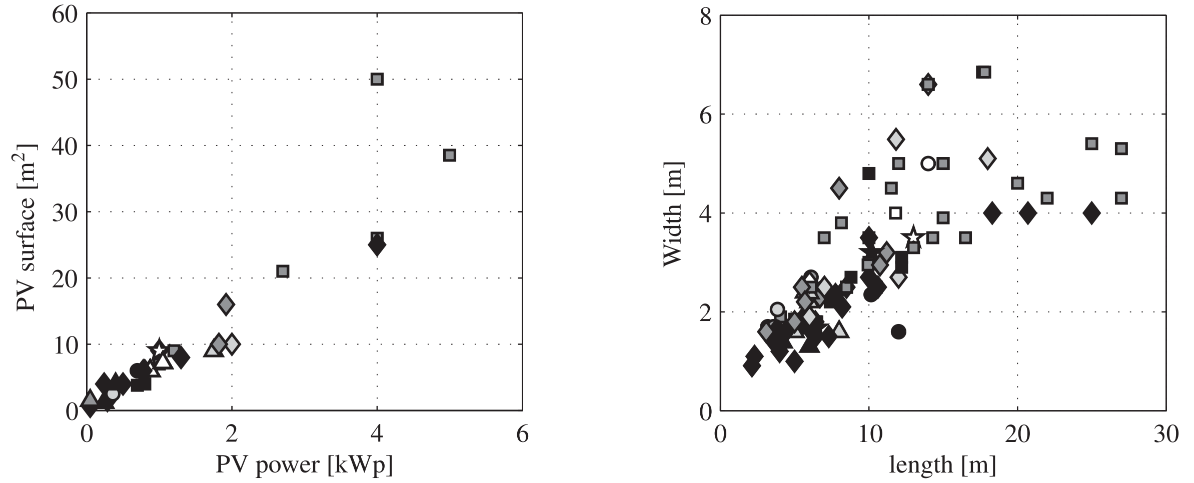
The database consists of 183 PV boats. Since the oldest PV boat in the database was built in 1975, see Figure 1.6, it shows that it is a relatively recent development. Most PV boats found and added to the database are boats retrofitted with PV (37%). A smaller number of PV boats is designed and built to be propelled with energy from PV (15%). From 52% of the boats it is unclear if they are retrofitted or not.

3.3.1 PV boat categorization

Figure 3.1 shows per boat the results of comparison of various design features. Note that the marker color and shape in the legend in Figure 3.1(f) and Figures 3.1(a) to 3.1(e) indicate the hull and use categories of the boats.

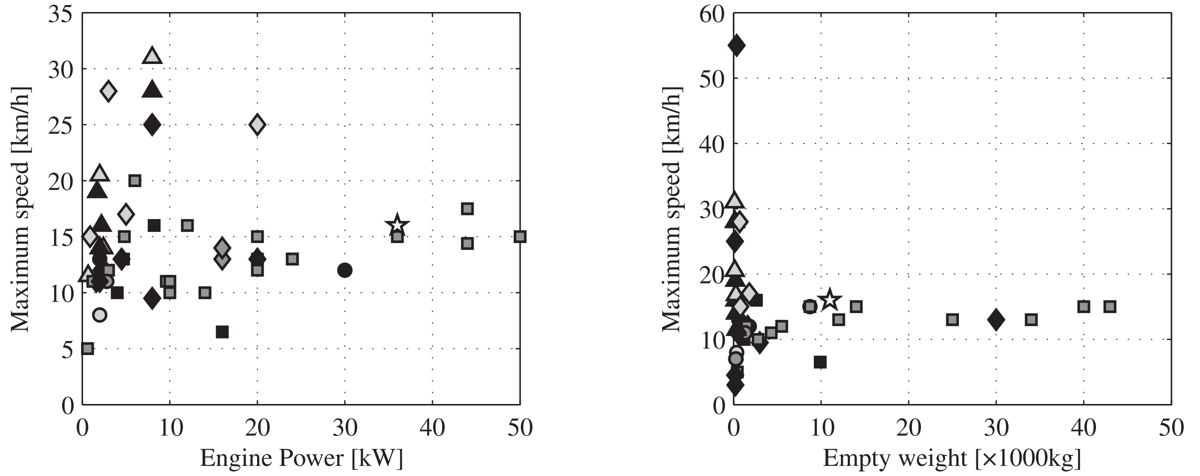
The 183 boats were placed into four key use categories [18]. The categorization indicates for what purpose the PV power is being used. The share of PV boats in the four categories are:

1. Recreation (7%).



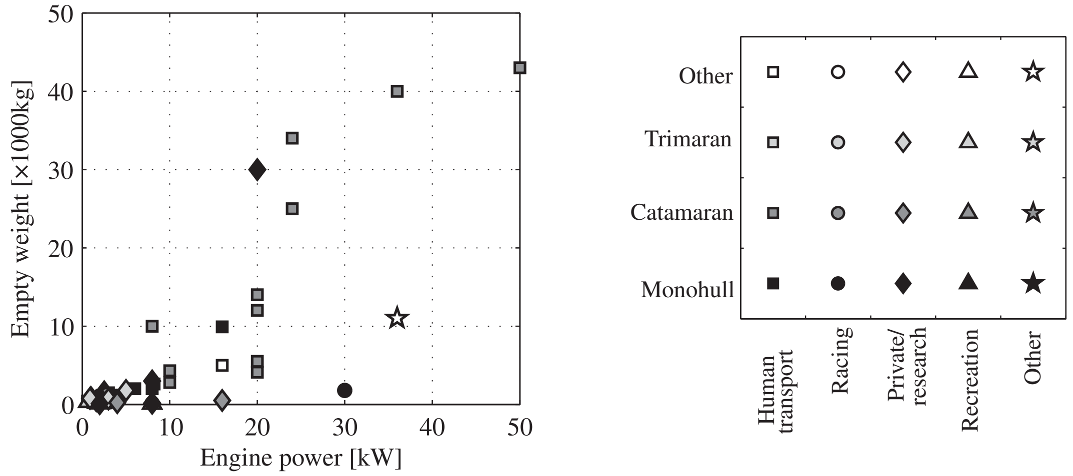
(a) PV surface versus PV power. Number of boats $n = 66$.

(b) Width versus length. Number of boats $n = 101$.



(c) Maximum speed versus motor power. Number of boats $n = 50$.

(d) Maximum speed versus empty weight. Number of boats $n = 46$.



(e) Empty weight versus motor power. Number of boats $n = 53$.

(f) Legend.

Figure 3.1: Results from the PV boat overview

(a) Sightseeing boat ‘The Blaustirns’ (picture taken by author).

(b) Commercial PV boat Aquawatt 550 [64].

(c) Research ship Planet Solar [65].

(d) Furia III; PV race boat, 2012 [66].

Figure 3.2: PV boats.

2. Private/research (34%).

3. Racing (28%).

4. Human transport (27%).

A small number of PV boats could not be categorized (4%). Boats in the human transport category are used for the commercial transport of people, as opposed to private use, see Figure 3.2(a). The recreation category encompasses vessels which are rented out to private individuals or small groups, see Figure 3.2(b). Boats categorized in the private/research category demonstrate what is possible with PV on boats, see Figure 3.2(c). Boats in the racing category are boats built with the main purpose to participate in races, such as the DSC, see Figure 1.8(d). These boats are mainly build to improve PV boat performance and to demonstrate the opportunities of sailing with solar power. These numbers show that for many applications, PV power can be used to transport people on the water.

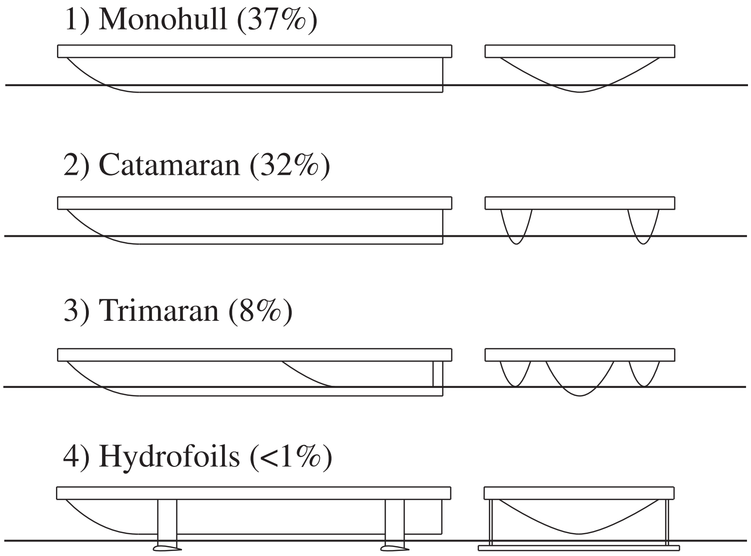


Figure 3.3: Hull types for PV-powered boats.

A second categorization was made with the type of hull used for a PV boat. Four key hull categories have been identified, which are:

1. Monohull (37%).
2. Catamaran (32%).
3. Trimaran (8%).
4. Hydrofoils (<1%), see Figure 3.2(d).

The hull type could not be concluded for 23% of the PV boats. Typical hull configurations are schematically shown in Figure 3.3. The hull type is important for the initial stability and usability of a PV boat. Furthermore, certain hull configurations show lower resistance in the water.

3.3.2 PV system

This section discusses various design features with regard to the PV system installed on boats. The features of the PV system on boats which are discussed are the placement of PV, the used PV technology, the PV surface area and the installed battery capacity.

The following placement topologies have been identified:

1. Horizontal PV placement on the roof (34%).
2. Horizontal PV placement on the deck (37%).
3. Adjustable PV placement (4%).

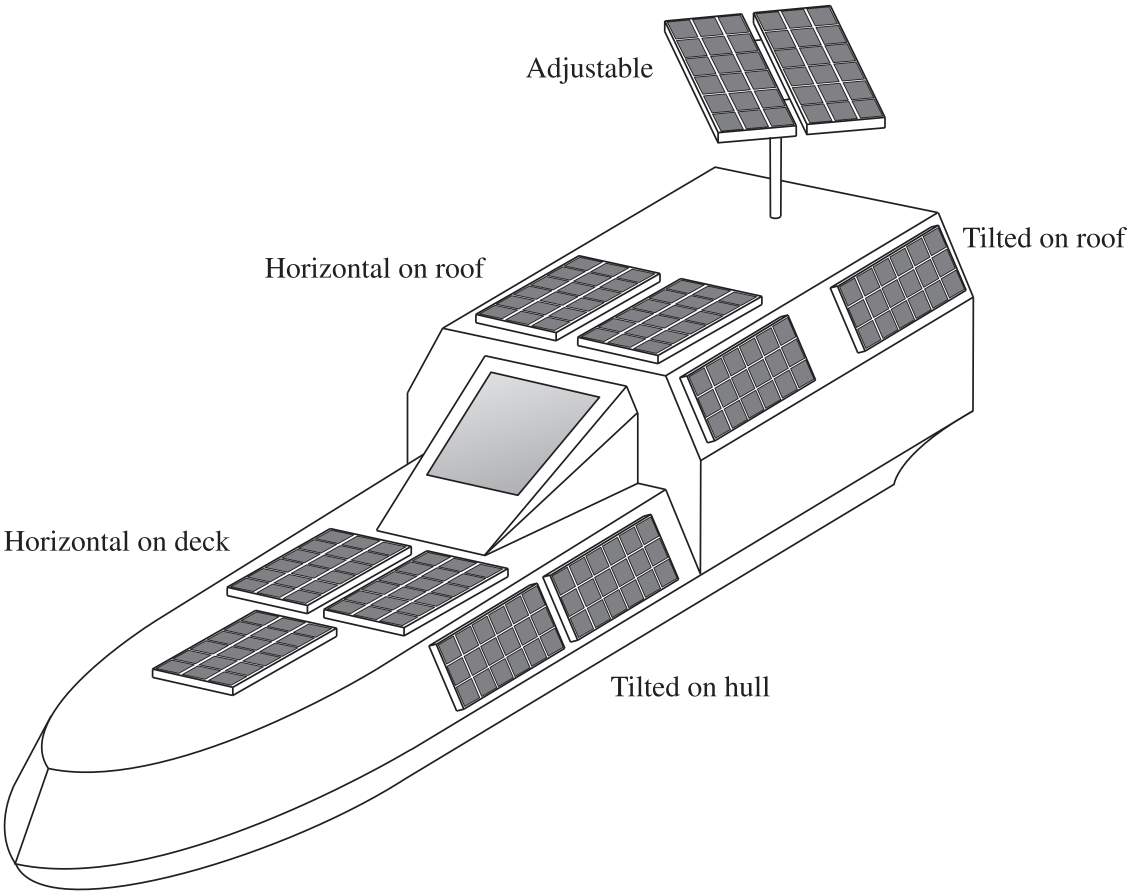


Figure 3.4: PV placement options on PV boats seen on 158 PV boats.

4. Tilted PV placement on the hull (4%).
5. Tilted PV placement on the roof (4%).

These topologies are schematically shown in Figure 3.4. For a small number of boats, the topology could not be determined (17%).

For 137 boats, the boat's installed PV power is known. Most PV boats are equipped with a maximum of 2 kWp installed PV power (82%). The installed PV technology could not be determined at all times. However, photos suggest that most PV modules use c-Si (mono as well as multi crystalline) technology and modules are of the glass laminate type.

For 75 boats, the PV surface area is known. The PV cell efficiency can be approximated by comparing the PV module's surface area with the installed PV power. Figure 3.1(a) shows a relation between the installed PV power on boats and the surface area of installed PV modules. This figure shows an average PV module efficiency of 15%. When calculating the efficiency per PV module, the efficiency varies mostly between 12% and 20%. This suggests the use of low to high efficient mono c-Si cells and/or middle to high efficient poly c-Si cells. This is consistent with Figure 3.1(a).

For 78 boats, the battery capacity was known. A large number of PV boats have a battery capacity of around 1 kWh (43%). However, this number is caused by the large amount of

PV boats which participate in the DSC. The employed battery technology is rarely specified.

3.3.3 PV boat dimensions

More than half of the PV boats have a length between 4 m and 8 m (53%). The large number of boats with these lengths is participant in the DSC and is bound by regulations to have a maximum length of 6 m or 8 m. (Longer boats can theoretically reach higher maximum speeds with the same amount of power.) Of the other PV boats, most of them have lengths under 10 m (71%). The stated length is measured overall above the waterline.

For 101 boats, the boat width is known. Most boats have a width under 4 m (74%). Boat width and boat length can give an estimate on how much surface area is available for PV modules.

In Figure 3.1(b), PV boat width is compared with PV boat length. In this figure, two boats are left out to improve clarity of the figure. These boats have a width of 15 m and 23 m. Boat width is measured overall. By dividing boat length with boat width, the LB-ratio (length-to-beam ratio) can be determined, which is an indicator for the initial directional stability of the ship. A higher Length-to-beam (LB) ratio means higher stability. Monohulls generally have a lower LB ratio compared to catamarans. From Figure 3.1(b) and Table A.2 it follows that most PV boats with monohulls have an LB ratio around 5:1. Catamarans show a more spread out ratio between 2:1 and 5:1.

When estimating the available PV surface, it suggests that not all surface area is optimally used for PV modules when Figure 3.1(a) is compared with Figure 3.1(b). This might be a cause of lower performance of some PV boats.

For 60 boats, the boat's empty weight is known. Boats with a weight over 5000 kg are mostly catamarans used for human transport. Weight for catamarans is in general much higher compared to the other hull types, concluding that they require more solar power for sailing.

3.3.4 Additional aspects

For 64 boats the maximum speed was found. Maximum speed is mostly between 5 km/h and 20 km/h (73%). Most boats however, have a maximum speed around 15 km/h. One exception exists: a boat with a maximum speed of 55 km/h. From Figure 3.1(c) it can be seen that mostly monohulls and trimarans have higher speeds compared to catamarans.

Catamarans with a relatively high amount of PV power installed do not necessarily reach the highest speed. Monohulls and trimarans show higher maximum speeds with less PV power installed. Table A.2 shows that most boats have a maximum speed up to 10 km/h. Furthermore, a large number of boats have a cruise speed between 6 km/h and 9 km/h for all categories (48%). These numbers indicate that some PV boats have a maximum sailing speed which is too slow to be practical. For example in the Netherlands, speed limits on canals is 6 km/h. However, on lakes and rivers, the speed limit can be 12 km/h. PV boats participating in the DSC show much higher maximum speeds although in most cases, less PV power is installed.

Relations between PV boat weight and installed motor power shows no correlation for boat use categories. However, when comparing the maximum speed with the installed motor power of the boat for different PV boat hull types, it can be seen that catamarans are mostly equipped with the most powerful motors with maximum speeds between 10 km/h and 20 km/h. This can be seen in Figure 3.1(c). A large number of PV boats have a maximum motor power of 5 kW (59%), however PV boats in the human transport category show also motor powers in the other ranges. PV boats in the private/research category have mostly motor powers under 5 kW. A mismatch between maximum rated motor power and installed PV power exists for most PV boats. This indicates that it might be difficult to have a positive energy balance on PV boats.

When comparing the empty weight of PV boats with the maximum speed, two trends can be distinguished (see Figure 3.1(d)). First, boats which reach the highest maximum speed have a relatively low weight. Second, most boats with an empty weight of 5000 kg or higher, have a maximum speed around 15 km/h. The larger number of PV boats which reach speeds over 20 km/h are participants of the DSC: lightweight boats which are build for speed and which are demonstrators of the usage of PV power on PV boats. When considering the empty weight versus the motor power of PV boats, it seems that most motors have a rated power under 10 kW (75%), see Figure 3.1(e). When Figure 3.1(e) is compared with Figure 3.1(d), it clearly demonstrates that most boats with a low weight reach higher maximum speeds compared to boats with a higher weight and have a motor power under 10 kW.

For 108 boats, the person capacity is known. Most PV boats show that they can hold 1 or 2 persons (39%). However, some PV boats can carry over 15 persons. These are mostly boats from the human transport category. They are a good example of the use of solar power to transport humans.

3.3.5 Important design features

To evaluate the performance of PV boats with respect to various variables, twelve key PV boat design features were selected which describe PV boats in operation. Ten of these twelve features are directly derived from Table 3.2. However, not all features which were found in this research were identified as important design features. For example, when the total motor power is described as well as the number of motors, then the total motor power is considered to be more important. The design choice to use two motors to gain that power, is considered irrelevant. The same reasoning can be made with for example the installed PV power and the used PV technology. Then, to reduce the identifiable number of design features of PV boats to a minimum, the following enumeration shows all the important design features of PV boats. These twelve design criteria are an aid to design PV boats and determine the boat's performance with respect to the technical performance and the financial performance. Furthermore, standardization of these design features can make the comparison of the performance of PV boats easier.

- *Hull type*
  The hull type plays an important role of the purpose of the boat. For example, catamaran hulls bring more stability to the boat and are easier to build. Depending on the purpose of the boat, the most common hull configurations are monohulls, catamarans and trimarans, see Chapter 3.

- Boat length [m]
  The boat length is a determinant for the top speed a boat can reach. Furthermore, the boat length and the boat width play an important role in what kind of hull will be used and how much space is available for PV power. The results in Chapter 3 show that boats up to 10 m are more likely to sail with a better performance than longer boats.

- Boat width [m]
  The boat width is a measure for the stability of the boat and depends primarily on the choice of the hull type.

- Boat weight [kg]
  The weight, or water displacement, of a boat is an indicator for the boat's resistance to go through the water. Especially for boats which have relatively lower speeds, such as solar boats which do not go into planning or do not use hydrofoils, the water displacement in combination with the wet surface of the hull can be expressed in friction directly. The displacement depends on the hull form and the speed the boat is sailing.

- Maximum speed [km/h]
  The choice for the maximum speed is dependent on the availability of PV energy, as well as the wishes of the end-user. Furthermore, regional legislation plays an important role in the determination of this design criterion. A well chosen maximum speed can have a great impact on the success of a PV boat. For larger ships, which can carry a larger number of people, such as 100, speeds up to 15 km/h seem sufficient.

- Cruise speed [km/h]
  The cruise speed, a value for speed which can be sailed for a longer period of time, without drastically depleting the energy storage, is an important factor for the impact on the success of PV boats. A well chosen cruise speed should match the hull resistance, battery capacity, and PV power. When looking at common cases, cruise speeds for boats can be around 10 km/h.

- PV power [kWp]
  The amount of installed PV power should be as high as possible. This depends on hull choice, available surface area and more. Since this is the main energy source on a PV boat, the performance of all electrical systems are influenced by the installed PV power.

- Motor power [W]
  The maximum installed motor power is a measure for the maximum speed of the PV boat. However, electrical motors should be chosen which satisfy the entire range of speeds with acceptable efficiencies.

- Battery capacity [kWh]
  The battery capacity should be chosen as such that sufficient PV energy can be stored and a high level of autonomy is reached.

- Person capacity [*number*]
  Depending on the user's needs or wishes, the proper number of persons should be selected for a PV boat. This is highly dependent on the purpose of the PV boat.

- Price [€]
  A price for a PV boat should be chosen as such that it fits with the user's financial capabilities. Best practice would be to price PV boats comparable with other, IC engine driven boats with the same features.

- Autonomy [h/(km/h)@I/m^2]
  The autonomy of the PV boat is a significant factor in the success of a PV boat. If the autonomy is not high enough, users will be unsatisfied with the performance of the PV boat and therefore the success will fail. The autonomy is determined by dividing the left-over capacity in the batteries by the nominal battery capacity at an average speed of 12 km/h over a distance of 30 km.

3.4 Discussion and conclusions

PV boat data has been collected from websites, datasheets, and questionnaires. Since no standardization exists on how to describe PV boat design features, it depends on the availability and accuracy of data. Analysis of the data resulted in an overview of design criteria for PV boats.

The data which was used in this research has been directly copied from the sources. However, it can be expected that some data might be over or under estimated, which might lead to errors in our overview. Not all data could be found for this research so it was impossible to compare all 183 PV boats' design features.

In general, only the boat's PV system, energy storage and motor power were looked at. HEP loads were neglected. Depending on the type and use of a PV boat, these loads can have a significant share in the energy demand on these boats.

When characterizing PV boats, certain variables are important, such as boat length, boat width, motor power and a particular boat speed with corresponding sailing autonomy. Another important parameter for PV boats, which also is an important indicator for the hull resistance, is the water displacement of the boat. The displacement is directly related to the weight of the boat, but depends on the hull form and the speed the boat is sailing.

Battery capacity is not consistently given in watt/hour or in ampere/hour in combination with a given nominal voltage for PV boats. This makes it difficult to compare battery capacities among boats.

The cost of PV boats is hard to determine, since various currencies are used at various times. This leads to non-uniform and incomparable costs for some PV boats.

Existing PV boats show the potential of sailing with solar power. Especially boats up to 10 m show good performance in terms of maximum speed. Larger boats are able to transport a relatively large number of people with solar power. However in general most PV boats show relatively low performance with respect to maximum speed compared to PV boats which participate in the DSC. These PV boats which participate in the DSC are characterized by a low weight design. Also, they have a comparatively large surface area available for PV modules and a small battery capacity as well as a small electrical motor. This indicates that PV boats participating in the DSC sail more efficiently, hence requiring less power for propulsion and showing a better energy balance compared to other PV boats. Other PV boats show lesser performance, partly because not all available surface area on these boats is used for PV modules. This conclusion is made because a relatively small amount of PV power is installed on PV boats (under 2 kWp, maximum 10 m^2). When looking at the available surface area on PV boats, more area could be used for PV to increase solar power output. This is especially the case for larger PV boats. Performance of these larger PV boats, but also for smaller PV boats, can be increased by dedicating more surface area to PV modules to increase the energy yield of the onboard PV system.

Mostly, data about sailing autonomy is not given, which for PV boats is a very important performance indicator.

PV boat designers can learn from this research and the results thereof and discover the opportunities to sail with solar power, such as the feasibility of relatively small racing boats or ferries for commerce. The DSC is a good example of relatively high efficient, well-performing PV boats.

As a result from this research it is proposed to describe PV boats according to the feature-list in Section 3.3.5.

When evaluating the performance of PV boats, the value for maximum speed of PV boats is not practical since it is not known how long the maximum speed can be maintained with respect to the battery capacity and the amount of available solar irradiation. Therefore, as addition to the feature-list, the sailing autonomy of a PV boat should be mentioned: sailing autonomy [h/(km/h)@I W/m^2], where I is a representative value for the amount of power from solar radiation. Sailing autonomy is an important feature of PV boats, which does describe how long a boat can sail with a certain speed with solar and battery energy. To conclude, this research suggests that if PV boats will be designed in a proper way that good criteria are met, the available PV energy should be kept in mind in an early design stage, instead of retrofitting boats with PV afterwards.

Chapter 4

PV boat monitoring

Parts of this chapter have been published in the Proceedings of the 38th peer-reviewed IEEE Photovoltaic Specialists Conference, Austin, Texas, USA, 2012. T. Gorter, E. Voerman, P. Joore, A. Reinders, and F. Van Houten, entitled 'PV system measurements of a PV-racing boat during the Frisian Solar Challenge 2010'.

4.1 Introduction

So far, little to none is known about the real performance of PV boats during use or operation. Therefore, two PV systems from two different boats have been monitored. The monitoring took place during two editions of the DSC. Furthermore, the PV system from one of the boats has been monitored as well, during various days after the race. The aim of the research was to establish relevant performance indicators for PV boats, through monitoring and analysis of the measurement data.

Monitoring of PV boats requires a different approach compared to conventional monitoring methods for stationary PV systems, such as described in [67–69] for several reasons. Firstly, regular PV systems are continuously in use whereas a PV boat is used for only a few hours per day. Secondly, previous research describes the monitoring of PV systems on recreational boats. These PV systems were monitored on an hourly basis with a data logger. This resulted in performance ratios for these boats between 0.1 and 0.4 [41]. In this research, existing methods for analytical monitoring have been used and adapted for measurements on PV systems on two boats. By monitoring with shorter time intervals, in the range of seconds, more accurate analysis of the data of the boat's PV system can be done.

But the question is if the performance of PV boats can be determined by only looking at the PV system. Especially when the PV system is an integral part of the propulsion system, either stand-alone or hybrid. Therefore, the efficiency of the PV system is not a good measure for the performance of a PV boat. For example, if the efficiency of the PV system is 80% but the energy conversion efficiency for propulsion only 50%, then the overall efficiency is still only 40%. Optimizing the PV system has then less impact on the overall efficiency. The propulsion efficiency or hull efficiency would be of higher interest. Therefore, this chapter addresses the sub-research question 'How is PV boat performance defined?'

To answer this question, this chapter covers the process of the monitoring of two PV boats, the resulting data, and the analysis thereof. These two boats participated in the DSC 2010 and 2012, see Figure 4.2. Furthermore, the 2012 boat has been monitored during a number of days in 2013 and that data has been analyzed as well. Figure 4.1 shows the (general) chain of losses in the electrical and mechanical system of PV boats.

Section 4.2 gives on overview of the boats which were evaluated. Section 4.3 describes the experimental setup of the two boats which have been used for monitoring. Furthermore, the monitoring systems have been described. Section 4.3.2 describes the analysis of the monitoring data and the results thereof are discussed in Section 4.4.

4.2 PV boats evaluated

This section describes the system setup of the two boats. Both boats share the same hull configuration, but different PV systems and drive trains.

4.2.1 2010 boat

The 2010 boat is shown positioned left in Figure 4.2 and its monitoring system is shown in Figure 4.3. The boat was equipped with 5 polycrystalline PV modules from Sharp with a nominal power of 175 Wp each and a module efficiency of 13.5% [70]. Each PV module was

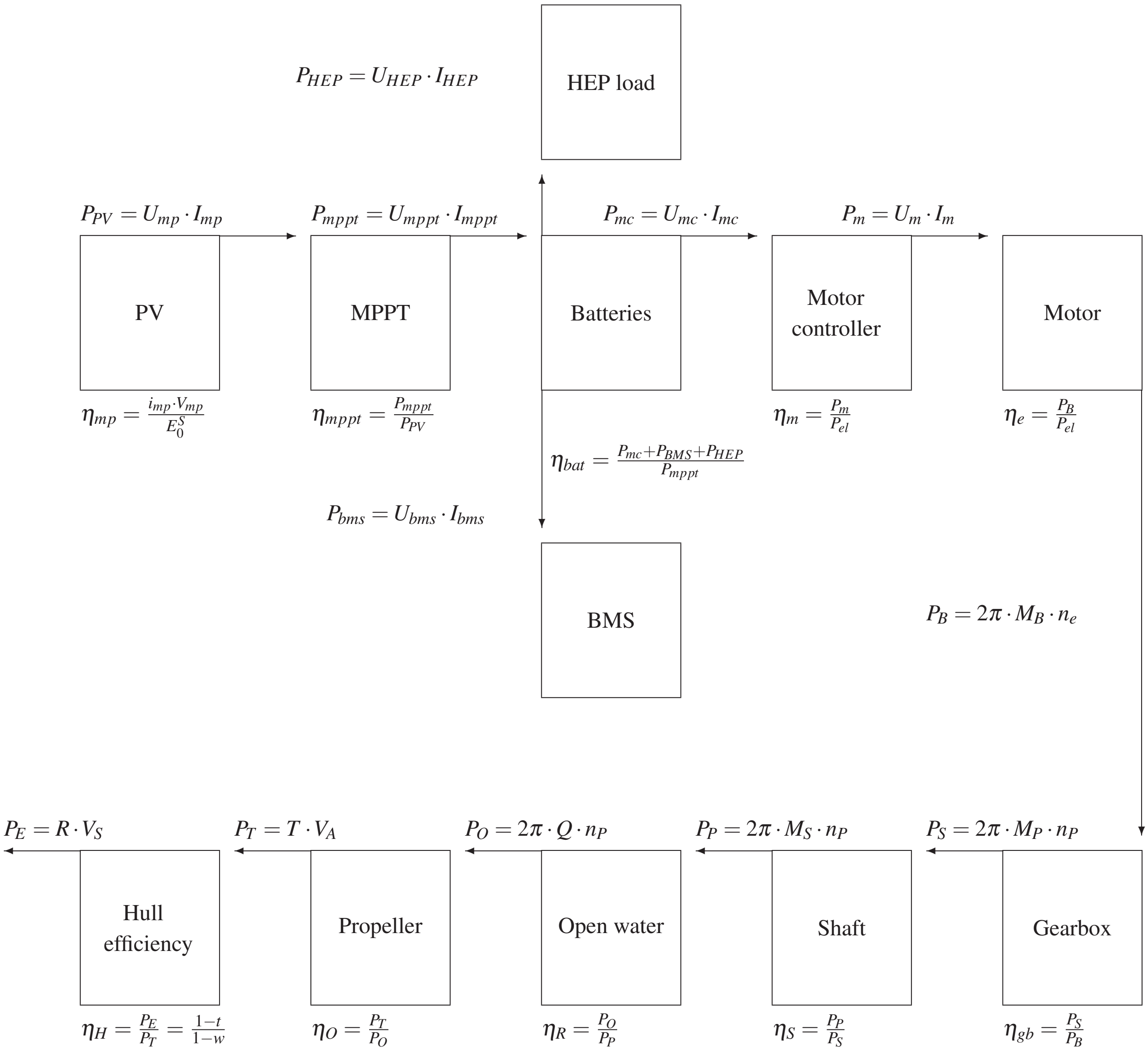


Figure 4.1: Losses in the PV system and drive train on a PV boat.

connected to an MPPT from DriveTek [71]. These five MPPTs were connected in parallel to the battery, see Figure 4.3. The boat was equipped with a 6.0 kg Lithium-polymer (LiPo) battery pack with a nominal capacity of 1050 Wh from MG-electronics [66]. The battery pack had an integrated BMS, which monitored the PV system. The BMS was also developed by MG-electronics. Loads were connected to the battery, such as a motor controller and onboard devices such as a Global Positioning System (GPS). The monitoring data was sent every 5 seconds to an online server with a General Packet Radio Service (GPRS) connection. The total boat weight was 165 kg [19].

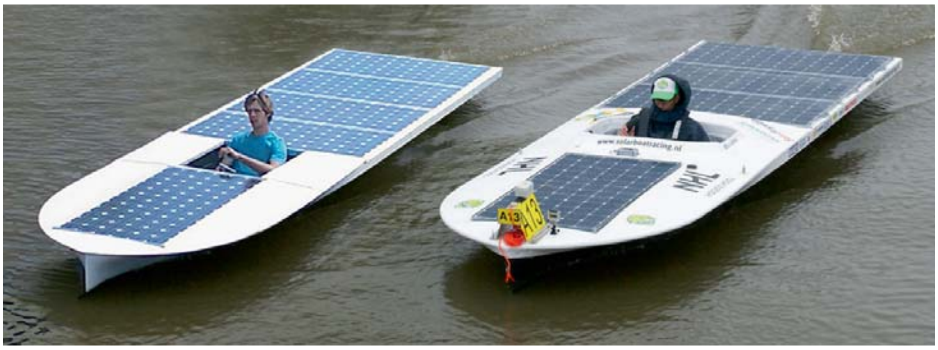


Figure 4.2: PV boats used for monitoring in 2010 (left), 2012 and 2013 (right) (picture taken by author).

4.2.2 2012 boat

The 2012 boat is shown positioned right in Figure 4.2 and the monitoring system is shown in Figure 4.4. The boat was equipped with 4 monocrystalline PV modules from Sunpower with a nominal power of 238 Wp and a module efficiency of 19.1% [72]. Two PV modules were connected in series and two pairs of modules were connected in parallel to one MPPT from Morningstar [73]. The boat was equipped with a 7.1 kg Li-Ion battery pack from MG-electronics with a nominal capacity of 1750 Wh. The battery pack had an integrated BMS, which monitored the PV system. The BMS was also developed by MG-electronics. Loads were connected to the battery, such as a motor controller and onboard devices such as a GPS. The total boat weight was 175 kg.

In 2012, monitoring data came partly from the BMS. PV module temperature, MPPT data and irradiance have been monitored as well with another monitoring system which was developed specially for this research. These data were sent every 3 seconds to an online server with a GPRS connection. In 2013, during 10 randomly chosen days, the boat was monitored again under various circumstances, using the same setup for data acquisition as in 2012 [35].

4.3 Monitoring system

Figures 4.3 and 4.4 show the setup of the monitoring system for the 2010 boat and 2012 boat. Both boats have been monitored for several days during the DSC. In Table 4.1 the measured variables, sensors used and their accuracies are shown. The various days of monitoring are shown in Figures 4.7 to 4.9. The monitoring interval was 3 seconds.

4.3.1 Sensors and accuracy

The majority of the data of both boats resulted from the BMS, such as battery voltage $V(t_i)_{bat}$, battery currents $I(t_i)_{bat_{in}}$ and $I(t_i)_{bat_{out}}$ and battery temperature $T(t_i)_{bat}$. In 2012, a reference cell and other sensors were added to the system. The maximum error for each type of measurement is given in Table 4.1.

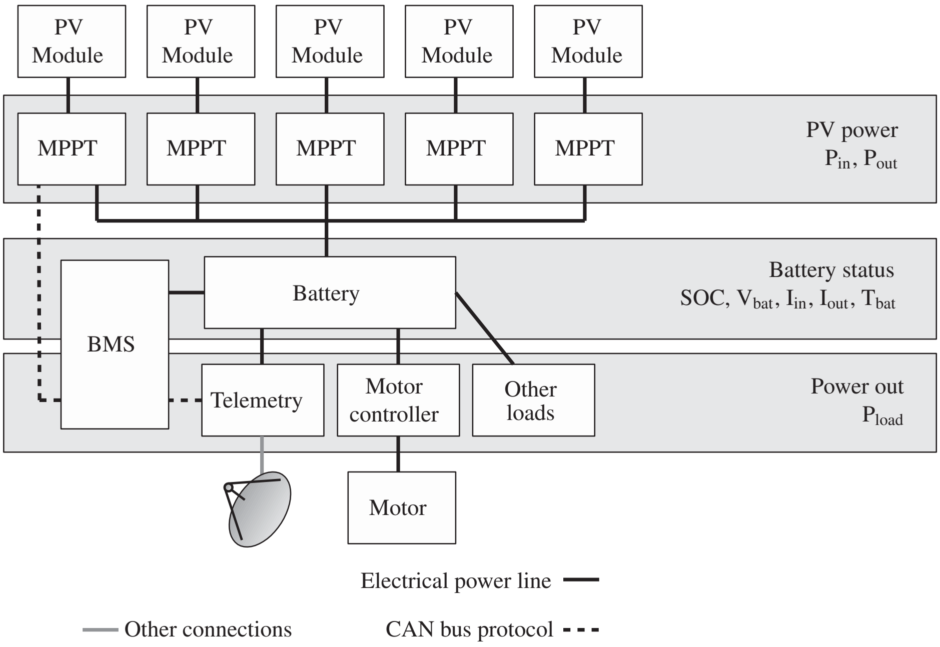


Figure 4.3: PV system and monitoring system of the 2010 boat.

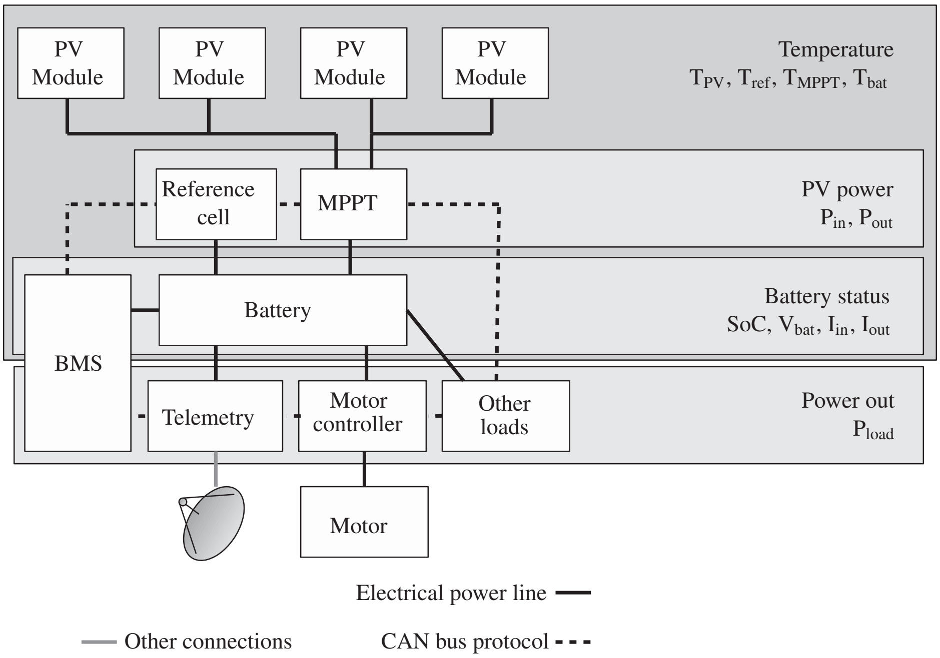


Figure 4.4: PV system and monitoring system of the 2012 boat.

Table 4.1: Variables measured, sensors used and their accuracy for the 2010 and 2012 boat.

Variable	Sensor	Accuracy
Battery voltage	Voltage divider with ADC	2mV (at +25°C)
Battery current in/out	Hall effect sensor	200mA (at +25°C)
Battery temperature	Negative temperature coefficient sensor	0.5°C (at +25°C)
Position (latitude, longitude)	Telit Wireless Solutions GE864-GPS	7.8m (95% confidence)
Speed	Telit Wireless Solutions GE864-GPS	0.2m/s/*axis* (95% confidence)
Reference irradiance[1]	Mencke&Tegtmeyer Si-01TC-T	5% (between -20°C and 70°C)
PV module temperature (6x)[1]	National Semiconductor Precision Centigrade Temperature Sensor LM35	0.5°C (at +25°C)

[1] These measurements where only executed in the 2012 boat.

4.3.2 Analysis

A conventional indicator for PV system performance is the performance ratio $\mathrm{R_P}$ [67–69]:

$$\mathrm{R_P} = \frac{Y_f}{Y_r} \tag{4.1}$$

With:

$\mathrm{R_P}$ = Performance ratio [-]
Y_f = Final yield, i.e. energy yield of the PV system [Wh]
Y_r = Reference yield, i.e. energy yield of solar irradiation [Wh]

However, the performance of a PV boat can be described with two additional indicators:

1. The power-speed relationship.
2. The energy-distance relationship.

The usefulness of these indicators has been pointed out by Leiner to monitor the available energy on a PV boat. By finding an optimum speed for the PV boat, the likelihood to arrive at the destination is increased. A simplified generic power-speed relationship for water displacing boats is given by Blidberg et al. [74] and Leiner [43]:

$$P_v \widehat{=} C_f \cdot v^3 \tag{4.2}$$

With:

P_v = Power required to sustain the respective speed [W]
C_f = Constant describing the hull resistance [-]
v = Speed over water of the PV boat [km/h]

The factor C_f can be used to describe the specific boat resistance. The resistance is determined greatly by the hull shape and boat weight. The energy-distance relationship is given by:

$$D = \frac{1}{\sqrt[3]{C_f}} \cdot \sqrt[3]{\Delta t^2} \cdot \sqrt[3]{E} \tag{4.3}$$

With:

D = Distance [km]
Δt = Sailtime [h]
E = Available energy [Wh]

Equation 4.3 is described by Blidberg et al. [74] to calculate the distance which a PV-powered submersible can travel with a given amount of energy. Distance D is therefore dependent on the energy E_{PV} generated with the PV system during a monitoring period τ:

$$E_{A,\tau} = \tau_r \cdot \sum_{t=0}^{n} P_{PV} \tag{4.4}$$

With:

$E_{A,\tau}$ = Energy yield of the PV system over a monitoring period τ [Wh]
τ_r = Monitoring interval [h]
n = Number of samples in data set [-]
P_{PV} = Power from PV modules [W]

4.4 Results

In this section the results of data analysis for the 2010 and 2012 boat are discussed.

4.4.1 2010 boat

The 2010 boat has been monitored for five days, from July 5th to July 10th 2010 with a monitoring fraction M of 0.86. The results from monitoring are shown in Figure 4.7. For comparison, hourly solar irradiation data has been appended to the monitoring data [75]. The weather was good with sunny periods and relatively high irradiance I_β. Only the incoming

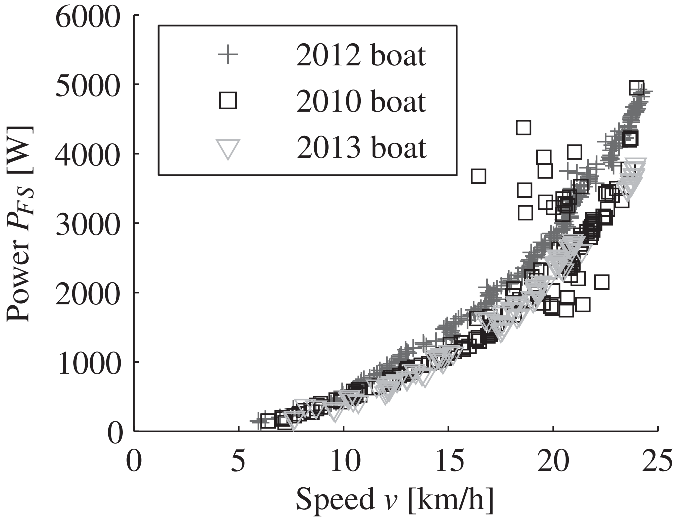


Figure 4.5: power-speed relationship for the 2010 boat and the 2012 boat in 2012 and 2013.

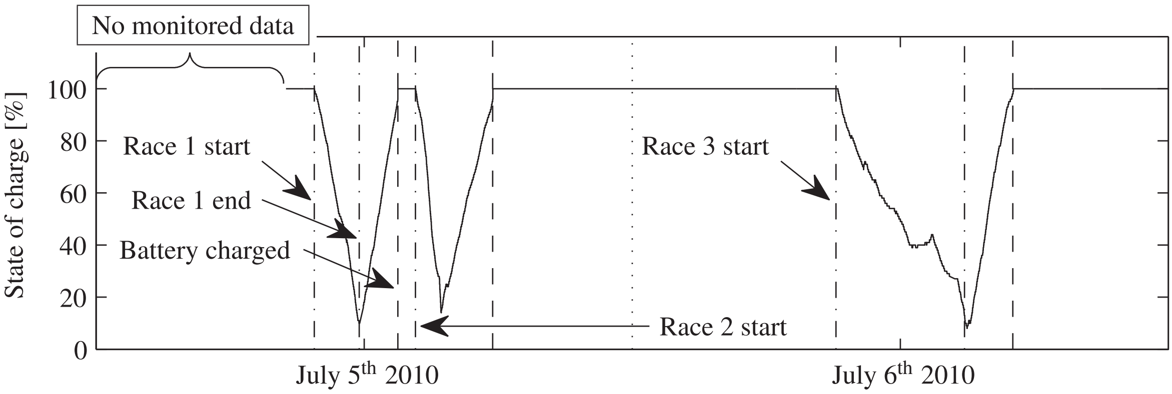


Figure 4.6: Detail of monitoring data from 2010.

power P_{TS} from the MPPTs to the battery has been monitored. With these data, the performance ratio R_P can not be determined because the irradiance was not measured. However, boat performance in total could be determined, which can be described as the power-speed efficiency: a measure of how much power P_{FS} is needed to reach a certain speed v.

Figure 4.5 shows the power-speed data. The boat had an average speed v for these days of 13.4 km/h. Figure 4.6 shows battery State Of Charge (SOC) data. Each V-shape represents a start and end of a sailing period (race leg during DSC) followed by the charging of the battery until the battery is full. Furthermore, it shows a gap (from 0 to 'Race 1 start'), where no monitoring took place.

4.4.2 2012 boat

The 2012 boat has been monitored for five days, from July 9th to July 14th 2012 with a monitoring fraction M of 0.98. The results from monitoring are shown in Figure 4.8. The weather was not as sunny as compared to 2010, with July 13th showing an average irradiance around 200 W/m^2. A reference cell was installed on the boat. However, analysis of the reference cell data showed that a malfunction had caused poor data. That data is therefore not included in the results.

The power-speed efficiency has also been determined for this boat. Figure 4.5 shows clearly that the boat had a less efficiently power-speed relationship compared to the 2010 boat (triangle). The boat showed a decrease of 13% in the power-speed relationship compared to the 2010 boat. The average speed v was 12.7 km/h for these days.

4.4.3 2012 boat in 2013

After the race in 2012, the malfunction of the reference cell had been corrected. Ten days have been monitored in 2013 with a monitoring fraction M of 0.97. Five of these ten days are shown in Figure 4.9. In this Figure, June 5th and June 9th show complete discharge and charge cycles for the battery. The performance ratio $\mathrm{R_P}$ has been determined in two ways. Firstly by using the method proposed by IEC [69], which resulted in a performance ratio $\mathrm{R_P}$ of 0.82. Secondly, the IEC method has been adapted to only calculate the performance ratio when the PV system is functioning. This resulted with the same data in a performance ratio $\mathrm{R_P}$ of 0.87, which is 5% higher compared to the standard method and is as a result a better representation of the efficiency of the PV system when it is in use. To determine how much influence the weight of the 2012 boat had on the power-speed relationship, the weight of the 2013 boat has been reduced with 60 kg. This resulted in a power-speed relationship of the 2013 boat, which was the same as the power-speed relationship of the 2010 boat, see Figure 4.5.

4.5 Discussion and conclusions

Performance indicators for PV boats can be described in various ways. The approach presented in this chapter describes three performance indicators: the power-speed relationship, the performance ratio for PV systems and the energy-distance relationship. The power-speed relationship is an indicator for the amount of power which is needed to reach a certain speed. In this power-speed relationship various sources of losses are included, such as mechanical losses in the propulsion system as illustrated in Figure 4.1 from *Motor controller* to *Hull efficiency*. The performance ratio is a measure for the performance of the PV system and covers the electrical losses from *PV* to *Batteries* (including *HEP load* and *BMS*) in Figure 4.1. The energy-distance relationship is an indicator for the autonomy of a PV boat, but is highly dependent on the two previously described indicators.

As conclusion to this research with regard to performance indicators of PV boats can be said that the monitoring of PV boats should be conducted differently compared to stationary PV systems. PV boats show different usage profiles, which is in favor of the performance ratio of PV systems. Whereas stationary systems are monitored throughout the year, under all circumstances and probably with continuous loads. The power-speed relationship is an indicator for the hull performance and mechanical performance of the boat. Furthermore, the power-speed relationship is a link between the performance ratio of PV systems and the energy-distance relationship. The latter is an important parameter for the autonomy of PV boats and thus the practical performance of the boat.

In order to monitor PV boats in a practical way, monitoring interval was 3 seconds. Compared to stationary systems, that is a very high monitoring frequency. The results from that data showed that the loads in the racing boats are highly varying. That has implications on the determination of the system components. For example, batteries should be able to deliver high currents instantaneously on demand.

In this research, the power-speed indicator is calculated using the power required to reach a given speed. However, many parameters influence the result of this indicator, such as weather conditions. The indicator for the distance a PV boat can travel, is dependent on several factors, including the indicator for the power-speed relationship and the irradiance. In practice, it is therefore impossible to determine one value for the power-speed performance and the exact distance a PV boat can travel under certain conditions. A set of standard test conditions for PV boats can give more comparable values for indicators 1 and 2.

In order to determine the performance ratio of the PV systems, the 2010 boat had a continuous data connection. During the night, when the 2010 boat was not in use, the PV system was still being monitored. The 2012 boat however, had a telemetric system which was disconnected to save energy when the boat was not in use. It is not clear if the poor performance of the PV systems of the 2012 boat is caused by the electric components operating less efficient under lower irradiance.

PV boats show very unique use profiles. For example, PV boat owners are more likely to use their boats on sunny days [6]. When the performance ratio is determined for only these days, it is most likely higher when compared to days when irradiance is relatively low.

For the 2012 boat, the performance ratio R_P has been determined in two ways. Firstly by using the method proposed by IEC [69], which resulted in a performance ratio R_P of 0.82. Secondly, the IEC method has been adapted to only calculate the performance ratio when the PV system is functioning. This resulted with the same data in a performance ratio R_P of 0.87, which is 5% higher compared to the standard method.

The 2010 boat showed better performance with respect to the power-speed relationship compared to the 2012 boat. The weight of the 2012 boat has been reduced with 60 kg in 2013 on various days. This results in the same performance as the 2010 boat (see Figure 4.5). This leads to the conclusion that the reduction in performance of the 2012 boat is not caused by a 10 kg increase of weight by the 2012 boat. Most likely, the electrical or mechanical system for propulsion is performing less.

For this research, the PV system of two boats have been monitored for a relatively short period τ. For future research, more periods of monitoring can lead to more accurate results. It might also lead to better insight in PV boat behavior with respect to the performance ratio in relation to the boat's power-speed relationship. The efficiency of the drive-train should be investigated as well to clarify in what way the performance of these boats is affected by the electrical and mechanical components. Since PV boats are not continuously used, it is better to compare the available irradiance with the used power during the time of use. This method results in a measure for the PV system efficiency instead of a measure of how much solar energy is effectively used.

Most likely, the performance ratio of grid-connected PV systems is higher compared to autonomous PV systems. Just like these PV boats, PV modules are disconnected from the battery by the BMS to protect the battery. This results in a lower performance ratio. It is expected that the performance ratio of PV boats is lower compared to stationary autonomous PV systems, such as an SHS. Where an SHS is carefully positioned to maximize irradiance, a PV boat moves and local shadows may be casted on the modules. This can decrease the performance ratio as well.

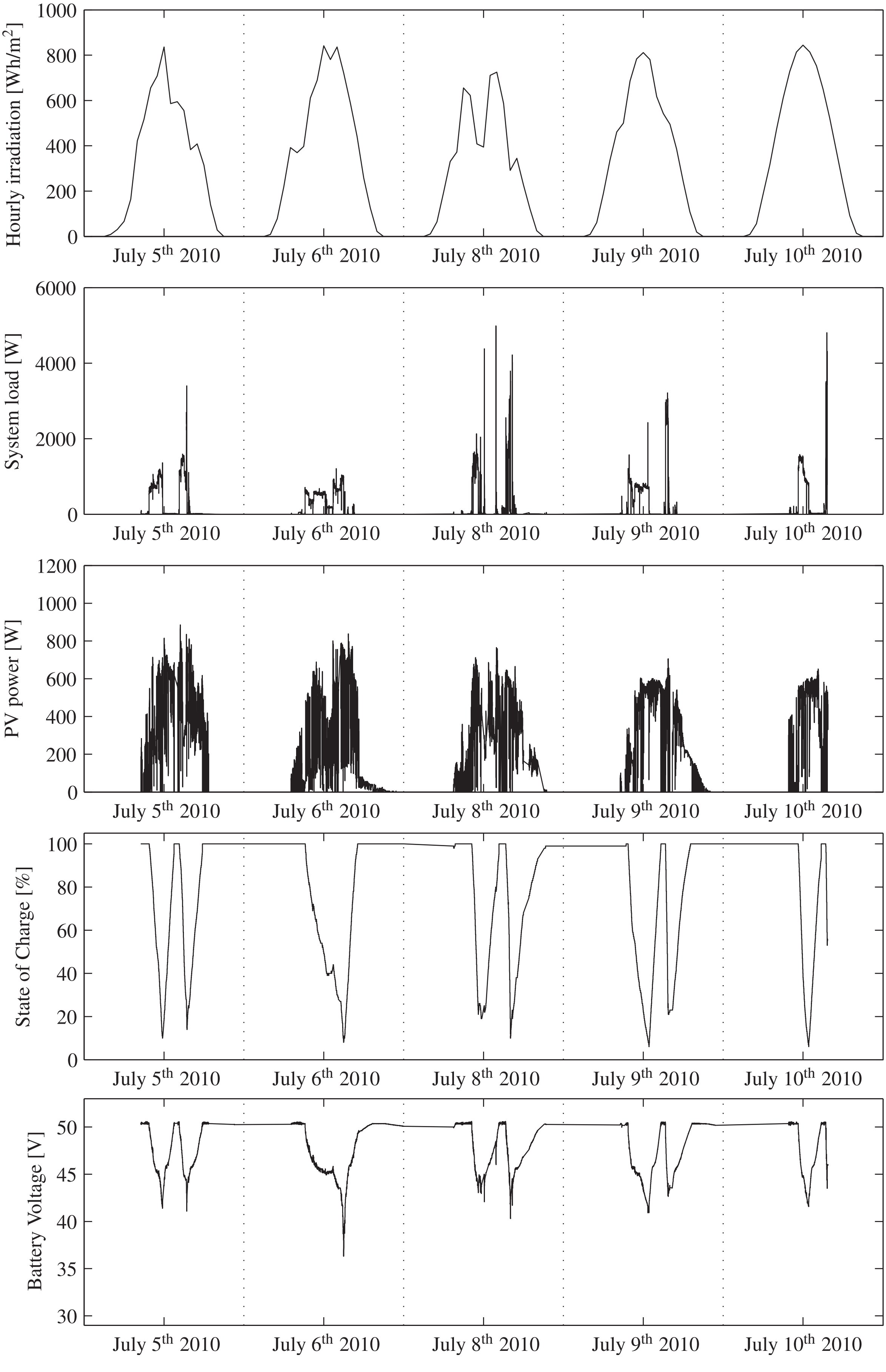


Figure 4.7: PV system data from the 2010 boat during various days in 2010.

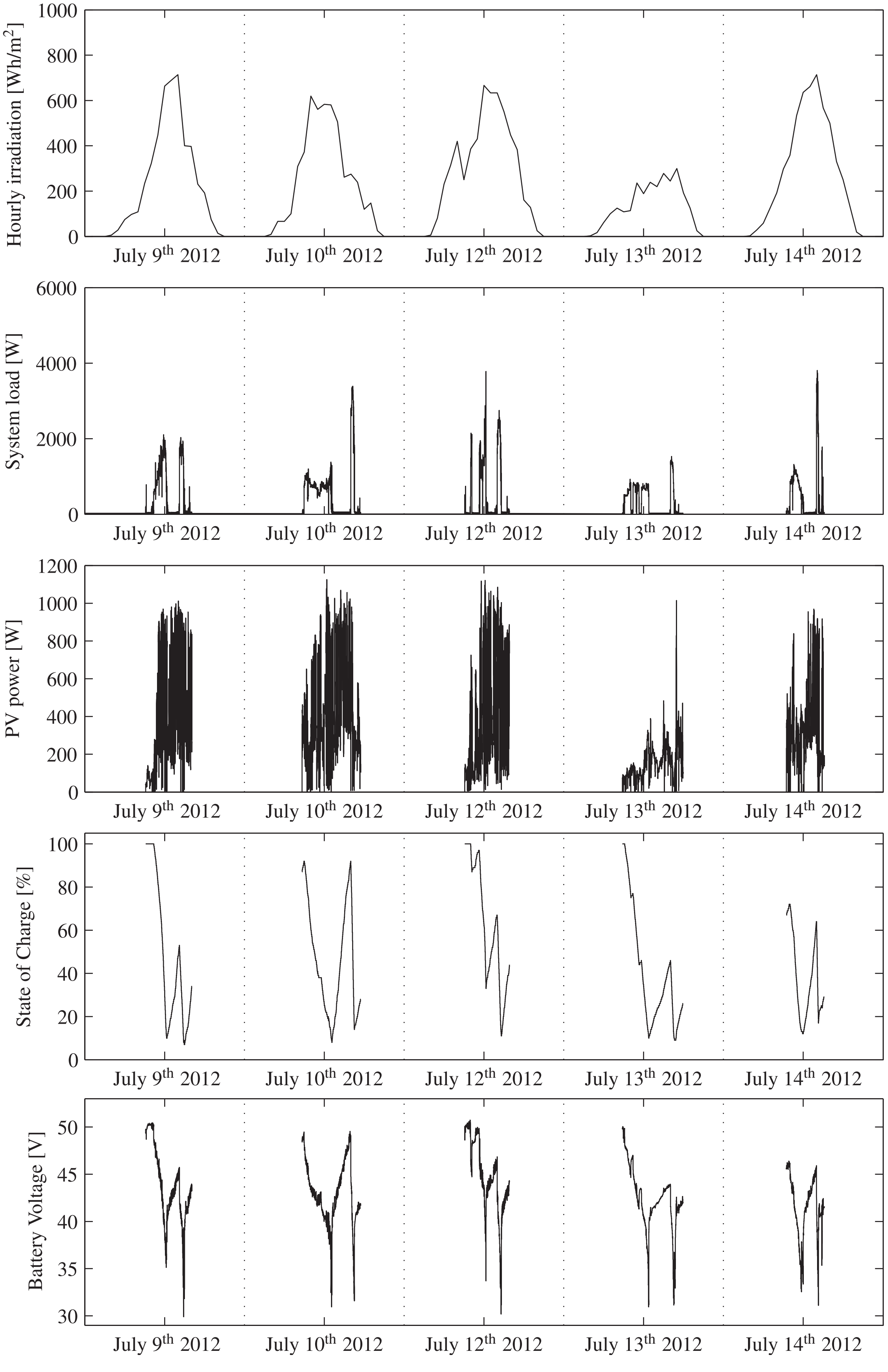


Figure 4.8: PV system data from the 2012 boat during various days in 2012.

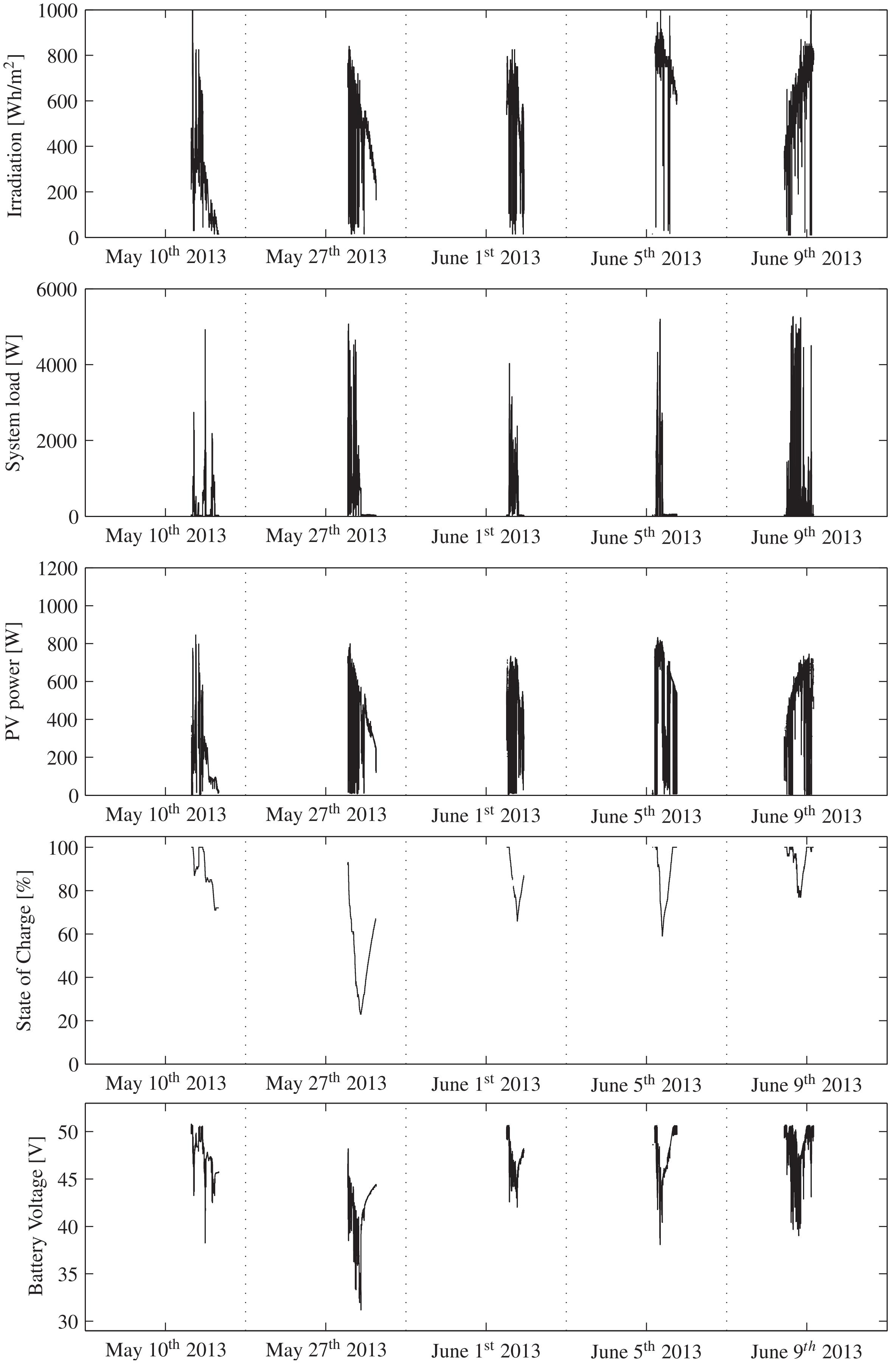


Figure 4.9: PV system data from the 2013 boat during various days in 2013.

Chapter 5

Design model and tool

Parts of this chapter have been published in the Proceedings of the 39th peer-reviewed IEEE Photovoltaic Specialists Conference, Tampa, Florida, USA, 2013. T. Gorter, E. Voerman, P. Joore, A. Reinders, and F. Van Houten, entitled 'Scenario-based simulation of PV boats in an early design stage'.

5.1 Introduction

This chapter describes the development of a *solar boat performance model* with which the performance of PV boats can be determined in an early design stage. The model is implemented in a tool, which is able to determine specific values for performance indicators of PV boats, see Section 2.4. This tool is developed as plug-in for Rhinoceros, a 3D modeling tool used by boat designers to design boats.

The aim of the solar boat performance model is to support boat designers in their PV boat designs. When the energy balance for a PV boat is known, values for performance indicators such as cost, speed and autonomy can be evaluated more easily and in an earlier stage of the design process. During the development of boats, accuracy of models and algorithms do not necessarily need to be very high. Sometimes rules of thumb are used to make fast design choices. One of the most important functions of a model is to get insight in the functioning of the product and the environmental variables acting on it. With models, simulations can be executed. The results from simulation can lead to adjustments to improve the conceptual design. Different methods with respect to simulation exist: firstly, simulations with models can be helpful to understand complex systems. Secondly, existing processes are simulated to keep the existing process under control. Finally, designs can be visualized and evaluated, before they are realized [61].

In order to answer the sub-research question 'Which models and their algorithms are needed to simulate the behavior of a PV boat', Section 5.2 describes the factors and models which influence the performance of a PV boat in real life, such as the irradiance and the hull resistance. Section 5.3 describes the mechanical and electrical system components and how they are related to each other with their models. Section 5.3 describes the implementation of the final model in C++, which resulted in a tool for Rhinoceros. The algorithms needed for a working model are explained in Section 5.4. This section holds all the irradiance and solar trajectory algorithms followed by the PV system models. Section 5.5 describes algorithms to determine the energy balance for PV boats such as the relationship between the available energy and the needed energy to cover distances.

Chapter 6 describes a case which has been used to validate the models used in the tool. Chapter 7 shows an example of the functionality of the tool described in this chapter.

5.2 PV boats

The energetic performance of a PV boat is influenced by four factors:

1. The irradiance.
2. The PV system.
3. The drive train.
4. The hydrodynamics of the boat.

The first three factors are illustrated in Figure 5.1. These four factors are needed to determine the energy balance for a PV boat. The efficiency of the PV system and drive train is dependent on system component choices.

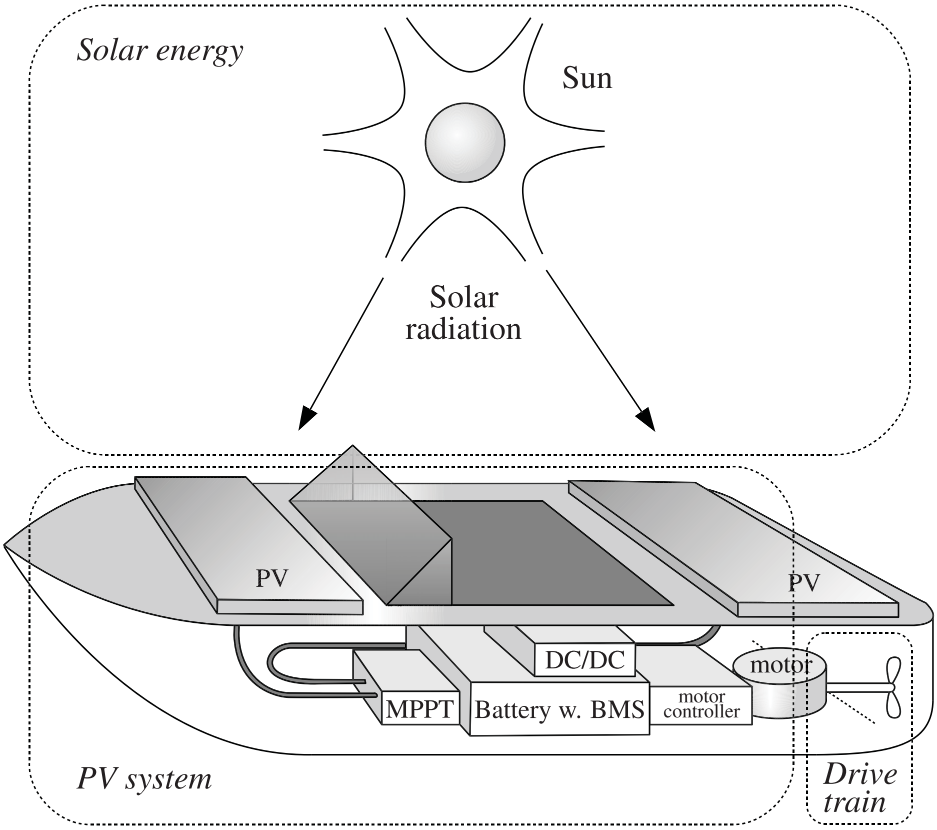


Figure 5.1: PV boat components.

Besides the physical properties of a PV boat as indicators for performance, the cost of a PV boat can also be an important indicator for PV boat performance. Cost of components does not have physical influence on a PV boat. However, a choice of a component, which is (partly) based on cost, might have physical influence on the PV boat. For example, cheaper lead-acid batteries most probably have a lower energy density compared to more expensive Li-Ion batteries. Such choices have influence on the weight of the batteries. Furthermore, it is expected that the success of a PV boat increases with a decrease of the PV boat's price.

Solar energy and PV system

The performance of the PV system determines how much solar energy is converted into electrical energy which can be used for propulsion or other electrical loads. Irradiance is converted into electrical power with PV modules. As a result, energy is then stored in batteries or used for propulsion. From the battery, power is converted with an MCU to drive an electrical motor.

Drive train

The performance of the drive train determines how much electrical power is converted into propulsion power (see Figure 5.1). A gearbox can be used to change the speed or the direction of the mechanical power from the electrical motor. The propeller is used to generate thrust to push the boat trough the water.

Hull resistance

The hull resistance is dependent on the hydrodynamic properties of the PV boat's hull. The hull resistance is an indicator for the amount of power needed to reach a certain speed.

Energy balance

The level of irradiance on the PV modules determines how much energy is eventually available for propulsion. The solar power goes through several conversion steps. Per conversion step, losses are involved.

5.3 PV boat modeling

Models can be made for the simulation of solar irradiation, the PV system, a drive train and the hydrodynamics. Models are representations of real life situations as described in Section 5.2. This section describes per component which approaches are needed to create a model for that component. Figure 5.2 shows a schematic overview of a PV boat and the components which need to be modeled. The validation of these models are discussed in Chapter 6.

5.3.1 Solar irradiation and PV system

The simulation of PV systems comprises various sub-models, such as irradiance and the weather, incident irradiance, reflection losses, PV module temperature, and so on. Two differences in PV systems can be identified. First, PV systems which are stationary, for example rooftop mounted PV systems and secondly, dynamic PV systems, for example as seen on PV boats.

The differences between stationary PV systems and dynamic PV systems require different modeling approaches. To simulate the power output of PV systems, four types of inputs can be used:

1. Ground point sensor irradiance data.
2. Comparable PV power plant output irradiance data.
3. Satellite irradiance data.
4. Location dependent synthesized irradiance data.

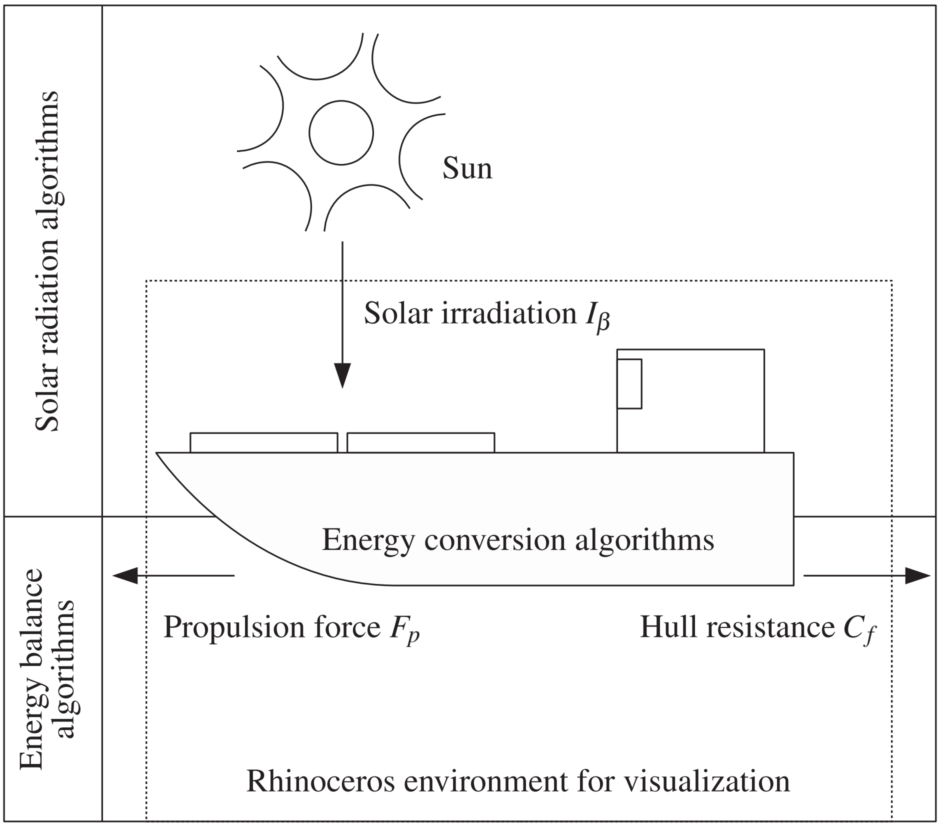


Figure 5.2: Model overview of a PV boat.

The latter is mostly a result from mathematical relations derived from the first three methods. In literature dynamic PV systems are usually of the sun tracking type.

The range of the monitoring interval among the first three sets of inputs vary between 1 second and 30 minutes [76]. These three types of input are based on empirical data and their accuracy depends on the accuracy of the monitoring setup. The first two methods of requiring solar irradiance data are more suitable for stationary systems. The last two methods for irradiance data use worldwide satellite data. These data contain high accuracy irradiance measurements and synthesized data based on mathematical relations for irradiance. As a result, they are more suitable for dynamic PV systems modeling, because they are less location dependent. An approach based on empirical satellite data or location independent synthesized data are as a result very suitable for the simulation of PV systems on PV boats.

Besides the simulation approach and which input is needed to achieve the desired results, a choice need to be made which performance indicators of simulation output are of interest. In the case of PV boats, the energy yield of the on-board PV system is of high interest. Outcomes from simulation can then be used to determine the cost of the PV system, which is also an important performance indicator, see Chapter 2.

Various tools exist to determine the yield of PV systems. Examples are the software packages Homer [77] or PVSyst [78]. These packages typically rely on the aformentioned approaches to simulate PV system output. For example, Homer is based on synthesized solar trajectory models from Reda and Andreas [79] and PVsyst relies on satellite datasets from Meteonorm [80]. With these packages, system cost and energy balance can be calculated for stationary PV systems in a high variety of configurations. However, these programs are more useful for calculating energy yields on a monthly or yearly basis, whereas energy yields for shorter periods, such as a couple of hours as described in Chapter 4, are of more interest for PV boats. Most approaches focus exclusively on the PV system components, which is suitable for stationary systems. However, PV systems can have impact on the performance of PV boats, see Chapters 2 and **??**.

A 3D-simulation tool for dynamic objects and the irradiance on that object is presented by Veldhuis and Reinders [81]. They demonstrated a Virtual Reality (VR) environment implemented in Quest3D[1] with which they simulate irradiance on moving objects using location dependent meteorological data. With this tool, energy yields of PV modules on stationary and moving objects can be simulated real time. They also demonstrated energy yield calculations on PV boats.

For PV boat developers, such a tool can be helpful to determine the energy yield and thus the energy balance of PV boats. However, the disadvantage of Quest3D is that it is relatively expensive and has a steep learning curve [82]. Furthermore, Quest3D is not a Computer Aided Design (CAD) environment and is therefore not a solution to combine CAD with PV simulation for PV boat developers.

5.3.2 Drive train

Drive trains have been described and modeled for various vehicles, of which most are conventional cars, electric cars and PV-powered cars. Shimizu et al. [83] researched PV cars demonstrating that a tuned speed and energy balance yields better performing PV cars. However, considerations regarding power and energy management were only conducted, after the car was built [83].

Hammad and Khatib [84] conclude that many iterations are required if the performance of a prototype PV vehicle is to be increased.

Other research has been presented which discusses the energy balance in aircraft. Xian-Zhong et al. [85] described the execution of simulations to support the design of PV-powered aircraft [85].

Basecq et al. [86] are working on models to determine the performance of electric boats and the impact of the drive train on that performance. Their research focuses mainly on the mechanical components and the losses therein. Implementation of PV in their model is also of importance, but not a key research factor [86].

Gillen and Barkow [87] are investigating the adaptation of automotive drive trains for use in boats. Their research focuses on how to decrease the cost for development of drive trains for boats with knowledge from the automotive industry [87].

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[1] Quest3D provides a real-time virtual reality framework which can be altered by users with very fast, high-end graphics.

5.3.3 Hydrodynamics

To determine the hydrodynamics of boats, a number of tools are available. The hydrodynamics of boats include various areas of interest, such as stability and hull resistance. ORCA is a plug-in for Rhinoceros which can perform basic calculations on a boat's hydrodynamics [88]. DELFTship is a tool developed by Delft University of Technology and can also perform basic calculations on hydrodynamics [89]. Another tool is Maxsurf [90]. The use of Computational Fluid Dynamics (CFD) is an upcoming technique to forecast the hydrodynamics of boats in water in their design stage. In this case, physical attributes such as dimensions and form of the boat are constant, which are then used to determine the hydrodynamics of boats [91, 92]. For example, with Friendship systems from Friendship Systems GmbH [93] hull shapes can be optimized with CFD calculations.

5.4 Implementation of the PV boat model

This section describes the algorithms which are needed to model a PV boat with solar radiation and energy balance. Boat designers in Friesland use the 3D modeling software package Rhinoceros [94] together with the ORCA Marine Design plug-in [88] to determine boat hydrodynamics in an early design stage. Rhinoceros is a NURBS[2] design software and offers support for plug-in development. It is relatively affordable compared to other 3D design software and it already has some support for boat designers in the form of plug-ins. However, Rhinoceros is not equipped with methods to determine the performance of PV boats in combination with solar energy. The models to determine the energy balance of PV boats have been implemented in C++. Rhinoceros has been used as interface for CAD and acts as Graphical User Interface (GUI) for the tool.

The tool is composed out of three key sets of functions and a set of files. The files contain generic models of PV system and drive train components and algorithms, see Figure 5.3. Specific components are then characterized with data from the files or by specific input from a user. *Interface* contains all the functions for menu structure and communications with Rhinoceros. *Functions* contains all the functions and models which are needed to execute simulations. *Solar module* contains all the functions to calculate solar trajectory data. A schematic of the organization of functions in the tool is illustrated in Figure 5.3.

The tool integrates in Rhinoceros with a menu item from which all functions can be accessed. Other inputs and outputs are entered and displayed with a Command Line Interface (CLI) in Rhinoceros. System component data, such as for PV modules, can be entered in independent files in a restricted format, see Section 5.4. In this way, components can be easily added or removed from the database, which is part of the tool in Rhinoceros.

5.4.1 Solar irradiation

Total solar irradiance is dependent on two key factors:

1. The location with its atmospheric conditions

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[2] NURBS stands for *Non-Uniform Rational B-Splines* and is a method to describe mathematically any geometry in 2D or 3D with high accuracy [95].

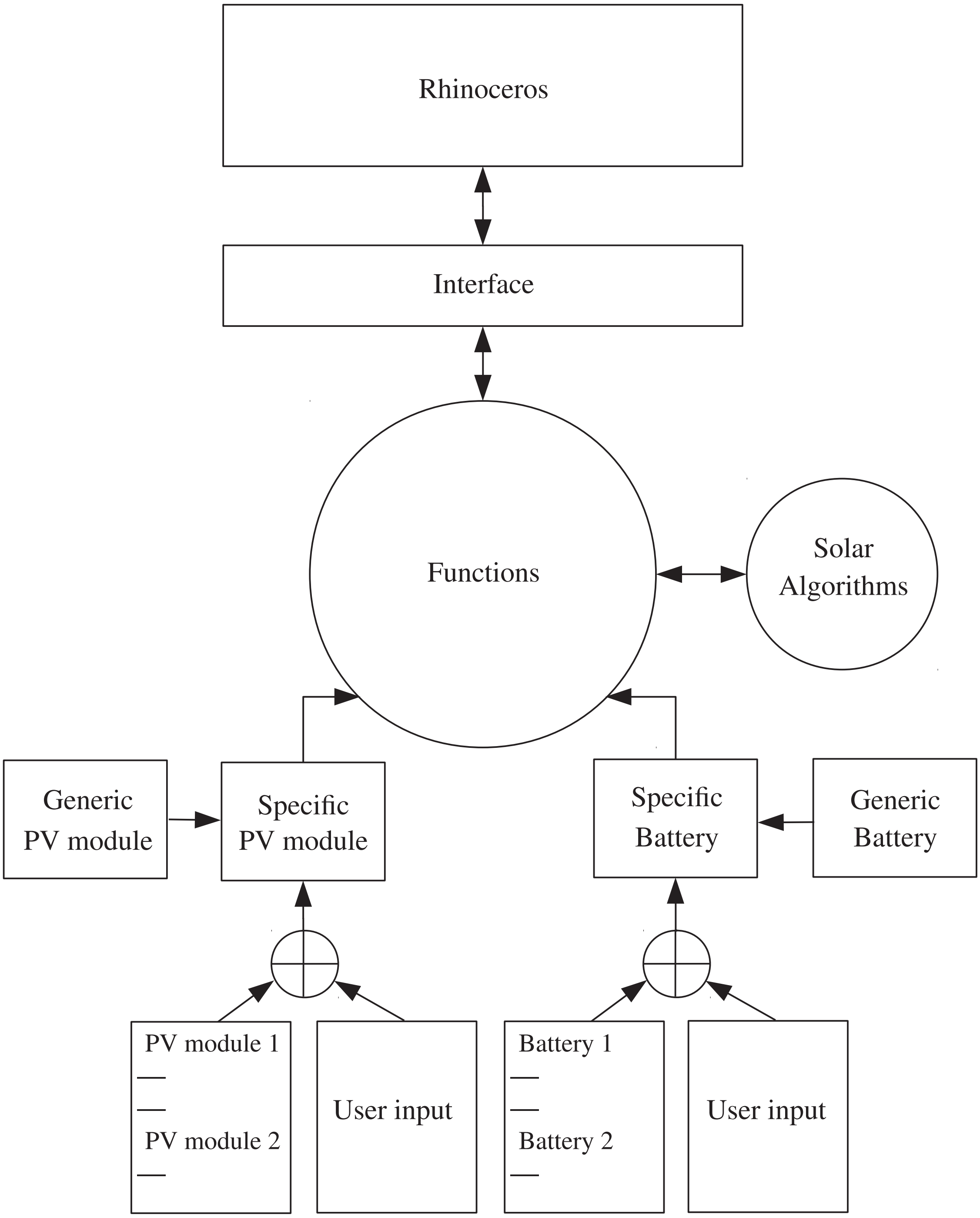


Figure 5.3: Organisation of functions implemented in tool.

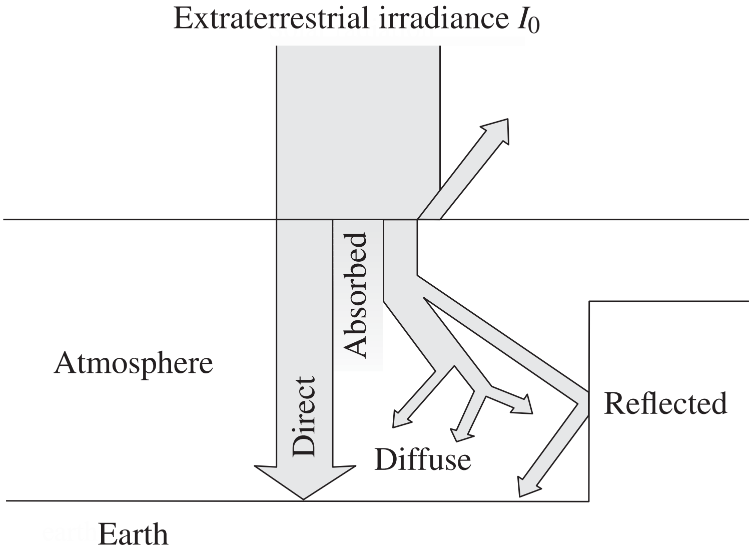


Figure 5.4: Effects of the atmosphere on solar radiation.

2. The time of day

Two approaches can be used to determine levels of irradiance at any location. The first approach is to use databases with irradiance information for every location. The second approach is the generation of synthesized data, based on physical attributes and location parameters. This section summarizes solar irradiation and solar trajectory algorithms to determine synthesized irradiance data, which depend on location and time. It is recommended to read the original work for a full explanation of the algorithms and models in these sections.

5.4.2 Irradiation on the surface of the earth

Irradiance I_β can be modeled as a 'plane' of sunlight [79, 80, 96]. It is composed out of three components and their relationship is shown in Equation 5.1:

$$I_\beta = I_{b,\beta} + I_{r,\beta} + I_{d,\beta} \tag{5.1}$$

With:

I_β = Total irradiance [W/m^2]
$I_{b,\beta}$ = Direct irradiance [W/m^2]
$I_{r,\beta}$ = Reflected irradiance [W/m^2]
$I_{d,\beta}$ = Diffuse irradiance [W/m^2] ($I_{d,\beta} = I_d \leftrightarrow \beta = 0$)

Direct extraterrestrial irradiance I_0 is considered to be 1367 W/m^2 [80]. When irradiation falls on the surface of the earth, it passes through the atmosphere which either absorbs, scatters or reflects parts of the extraterrestrial irradiance, see Figure 5.4.

Direct irradiance

Direct irradiance $I_{b,\beta}$ is the beam irradiance on a surface and is mainly dependent on the solar angle with respect to the surface and the absorbance of the atmosphere, through which the irradiance passes.

Direct irradiance on a horizontal or tilted surface is determined as follows [80, 97]:

$$I_{b,\beta} = I_0 \cdot \varepsilon \cdot \cos\beta \cdot e^{\left(-m \cdot 0.8662 \cdot T_L \cdot \delta_{Rayleigh}\right)} \tag{5.2}$$

With:

I_0 = Extraterrestrial irradiance [W/m^2] (I_0 = 1367 W/m^2)
ε = Correction factor of the actual solar distance at any specific time of the year [-]
β = Solar incidence angle [°]
m = Correction factor of the thickness of the atmosphere seen by the sun's rays [-]
T_L = Linke turbidity [-]
$\delta_{Rayleigh}$ = The Rayleigh optical thickness due to molecular scattering [m]

The solar incidence angle β can be determined as follows [79]:

$$\beta = \cos^{-1}\left(\cos\omega_{PV} \cdot \cos\omega_s + \sin\omega_{PV} \cdot \sin\omega_s \cdot \cos(\gamma_s - \gamma_{PV})\right) \tag{5.3}$$

With:

ω_{PV} = Slope of the PV module with respect to horizontal [°]
ω_s = A representation of time in angular degrees (24 h = 360°) [°]
γ_s = Position of the sun projected on a horizontal plane while facing north (clockwise) [°]
γ_{PV} = Direction the PV module is facing [°]

Reflected irradiance

Reflected irradiation $I_{r,\beta}$ is determined as follows [96]:

$$I_{r,\beta} = \frac{1}{2}\rho_w \cdot I_\beta \cdot (1 - \cos\omega_{PV}) \tag{5.4a}$$

With:

ρ_w = Albedo of water [-]

However, reflected irradiance $I_{r,\beta}$ is part of the total irradiance I_β, see Equation 5.1. Therefore, Equation 5.4a can be rewritten as such that $I_{r,\beta}$ is isolated and becomes a function of albedo ρ_w, direct irradiance $I_{b,\beta}$, diffuse irradiance $I_{d,\beta}$ and the tilt angle of the PV module ω_{PV}. This is shown in Equation 5.4b. The rewritten equation for reflected irradiation without the dependency on Irradiance I_β:

$$I_{r,\beta} = \frac{\rho_w (I_{b,\beta} + I_{d,\beta})(1 - \cos\omega_{PV})}{2 - \rho_w} \tag{5.4b}$$

Albedo

The albedo ρ_w of water changes according to the solar altitude hs, see Equation 5.4c. The estimate of the albedo value is less accurate near the equator (underestimate up to 50%) and near the pole (overestimate up to 24%) [98].

To determinate the albedo ρ_w for water, Equation 5.4c can be used [98]:

$$\rho_w = 50\left(\frac{\sin^2(hs - r)}{\sin^2(hs + r)} + \frac{\tan^2(hs - r)}{\tan^2(hs + r)}\right) \tag{5.4c}$$

With:

hs = Solar altitude angle [°]
r = Refraction angle of water [°]

The refraction angle for water is determined as follows:

$$r = \sin^{-1}\left(\frac{\sin hs}{n}\right) \tag{5.4d}$$

With:

n_w Refraction index of water: n_w = 1.33

Diffuse irradiance

To determine the diffuse irradiance I_d on a horizontal surface, the following equation can be used [80, 97]:

$$I_d = I_0 \cdot \varepsilon \cdot F_d(hs) \cdot T_{rd}(T_L^*) \tag{5.5}$$

With:

I_d = Horizontal diffuse irradiance [W/m^2]
$F_d(hs)$ = Correction factor for the diffuse zenith transmittance depending of hs [-]
$T_{rd}(T_L^*)$ = Diffuse transmittance function for transmittance with the sun at the zenith [-]

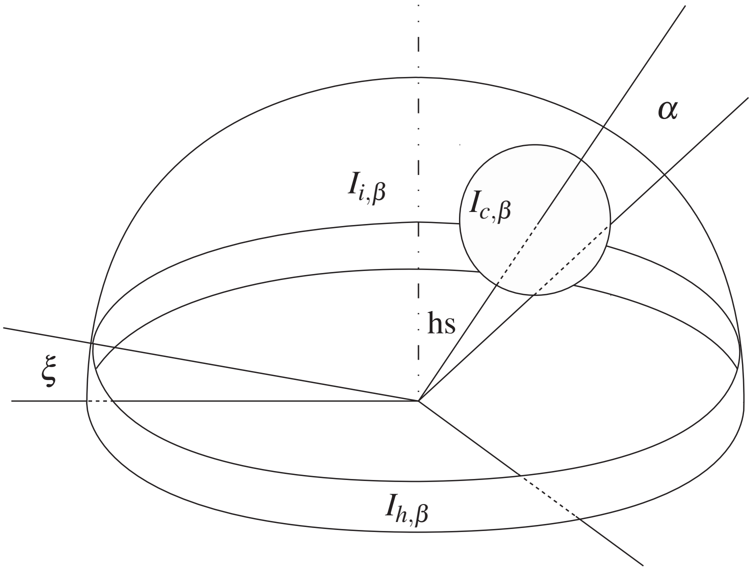


Figure 5.5: The three components to determine diffuse irradiation on tilted surfaces: the horizontal ribbon component $I_{h,\beta}$ parametrized with F_1, the circumsolar component $I_{c,\beta}$ parametrized with F_2 and Z and the isotropic component $I_{i,\beta}$, also parametrized with F_1.

Diffuse irradiance on tilted surfaces

Diffuse irradiance on tilted surfaces is different than on horizontal surfaces. However, Diffuse irradiance on tilted surfaces can be calculated if the diffuse irradiance on horizontal surfaces is known, see Equation 5.6. To calculate the diffuse irradiance on tilted surfaces (solar incidence angle $\beta \neq 0$), the Perez diffuse irradiation model can be used. Equations 5.1 to 5.7d show the chain of algorithms to calculate diffuse irradiance on tilted surfaces [80, 96, 97, 99]. The diffuse irradiance on tilted surfaces is parametrized with three components. First, the horizontal ribbon component $I_{h,\beta}$ parametrized with F_1. Second, the circumsolar component $I_{c,\beta}$ parametrized with F_2 and Z and third, the isotropic component $I_{i,\beta}$, also parametrized with F_1. These components are shown in Figure 5.5.

The relationship between the components of diffuse irradiation on tilted surfaces with respect to horizontal surfaces is as follows:

$$I_{d,\beta} = I_d \cdot \left(I_{i,\beta} + I_{c,\beta} + I_{h,\beta}\right) \tag{5.6}$$

With:

$I_{i,\beta}$ = Isotropic diffuse irradiance parameter [-]
$I_{c,\beta}$ = Circumsolar diffuse irradiance parameter [-]
$I_{h,\beta}$ = Horizontal diffuse irradiance parameter [-]

The isotropic parameter for diffuse irradiance is determined as follows [80, 100]:

$$I_{i,\beta} = (1 - F_1) \cdot \frac{1 + \cos\beta}{2} \tag{5.7a}$$

With:

F_1 = Parameter for circumsolar irradiance [-]

The circumsolar parameter for diffuse irradiance $I_{c,\beta}$ is determined as follows [80, 100]:

$$I_{c,\beta} = F_1 \cdot \frac{a}{b} \tag{5.7b}$$

$$\begin{aligned} a &= \begin{cases} \cos\beta & \text{if } \cos\beta \geq 0 \\ 0 & \text{if } \cos\beta < 0 \end{cases} \\ b &= \begin{cases} \cos Z & \text{if } \cos Z \geq 0.087 \\ 0.087 & \text{if } \cos Z < 0.087 \end{cases} \end{aligned} \tag{5.7c}$$

The horizontal ribbon parameter for diffuse irradiance $I_{h,\beta}$ is determined as follows [80, 100]:

$$I_{h,\beta} = F_2 \cdot \sin\beta \tag{5.7d}$$

With:

F_2 = Parameter for horizontal ribbon irradiance [-]

The parameters F_1, F_2 and Z are explained in detail by Perez et al. [101]. The error with the Perez diffuse model for tilted surfaces can be relatively large: up to 33%. This depends on environment and location, but it shows, compared to other models, relative good results [96].

Linke Turbidity

Horizontal diffuse irradiance I_d depends on turbidity in the atmosphere (see Equation 5.5). This turbidity is caused by particles varying in size and particle density. These particles in the atmosphere can have several origins, such as natural occurring water vapor but also emissions from industrialized regions. A measure for the amount of turbidity is the Linke turbidity (TL) factor. These TL factors are measured worldwide and TL data per location can be found in literature (from for example Meteonorm [80], Remund et al. [97, 102]). TL data are composed out of measured and averaged data in grids with a size of 280 km × 280 km on the equator and smaller towards the poles. Figure 5.6 shows an example of worldwide TL data for the month of August. A TL value of 1 indicates a clear sky. A TL value of 7 indicates a sky with low transmittance [80, 102].

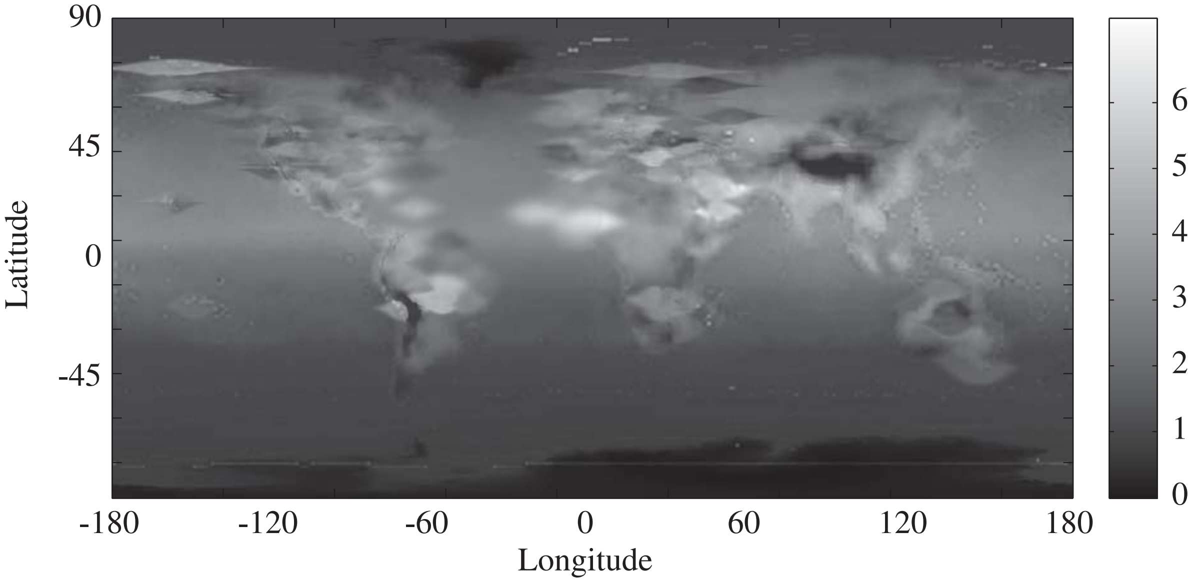


Figure 5.6: TLvalues for the month of August.

The chain of algorithms to determine the corrected TL factor for pressure and altitude:

$$
\begin{aligned}
T_L^* &= \frac{p_h}{p_0} \cdot T_L \\
A_0 &= 0.26463 - 0.061581 \cdot T_L^* + 0.0031408 \cdot T_L^{*2} \\
A_1 &= 2.04020 + 0.018945 \cdot T_L^* - 0.011161 \cdot T_L^{*2} \\
A_2 &= -1.33025 + 0.03231 \cdot T_L^* - 0.0085079 \cdot T_L^{*2} \\
F_d(hs) &= A_0 + A_1 \cdot \sin hs + A_2 \cdot \sin^2 hs \\
T_{rd}(T_L^*) &= -1.5843 \cdot 0.01 + 3.0543 \cdot 0.01 \cdot T_L^* + 3.797 \cdot 0.0001 \cdot T_L^{*2}
\end{aligned}
\tag{5.8}
$$

With:

p_h = Atmospheric pressure at altitude h [Pa]
p_0 = Atmospheric pressure at sea level [Pa]

5.4.3 Solar trajectory

In order to determine the irradiance per location, the solar trajectory needs to be modeled. Solar trajectory models from Reda and Andreas [79] and Meteonorm [80] calculate the sun's position with respect to any location on earth with a maximum error of 0.2° [79, 80, 103]. When the relative position of the sun compared to the point $P_{boat}(t)$ is known, the incidence angle β of the sun's rays on any (tilted) surface can be determined (Equation 5.3). This is illustrated in Figure 5.7. Since a PV boat changes its location in time, the time index t is appended to the symbols which values are time dependent.

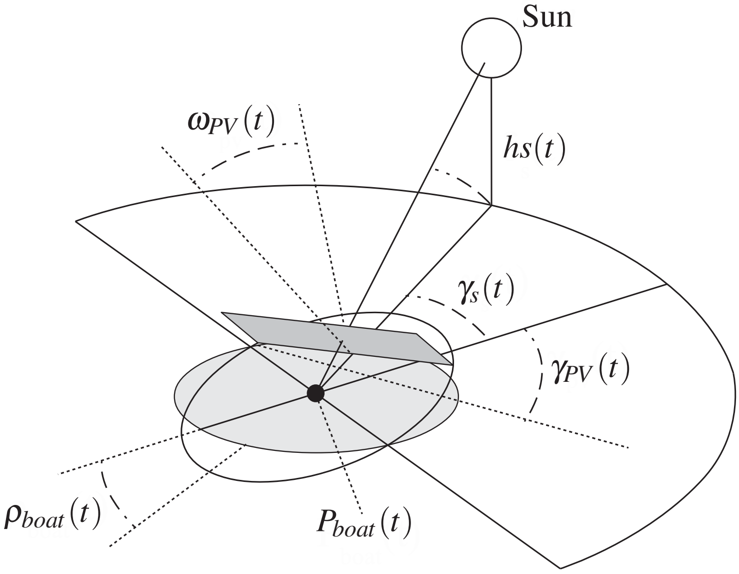


Figure 5.7: The sun's position with respect to the dynamic position of a PV boat P_{boat} on the surface of the earth.

The position of the sun with respect to any point on earth for a specific time can be described with the solar altitude $hs(t)$ and the solar azimuth angle $\gamma_s(t)$. The position of the PV boat $P_{boat}(t)$ is described with the latitude $\lambda(t)$ and the longitude $\phi(t)$. Another factor which can be accounted for is the rolling and pitching behavior of the boat $\rho_{boat}(t)$. Since rolling and pitching goes in both ways, the net result of rolling and pitching will be zero, ruling this variable out [46]. For clarity, the algorithms described in this section are written in the general form, without the time index t. The solar altitude hs is an angle which describes the elevation of the sun seen from the position P_{boat} [80]:

$$hs = \sin^{-1}\left(\sin\phi\sin\delta_s + \cos\phi\cos\delta_s\cos\omega_s\right) \tag{5.9}$$

With:

ϕ = Longitude of the PV boat's position [°]
δ_s= Angle of the sun with respect to the equatorial plane [°]

The solar declination angle δ_s describes the tilt of the earth projected on the celestial sphere. In summer, δ_s is 23.4° [80, 103]:

$$\begin{aligned}\delta_s = {} & 0.0064979 + \\ & 0.4059060 \cdot \sin\omega_t + 0.0020054 \cdot \sin(2\omega_t) - \\ & 0.0029880 \cdot \sin(3\omega_t) - 0.0132296 \cdot \cos\omega_t + \\ & 0.0063809 \cdot \cos(2\omega_t) + 0.0003508 \cdot \cos(3\omega_t)\end{aligned} \tag{5.10a}$$

With:

ω_t = Day and year dependency on solar time [°]

ω_t is calculated as follows [80]:

$$\begin{aligned}\omega_t &= \omega_0(DoY + t_1) \\ \omega_0 &= \frac{2\pi}{365.3422} \\ t_1 &= -0.5 - \frac{\lambda}{2\pi} - n_0 \\ n_0 &= 78.8946 + 0.2422(y - 1957) - \left\lfloor \frac{y - 1957}{4} \right\rfloor\end{aligned} \tag{5.10b}$$

With:

DoY = Day of year
y = Year

The hourly angle ω_s describes in which 'timezone' the point P_{boat} is [80]:

$$\omega_s = \cos^{-1}\left(-\tan\phi \tan\delta_s\right) \tag{5.11}$$

The solar azimuth angle γ_s describes the position of the sun projected on a horizontal plane. This angle is negative when seen from the southern hemisphere [79]:

$$\gamma_s = 2\tan^{-1}\left(\frac{\sin\omega_s}{\sqrt{\left(\cos\omega_s \sin\phi - \tan\delta_s \cos\phi\right)^2 + \sin\omega_s^2} + \cos\omega_s \sin\phi - \tan\delta_s \cos\phi}\right) \tag{5.12}$$

Optical air mass

Optical air mass m is the thickness of the atmosphere seen from the sun with respect to a location on earth. When the sun is perpendicular to a horizontal surface on the earth, then $m = 1$ at sea level. Near sunset and sunrise, m is much larger than 1. With increasing altitude, m can be smaller than 1. This is illustrated in Figure 5.8.

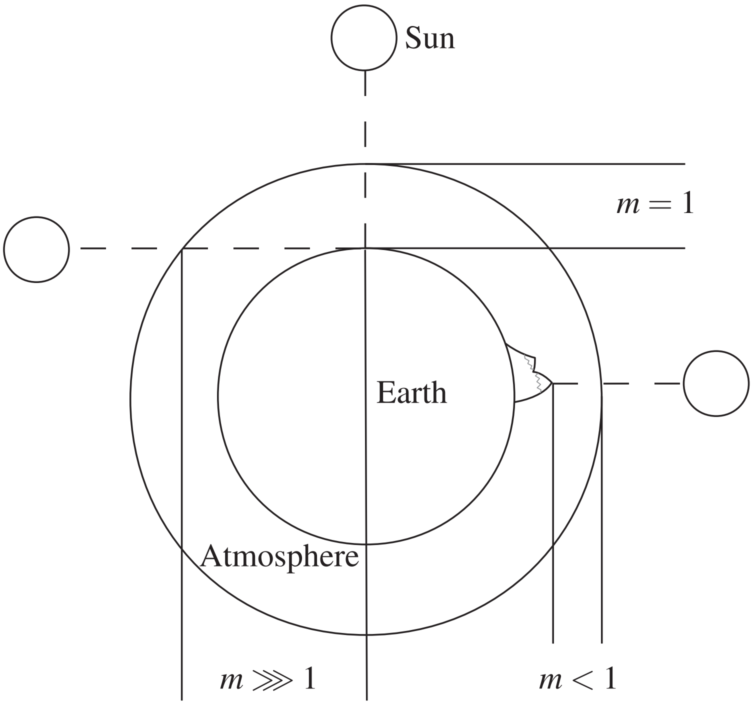


Figure 5.8: Various examples of the optical air mass value.

The optical airmass m can be determined as follows [80, 97]:

$$m = \frac{p}{p_0} \cdot \frac{1}{\sin hs_t + 0.50572(57.29578hs_t + 6.07995)^{-1.6364}} \tag{5.13a}$$

With:

$hs_t >=$ Solar altitude hs corrected for the refraction index of the atmosphere [°]

The corrected solar altitude angle hs_t accounts for the refraction index of the atmosphere [80]:

$$hs_t = hs + 0.061359 \cdot \frac{0.1594 + 1.1230hs + 0.065656hs^2}{1 + 28.9344hs + 277.3971hs^2} \tag{5.13b}$$

Rayleigh optical thickness $\delta_{Rayleigh}$ is a measure of the absorbance of radiation by particles in the atmosphere [97]:

$$\delta_{Rayleigh} = p_c \cdot \begin{bmatrix} 6.625928 + \\ 1.929690 \cdot m_0 - \\ 0.170073 \cdot m_0^2 + \\ 0.011517 \cdot m_0^3 - \\ 0.000285 \cdot m_0^4 \end{bmatrix}^{-1} \tag{5.14}$$

With:

P_c = A factor to correct the pressure p_h for increasing altitude [-]

The real solar angle ε corrects for the actual solar distance at any time in the year [80]:

$$\varepsilon = 1 + 0.0334 \cos\left(DoY \cdot \frac{2\pi}{365.25} - 0.048869 \right) \tag{5.15}$$

5.4.4 PV system

The PV system is a chain of components which transfer power from the PV modules to the electrical motor. Each component has losses, but all of them are necessary for the power conversion process.

PV modules

This section describes the chain of algorithms which are needed to calculate an IV-curve for an arbitrary PV module with high accuracy. An IV-curve is a representation of the behavior of one or more PV cells under various conditions, such as varying irradiance or temperature. An IV-curve shows the range of currents with respect to the voltage domain, which is usually between 0 and V_{max}. Values within this range are dependent on the load connected to the PV module. IV-curves can be simulated by using the one-diode-equation-model as presented by Phang et al. [104]. Phang et al. report that this one-diode-equation-model shows over 95% accuracy for almost all PV modules. A fast approximation using the Newton-Raphson method to solve the one-diode-equation is described by González-Longatt [105].

The parameters for the one-diode-equation are determined by the parameters of PV modules, such as open circuit voltage V_{oc} and short circuit current I_{sc}. An example of IV-curves for a PV module under different insolation conditions, is shown in Figure 5.9. The IV-curves as shown in Figure 5.9 are determined with the one-diode-equation-model and the Newton-Raphson method in Equation 5.17.

Every PV module is characterized with parameters which can be applied to the one-diode-equation model:

- Open circuit voltage V_{oc} [V].
- Short circuit current I_{sc} [A].
- Irradiance I_β [W/m^2].
- PV module temperature T_1 [K].
- Thermal coefficient k_0 [-].
- The amount of cells in series n_c [$n_c \in \mathbb{Z}_0^+$].

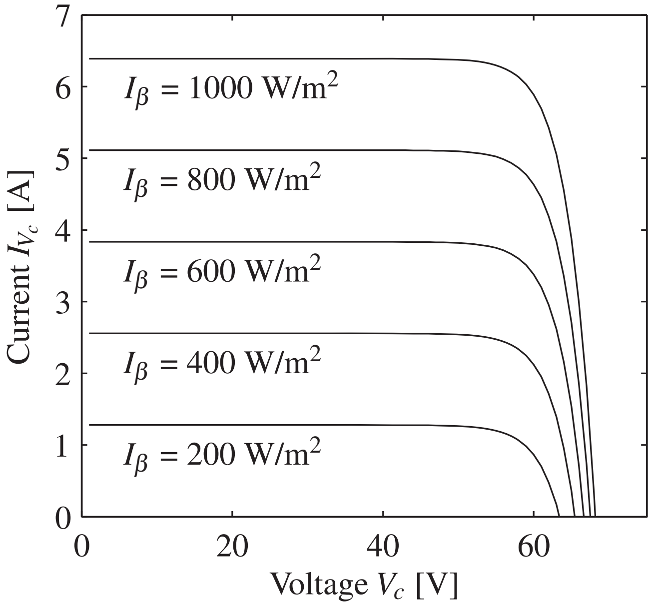


Figure 5.9: Examples of IV-curves for a PV module with different irradiances I_β determined with the one-diode-equation model from Phang et al..

Calculation of IV-curves with the one-diode-equation-model:

$$
\begin{aligned}
V_{oc,T1} &= \frac{V_{oc}}{n_c} \\
T_aK &= 273 + T_aC \\
I_{L,T1} &= I_{sc} \cdot n_s \\
I_{0,T1} &= \frac{I_{sc}}{e^{\left(q \cdot \frac{V_{oc,T1}}{F_n \cdot k \cdot T_1}\right)} - 1} \\
I_S &= I_{0,T1} \cdot \left(\frac{T_aK}{T_1}\right)^{\frac{3}{F_n}} \cdot e^{\left(-q \cdot \frac{V_g}{F_n \cdot k} \cdot \frac{1}{T_aK} - \frac{1}{T_1}\right)} \\
X_v &= I_{0,T1} \cdot \frac{q}{F_n \cdot k \cdot T_1} \cdot e^{\left(q \cdot \frac{V_{oc,T1}}{F_n \cdot k \cdot T_1}\right)} \\
R_s &= -\frac{1}{2} \cdot \frac{1}{n_c} - \frac{1}{X_v} \\
V_T &= F_n \cdot k \cdot \frac{T_aK}{q} \\
V_c &= \frac{V_m}{n_c} \\
I_{V_c} &\overset{\substack{\text{Newton} \\ \text{Raphson}}}{=} I_{V_c} - \frac{I_L - I_{V_c} - I_S \cdot exp\left(\frac{V_c + I_{V_c} \cdot R_s}{V_T} - 1\right)}{-1 - I_S \cdot exp\left(\frac{V_c + I_{V_c} \cdot R_s}{V_T} - 1\right) \cdot \frac{R_s}{V_T}}
\end{aligned}
\tag{5.16}
$$

With:

$V_{oc,T1}$ = Open circuit voltage for one cell with temperature [V]
V_{oc} = Open circuit Voltage [V]
n_c = Number of cells in series
T_aK = Ambient temperature [K]
T_aC = Ambient temperature [°C]
$I_{L,T1}$ = Temperature dependence of the photo current of one cell [A]
I_{sc} = Short circuit current [A]
n_s = Number of suns (1 sun = 1000 W/m^2)
$I_{0,T1}$ = Diode saturation current for one cell at 25°C [A]
q = Electron charge constant ($1.602 \cdot 10^{-19}$) [C]
F_n = Diode quality factor (Values between 1 and 2. Value used in model: 1.2) [-]
k = Boltzman's constant ($1.380 \cdot 10^{-23}$) [J/K]
T_1 = Cell temperature [K]
I_S = Diode saturation current [A]
V_g = Bandgap Voltage (*e.g 1.12 eV for c-Si, 1.75 eV for a-Si*) [V]
Xv = *Intermediate value*
Rs = Module series resistance [Ω]
V_T = Thermal Voltage [V]
V_c = Cell Voltage as variable to determine cell current ($0 \leqq V_c \leqq V_{oc}$) [V]
k_0 = Temperature coefficient
V_m = Module Voltage [V]
I_{V_c} = Cell current with respect to cell Voltage [A]
I_L = Temperature dependence of the photo current

5.4.5 Tilted PV on a PV boat

In order to determine the heading of a PV boat, longitude and latitude data can be used. Knowledge of the heading of the boat is of interest, since tilted PV modules will change their orientation when the boat is maneuvering. This does not apply to horizontally oriented PV modules, see Figure 5.7. When data are available for relatively small regions in which the boat sails, the heading of a boat can be determined with the direction vector from a current longitude and latitude position (ϕ_t,λ_t) and a previous longitude and latitude position ($\phi_{(t-1)}$,$\lambda_{(t-1)}$).

The heading αP_{boat} of a boat is a 2 dimensional problem when viewed from above. Therefore, the heading of the boat is the angle of a vector between two coordinates in the domain 0 to 2π. First, the difference between the current position and the old position needs to be calculated with respect to the longitude ϕ and latitude λ:

$$\begin{aligned} \Delta\phi &= \phi_t - \phi_{(t-1)} \\ \Delta\lambda &= \lambda_t - \lambda_{(t-1)} \qquad (5.17) \end{aligned}$$

(5.18)

By using Equation 5.18, the result is in the domain 0 to π. This leads to two distinctive cases for the vector of the longitude and latitude (ϕ, λ) with respect to the sign of ϕ and latitude $\Delta\lambda \neq 0$. Since all solar trajectory calculations depends on Euler angles, the heading αP_{boat} can be calculated as follows when considering the following two cases:

$$\alpha P_{boat} = \begin{cases} \tan^{-1}(\Delta\phi/\Delta\lambda) & \Delta\phi \geq 0 \;\&\; \Delta\lambda \neq 0 \\ \tan^{-1}(\Delta\phi/\Delta\lambda) + \pi & \Delta\phi < 0 \;\&\; \Delta\lambda \neq 0 \end{cases} \tag{5.19}$$

Batteries

To calculate the power input and output of energy storages, a value representing an energy capacity can be used, together with a value for losses in the charging and discharging process. This is accurate for low power consumption situations, but when power demand increases from batteries, battery capacity can decrease momentarily down to 60% of the nominal capacity [19, 35, 106].

Converters

Maximum powerpoint trackers
For PV power calculations, it is assumed that every PV module works in its MPP with a constant efficiency value.

Motorcontrollers
MCUs, which are basically systems for power conversion, have not been modeled yet. So it is assumed that power conversion efficiency has a constant value as well.

Losses in the DC/DC conversion systems are in general not significant to the output of the PV systems and a constant efficiency such as 0.99 is appropriate for modeling [76].

5.4.6 Physical properties of the PV system components

Besides the electrical properties of the PV system components such as power conversion efficiencies, the physical properties of the components are also important for modeling and simulations. Examples of physical properties of components are dimensions and weights. Figure 5.10 and Table 5.1 show an example of a battery and its parameters.

5.4.7 Drive train

The drive train is the part of the PV boat from the electrical motor to the propeller. Usually, the drive train consist out two shafts, couplings and a gearbox. And finally a propeller is connected to a shaft. The efficiencies in the drive train are modeled as constant values.

Figure 5.10: Example battery pack [66].

Table 5.1: Example values.

Property	value
Length [mm]	285
Width [mm]	104
Height [mm]	150
Nominal capacity [Wh]	1000
Charge efficiency [%]	92
Price [€]	3000

5.4.8 Hydrodynamics

For water displacement hulls, the resistance which is proportional to the speed of the boat, can be estimated with Equation 5.20. The correction factor k_{C_f} depends on various factors, such as the hull roughness. The range for k_{C_f} is usually between 0 and 0.2 [86]

$$R_f = 500 \cdot S \cdot v^2 \cdot C_f(1 + k_{C_f}) \tag{5.20}$$

With:

S = Wet hull surface area [m^2]
k_{C_f} = Correction factor for hull resistance [-]
C_f = Constant for hull resistance [-]

C_f can be calculated as follows:

$$C_f = \frac{0.075}{\log_{10}(\mathrm{Re} - 2)^2} \tag{5.21}$$

With:

Re = The Reynolds number [-]

The Reynolds number can be calculated with Equation 5.22:

$$\mathrm{Re} = \frac{10^6 \cdot v \cdot L}{\nu} \tag{5.22}$$

With:

L = The hull length at the water line [m]
ν = Kinematic viscosity [m^2/s]

Calculations on boat hulls depend on many empirical relations. For water displacement hulls, the error can be larger than 10% [86]. After a boat hull is designed in Rhinoceros, finding the correct empirical data and methods to determine the hull's hydrodynamics is time consuming and difficult. However, the ORCA plug-in allows calculation of hull parameters, such as stability and frictional losses, within Rhinoceros.

Figure 5.11 shows examples of output generated by ORCA on 3 different boat hulls: displacement hull, (semi-)planing hull and a hydrofoiling boat. The results from ORCA are relationships between the power which is needed to reach that speed. The relationship between power and speed is given in Equation 4.2.

Other hull types, such as (semi-)planing hulls and hydrofoiling boats, do not follow the relationship shown in Equation 4.2. This is illustrated in Figure 5.11. Although this relationship simplifies calculations of the energy balance for water displacing boats, it is not required for these calculations. An array with values for power P_v with every speed v is sufficient to do energy balance calculations. Between values of P_v, an estimation of speeds in between can be done with linear interpolation.

5.5 Energy balance

This section describes the equations used to determine the energy balance of PV boats. The equations discussed in this section, depend strongly on equations described in Sections 5.4.1 to 5.4.8. The determination of the energy balance can result in values for a number of performance indicators, such as the average speed a boat can sail over a certain distance. To determine the energy balance, three major influences can be identified:

- The available energy for sailing $E_{in,\tau}$ which is a summation of the PV energy $E_{A,\tau}$ and the battery energy $E_{FSN,\tau}$, see Equation 5.23.
- Energy need for loads E_L.
- Distance D.

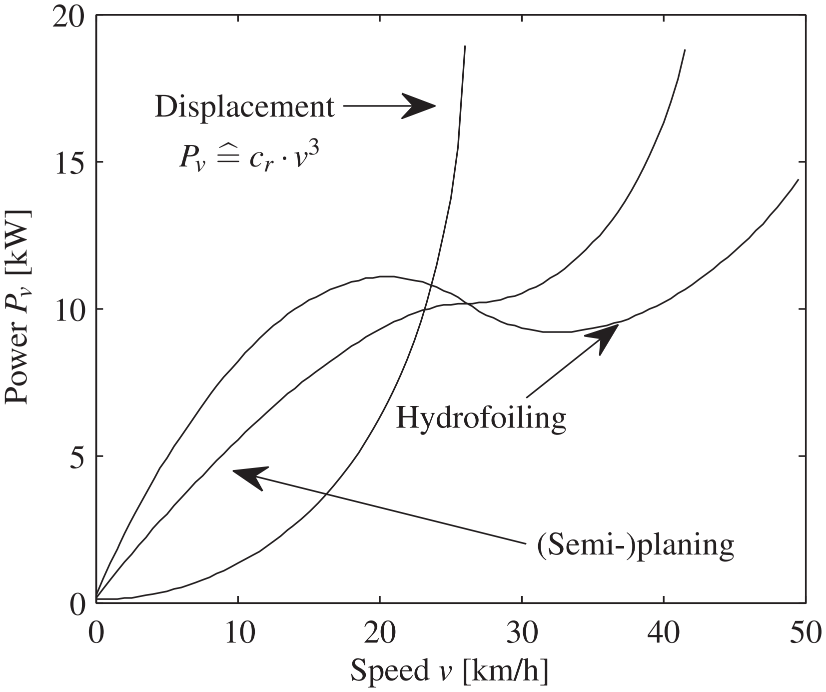


Figure 5.11: Generic examples of different hull shapes and their power-speed relationship.

The available energy for sailing $E_{in,\tau}$ can be calculated as follows:

$$E_{in,\tau} = E_{A,\tau} + E_{FSN,\tau} \tag{5.23}$$

With:

$E_{in,\tau}$ = Available energy [Wh]
$E_{FSN,\tau}$ = Energy from batteries [Wh]

During a simulation, energy from PV modules $E_{A,\tau}$ can be determined with Equation 4.4. This is the same approach to determine the energy yield of PV modules from monitored data with a monitoring interval τ_r [69]. The relationship between the ingoing and outgoing energy for a PV boat with constant speed v and with varying speed $v(t)$ is given in Equation 5.19. The power needed for the propulsion and HEP loads can be determined with equation 5.24.

$$P_L = P_v + P_{HEP} \tag{5.24}$$

With:

P_L = Power for loads [W]

P_{HEP} = Hotel electric power [W]

The relationship for the distance a PV-powered water displacing boat can travel is described with Equation 4.3. If the distance is considered constant and the speed which the PV boat can sail or how much energy is needed to sail with a certain speed to reach a distance is to be calculated, three new equations can be derived. This results in Equations 5.25a to 5.25c.

$$\frac{E_L}{\Delta t} \mathrel{\widehat{=}} C_f \cdot v^3 \tag{5.25a}$$

With:

E_L = Energy for loads [Wh]
C_f = Constant describing the hull resistance [-]

With substitution of Δt with D/v, two new equations can be formed. First, to calculate the energy need E_L with respect to the distance D and the speed v:

$$E_L \mathrel{\widehat{=}} D \cdot C_f \cdot v^2 \tag{5.25b}$$

To calculate the speed v with respect to the available energy E_L and the distance D:

$$v \mathrel{\widehat{=}} \sqrt{\frac{E_L}{D \cdot C_f}} \tag{5.25c}$$

These general equations do not apply to PV boats which sail with varying speeds. To determine the energy balance for boats with varying speeds, a sailing profile or a sailing scenario as input can be used to determine the energy balance.

5.6 Discussion and conclusions

Experts are able to ‘predict’ the performance of boats, even equipped with PV, at forehand based on experience. With the models proposed in this chapter, the limits of use of PV power on boats can now be proven mathematically. However, these limits depend on many parameters, such as the choice of hull, the water displacement, the speed of which the boat is designed for and what speed is sailed, the amount of irradiation, the health of the batteries and so on. It will therefore not give one value for a boat which is able to sail 100% on PV. However, predictions can be made for various scenarios if 100% sailing is feasible or if measures need to be made to equip the boat with auxiliary power from for example diesel generators.

Solar trajectory algorithms were used, which have a maximum error of 0.2°. By using the Perez diffuse irradiation model, diffuse irradiation on tilted PV modules can be estimated, however the Perez diffuse irradiation model for tilted surfaces can have a relative large error up to 33%, depending on the location and environmental circumstances.

An alternative albedo ρ fit for water surroundings is used to determine the reflectance on PV modules which are in a water environment. In the simulations, an ambient temperature of 20°C and a wind speed of 1 m/s were assumed.

PV modules in this tool are described with a model from Phang et al. which shows an accuracy of 95%.

Batteries might show low accuracy, when high power is demanded from the battery. For the case of PV boats, power demand can occasionally be high, as seen in previous research [19, 35].

Not all electrical and mechanical components are integrated in this model yet. Reliable models for PV modules and the solar positions are integrated. However, reliable generic models for battery packs and other electrical components have not been used yet. These components which are not modeled in detail, are considered as a source of losses which is proportional of percentage loss. The same is the case for mechanical losses, such as seen in the drive train.

To determine the hull resistance for a boat model, ORCA can be used. However, the error in the results from the hydrodynamic calculations is unknown. Furthermore, it is likely that the error can be different for different boat hulls.

A more in-depth research into various models to determine the hull's hydrodynamics should be done, since a number of experts working in the field of CAD boat design do not share a common opinion on which tool fits best purpose or shows best results to determine a boat's hydrodynamics.

Chapter 6

Model validation

6.1 Introduction

The models described in Chapter 5 are validated using experimental data. These data were collected on five days in 2013. The method of validation is described in Section 6.2. This section also describes the inputs which were used for validation. The results are presented in Section 6.3.

6.2 Model validation

The boat from 2012 has been modeled and simulated with the models described in Chapter 5 which resembles the existing boat as described in Section 4.2 which was built in 2012. The monitoring setup of the boat is described in Figure 4.4. As input in the model, parts of data which resulted from monitoring on five different days were used, see Chapter 4. The following parameters have been monitored during the five days:

- Timestamp t_i [h].
- Battery Voltage $V(t_i)_{bat}$ [V].
- Battery current in $I(t_i)_{bat_{in}}$ [A].
- Battery Current out $I(t_i)_{bat_{out}}$ [A].
- State of Charge [%].
- Battery temperature $T(t_i)_{bat}$ [°C].
- longitude $\phi(t_i)$ [°].
- lattitude $\lambda(t_i)$ [°].
- Speed $v(t_i)$ [km/h].
- MPPT Voltage $V(t_i)_{MPPT}$ [V].
- MPPT current $I(t_i)_{MPPT}$ [A].
- PV module Temperature $T(t_i)_{PV}$ [°C].
- Irradiance $I_\beta(t_i)$ [W/m^2].

From this data, the following four parameters were used as input in simulation:

1. Timestamp t_i.
2. Speed over the water $v(t_i)$.
3. Irradiance $I_\beta(t_i)$.
4. PV module temperature $T(t_i)_{PV}$.

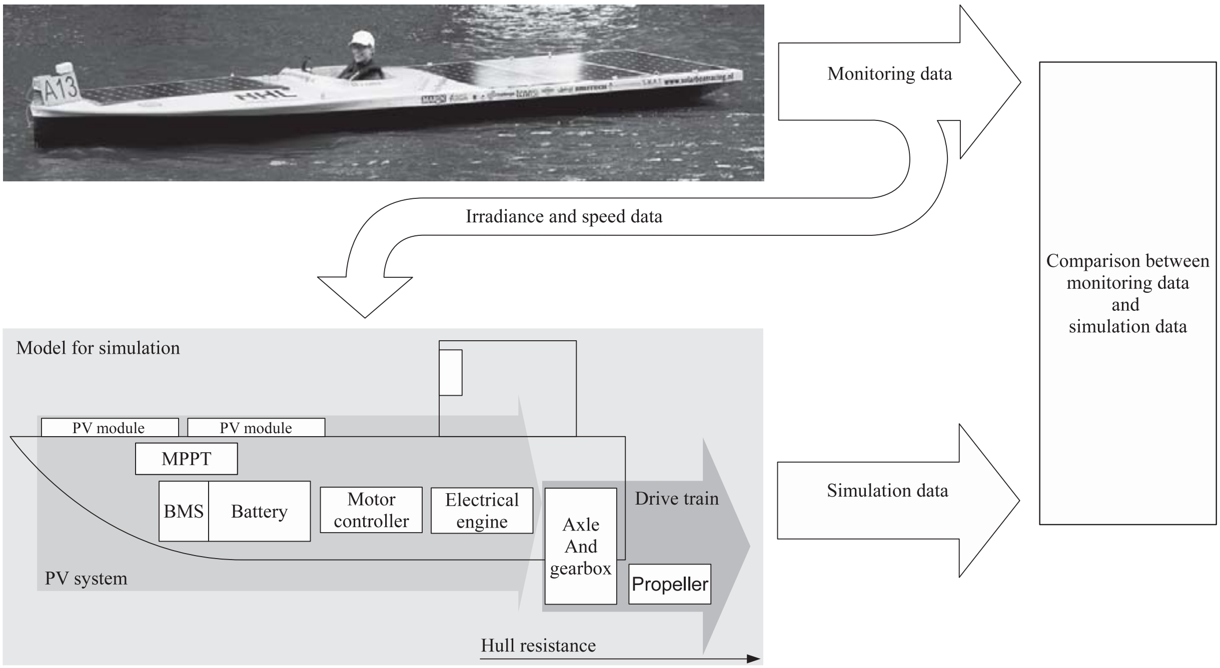


Figure 6.1: Comparing monitoring data with simulation data.

The timestamp data are in an array of succeeding timestamps. In general, the timestamp data represent a monitoring interval τ_r of 3 s. However, since simulation also takes into account the difference between the time t_i and t_{i-1}, which are two consecutive values from the timestamp data, it is assumed that no difference exist for the energy calculation between the simulation data and the monitoring data.

With an increase of PV module temperature, the efficiency of the PV module decreases, see Equation 5.17. It is assumed that all PV modules are of the same temperature.

For PV boats which are equipped with tilted PV modules, the longitude $\phi(t_i)$ and latitude $\lambda(t_i)$ are required for simulation as well, see Equations 5.18 and 5.19. However, since the simulated PV boat has only horizontal PV modules, these two inputs can be neglected. The geometrical position of the PV boat is also not of significance, because the irradiance $I_\beta(t_i)$ is known from the monitoring data. Therefore, the solar position algorithms are not included in the simulation and validation of the model, since the irradiance data is already location independent because it resulted from monitoring data.

The parameters which were monitored during the various days are shown in Figure 4.4. The following monitoring data are compared with simulation data:

- Power which goes in the battery $P(t_i)_{bat_{in}}$ [W].
- Power which comes from the battery $P(t_i)_{bat_{out}}$ [W].
- Battery SOC [%].

These data are the result from Equations 6.1 and 6.2.

The power which goes from the PV modules to the battery can be calculated as follows:

$$P(t_i)_{bat_{in}} = V(t_i)_{bat} \cdot I(t_i)_{bat_{in}} \tag{6.1}$$

With:

$P(t_i)_{bat_{in}}$ = Monitored battery charge power [W]
$V(t_i)_{bat}$ = Monitored battery voltage [V]
$I(t_i)_{bat_{in}}$ = Monitored battery charge current [A]

Determination of the power from the batteries to the loads:

$$P(t_i)_{bat_{out}} = V(t_i)_{bat} \cdot I(t_i)_{bat_{out}} \tag{6.2}$$

With:

$P(t_i)_{bat_{out}}$ = Monitored battery discharge power [W]
$I(t_i)_{bat_{out}}$ = Monitored battery discharge current [A]

Determination of the energy from power over time:

$$E_{d(t_i)} = \left(P(t_i)_{bat_{in}} - P(t_i)_{bat_{out}}\right) \cdot \tau_r(t_i, t_{i-1}) \tag{6.3}$$

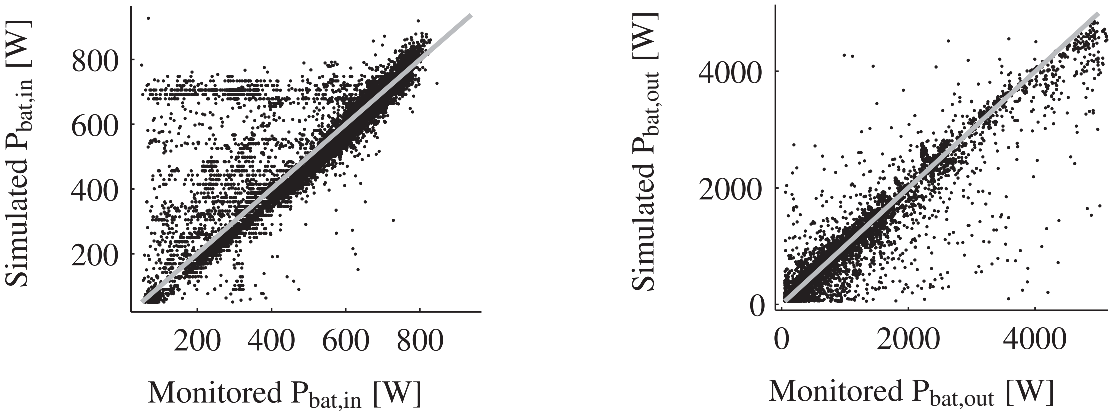
With:

$E_{d(t_i)}$ = Energy out of power over time [Wh]

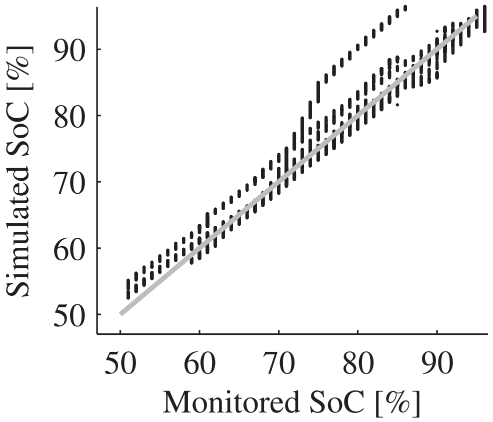
Figure 6.2 shows the results from the simulation data compared with the monitoring data for all days. Figure 6.2(a) shows the simulated and monitored power P_{PV}. Figure 6.2(b) shows the simulated and monitored power P_L. Figure 6.2(c) shows the simulated and monitored battery SOC.

In all figures, monitoring and simulation data have been used with values higher than 50 W. In Figure 6.2(c), a specific line in the range between 75% and 90% can be seen, which is significantly higher than other data. Here, data seems to have a large error. This range corresponds with simulation data as seen in Figure 6.2(a) horizontally around 700 W on the Y-axis. In that case, during monitoring, two out of four PV modules were disconnected. However, during simulation, the lack of irradiance has not been compensated, resulting in differences between the monitoring and simulation data.

Furthermore, in Figure 6.2(c), monitoring data seems discrete on the X-axis compared with simulation data on the Y-axis. This is the result from monitoring data which have been rounded off to values in the domain of integers $\mathbb{Z}$. This introduces an error when comparing simulation data with monitoring data.



(a) Monitoring and simulation data from $P_{bat,in}$. (b) Monitoring and simulation data from $P_{bat,in}$.



(c) Monitoring and simulation data from SoC.

Figure 6.2: Results from comparison between simulation and monitoring data.

To calculate the Root Mean Square Error (RMSE) and Maximum Average Error (MAE) from simulation data $d(t_i)_{sim}$ and monitoring data $d(t_i)_{mon}$, the following equations are used:

$$RMS_{E,d} = \sqrt{\frac{\sum_{t=0}^{n}\left(d(t_i)_{sim} - d(t_i)_{mon}\right)^2}{n}} \cdot \frac{100 \cdot n}{\sum_{t=0}^{n}\left(\sqrt{d(t_i)_{mon}^2}\right)} \tag{6.4}$$

With:

$RMS_{E,d}$ = Total root-mean-square error for all monitoring data [-]
n = Number of samples in data set [-]
$d(t_i)_{sim}$ = Data sample from simulation [-]
$d(t_i)_{mon}$ = Data sample from monitoring [-]

Table 6.1: RMS and MAE error for monitoring and simulation.

	RMSE [%]	MAE [%]
Power from PV modules	21.4	19.7
Power to loads	32.3	27.5
Battery SOC	3.1	1.9

Calculation of the maximum average error from a dataset:

$$MAE_{E,d} = \left. \frac{100 \cdot d(t_i)_{mon}}{n \cdot \sum_{t=0}^{n} \left(\frac{\sqrt{\left(d(t_i)_{sim} - d(t_i)_{mon}\right)^2}}{\sqrt{d(t_i)_{mon}^2}} \right)} \right| d(t_i)_{mon} \neq 0 \tag{6.5}$$

With:

$MAE_{E,d}$ = Total maximum average error for all monitoring data [-]

Table 6.1 shows the results of the RMSE and MAE for the monitoring and simulation data.

6.3 Analysis of Results

When comparing the values for RMSE and MAE in Table 6.1, the error for the PV power P_{PV} and power for loads P_L seems relatively high when compared to the error for SOC. SOC is calculated by comparing ingoing and outgoing energy at the battery. Energy is calculated with Equation 6.3. When comparing energy over a certain interval n instead of comparing the power data at a time index, the error will decrease. This is illustrated in Figure 6.3. In this figure, the interval n is increased, which results in a decreasing RMSE and MAE error.

6.4 Discussion and conclusions

Only one boat has been modeled and simulated and a validation has been done for 5 days. This does not prove that the model as described in Chapter 5 is generic. Furthermore, a relatively short period of monitoring has been used to compare monitoring data with simulation data.

The validation of monitoring and simulation data for five specific cases and one boat shows RMSE and MAEvalues in the range of 1.9% to 32.3% . When comparing the power which goes into the battery for monitoring and simulation data, the RMSE and MAE values are respectively 21.4% and 19.7%. The RMSE and MAE values for the power which goes out of the battery are respectively 32.3% and 27.5%. For battery SOC, the RMSE and MAE values are respectively 3.1% and 1.9%.

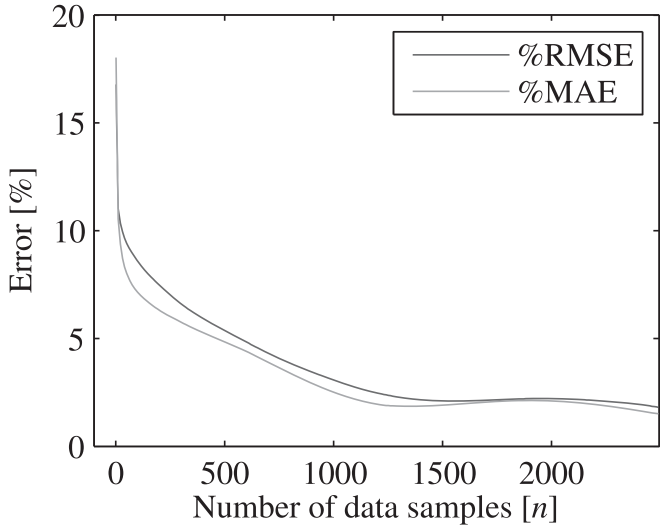


Figure 6.3: Decreasing error with increasing interval n when comparing energy values.

To conclude, when comparing values for in- and outgoing power between monitoring and simulation data, the RMSE and MAE errors are relatively large. This is not the case for RMSE and MAE values for battery SOC. The range for The RMSE and MAE values decreases when summing the energy values for an increasing number n of timestamps. This suggests that with a number of timestamps which is large enough, a more accurate estimate of the maximum error can be made, when considering energy values instead of power values.

More boat hulls and configurations should be simulated in the tool described in Chapter 5. The results can conclude that the models used in this tool are either specific or generic. If the models used in this chapter are specific for the boat used in validation, steps have to be taken to create a more generic model.

More monitoring data are required from other system components such as electrical motors and MCUs to validate models in the tool for these components.

Chapter 7

Potential application of the tool

7.1 Introduction

In order to demonstrate the functionality of the models described in Chapter 5, a tool has been developed. With this tool, a number of simulations have been executed with a modeled PV boat. Section 7.2 states the parameters and conditions used for the demonstration case. In Section 7.3 this case is then used as a basis for optimization of the boat described in Section 7.2. Section 7.3 describes the results from the demonstration and compares the simulated outcomes with monitoring data described in Section 4.2.2.

7.2 Demonstration case

In this demonstration case, a PV boat has been modeled and simulated. The PV boat which participated in the DSC in 2012 has been used, see Figure 4.2. For this demonstration, the conditions of a racing day during the DSC in 2012 were simulated. The boat costs € 30 000 and has four PV modules with total cost of € 1600 (PV module 1 from Table 7.2) and a battery installed which costs € 3000 (Battery A from Table 7.2). The weight of the boat is 115 kg, excluding PV modules and batteries. The modules are horizontally oriented in this boat. The 10th of July has been simulated, starting at 10:30 am under clear sky conditions. The sailing distance for the simulation is 30 km. At the start of the simulation, it is assumed that the PV boat has a fully charged battery. The simulation results have been compared with an existing boat's configuration taking into account the cost of the PV system, the boat's autonomy and speed.

In this simulation, the configuration of the PV boat has been varied with nine PV modules and six batteries, see Table 7.2. This resulted in various performance indicators, from which cost, maximum speed and autonomy were evaluated.

The lifespan of the batteries is considered to be 5 years and for the PV system this is assumed to be 10 years. Therefore, the total cost is the sum of the PV modules and twice the sum of the batteries.

Maximum speed is an indicator for the speed the PV boat can sail when fully utilizing the battery's capacity, after simulation of a 30 km trajectory.

Autonomy $\widetilde{a}$ is determined by dividing the left-over capacity in the batteries by the nominal battery capacity at an average speed v of 12 km/h, as shown in Equation 7.1. The sailing speed is set at 12 km/h, as this coincides with the speed limit in Frisian waters. If $\widetilde{a} \geq 1$, it means that the batteries are still fully charged after 30 km of sailing with a speed v of 12 km/h.

The PV modules considered in this simulation are randomly chosen from commercial manufacturers. This ensures a representative group of products which reflects the current market offering. The same method is applied to the batteries.

Determination of the autonomy of a PV boat:

$$\widetilde{a} = \frac{E_{FSN,\tau}}{E_{nom}}|_{v=12} \tag{7.1}$$

With:

$\widetilde{a}$ = PV boat autonomy [-]
E_{nom} = Nominal battery capacity [Wh]

Table 7.1: PV boat's parameters used in simulation.

Parameter	Value
Length	6.0 m
Width	1.5 m
Weight	115 kg
Cost	€ 30 000

Table 7.2: Various PV modules and batteries used in simulation.

PV module	Efficiency [%]	Cost [€]	Weight [kg]	Configuration*
1	19.1	400	15.0	4×
2	15.4	155	7.5	9×
3	15.4	393	22.5	3×
5	15.6	195	15.5	4×
6	14.4	255	25.0	3×
7	14.2	200	25.0	3×
8	11.1	225	12.0	8×
9**	19.1	1000	0.5	4×

*This is determined by the size of the PV module, not the power output

**This is a highly efficient flexible PV module under development

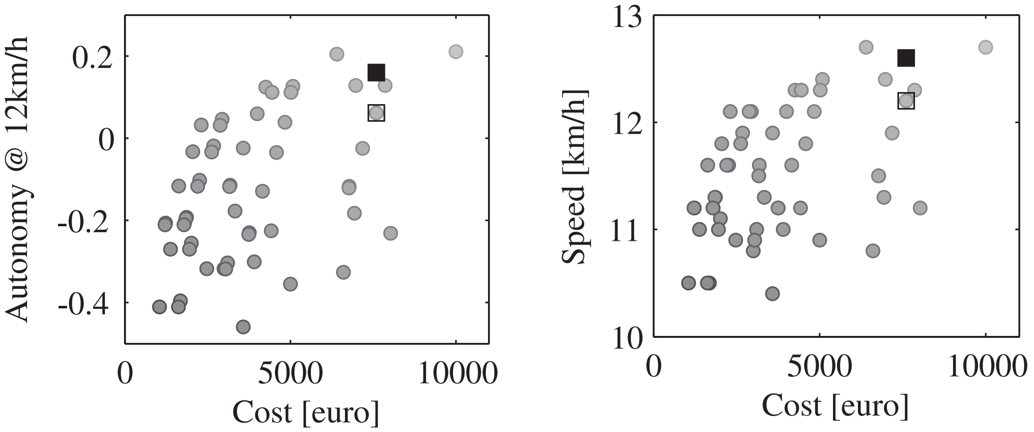
Battery	Capacity [Wh]	Cost [€]	Weight [kg]	Configuration*
A**	1750	3000	7.1	1×
B	200	25	6.1	9×
C	300	200	3.1	6×
D	120	36	3.3	15×
E	600	170	18.5	3×
F***	1600	1488	10.0	1×

*Based on a battery capacity of 1800 Wh

**Capacity in the simulation was 1750 Wh

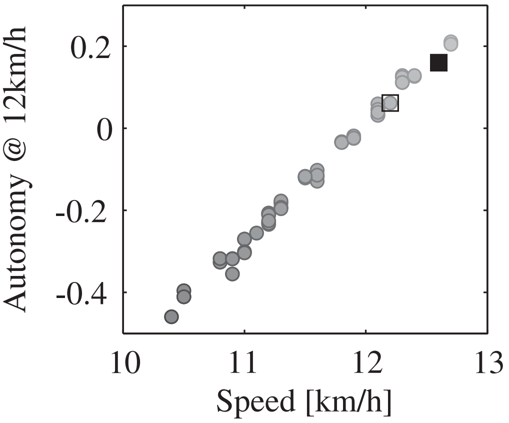
***Capacity in the simulation was 1600 Wh

The tool accepts any PV boat model. The user can select surfaces which are suitable for PV modules. The outline of the surface automatically determines the constraint for the size of the PV modules. Therefore, the maximum available PV power can be found, limited by the surface area which is available for PV. Furthermore, the maximum battery energy capacity is required to do simulations. Various optimization parameters can be chosen, such as orientation of PV modules. In this case, empirical data were used to determine the hull resistance of the boat which was used in this demonstration.



(a) Cost versus autonomy.

(b) Cost versus speed.



(c) Speed versus autonomy.

Figure 7.1: Simulation results from demonstration case to optimize PV boat configuration.

7.3 Results from demonstration

Figures 7.1(a) to 7.1(c) show the simulation results for optimization of PV system components on a PV boat. Each dot in the figures represent one of the 54 simulation results. In each figure, a black square represents a value which resulted from monitoring data from the existing PV boat. Furthermore, the dot which contains a black square outline, represents the existing system configuration as result from simulation. In Figures 7.1(a) and 7.1(c), the value for cost is evidently identical for the simulation and the monitoring result.

Figure 7.1(c) demonstrates that the results from simulations are correct. Fact is that a almost perfect correlation is the result from simulation for autonomy. Therefore, the simulation results are consistent with Equation 7.1.

Although the existing configuration scores relatively high (PV module 1, battery A), other simulation configurations exist with improved values for either cost, speed, autonomy or combinations of all three. The values for the existing configuration are given in Table 7.3:

configuration 1. The next section describes optimization scenarios for the PV boat design with respect to a number of performance indicators.

Maximizing cost versus autonomy

When looking at a comparison between cost and autonomy, various options exist to optimize the autonomy and lower the cost. When the existing configuration (PV module 1, battery A) is the benchmark for optimization, configurations with a cost lower than € 7600 and an autonomy higher than 0.06 are options. Several options exist, however the most optimal option with respect to cost is configuration 2 with PV module 2 and battery C, see Table 7.3. This combination shows a relatively low combined price for PV modules and batteries of € 4260: a reduction of 44%. Furthermore, autonomy is higher for a speed of 12 km/h. The maximum speed for this trajectory can be 12.3 km/h which is not a significant difference compared to a speed of 12.2 km/h in configuration 1.

The best option with respect to autonomy is configuration 3 with PV module 9 and battery A, see Table 7.3. This combination shows a relatively high autonomy of 0.21. However, system cost is relatively high: € 10 000 for both PV modules and batteries. The maximum speed for this trajectory can be 12.7 km/h which is an increase of 4% compared to a speed of 12.2 km/h in configuration 1.

Maximizing cost versus speed

When looking at a comparison between cost and speed, various options exist to optimize the speed. When the existing configuration (PV module 1, battery A) is the benchmark for optimization, configurations with a cost lower than € 7600 and a speed higher than 12.2 km/h are good options. The most optimal configuration with respect to speed is configuration 3 with PV module 9 and battery A, see Table 7.3. This combination shows a relatively high speed of 12.7 km/h. However, system cost is € 10 000.

Minimizing cost versus autonomy

When looking at a comparison between cost and autonomy, various options exist to lower the cost and still have a positive value for autonomy. When the existing configuration (PV module 1, battery A) is the benchmark for optimization, configurations with a cost lower than € 7600 and an autonomy higher than 0.00 are good options. Several options exist, however the most optimal option with respect to cost is configuration 4 with PV module 2 and battery B, see Table 7.3. This combination shows a relatively low combined price for PV modules and batteries of € 2310. Furthermore, autonomy is still positive for a speed of 12 km/h. The maximum speed for this trajectory can be 12.1 km/h which is not a significant difference compared to a speed of 12.2 km/h in configuration 1.

The most optimal configuration with respect to autonomy is configuration 3 with PV module 9 and battery A, see Table 7.3. This combination shows a relatively high autonomy of 0.21. However, price is relatively high: € 10 000 for both PV modules and batteries. The maximum speed for this trajectory can be 12.7 km/h which is an increase of 4% compared to a speed of 12.2 km/h in configuration 1.

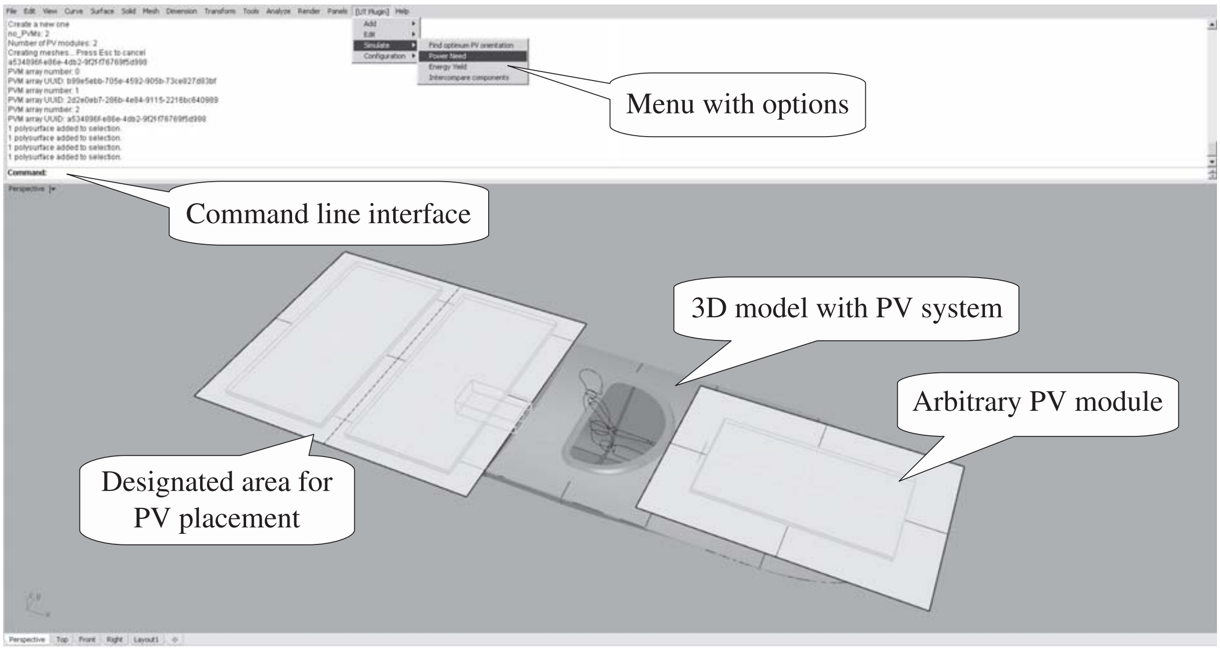
Table 7.3: Results from simulation for PV boat optimization.

Config.	PV module	Battery	PV module cost [€]	Battery cost [€]	Speed [km/h]	Autonomy
1	1	A	1600	6000	12.2	0.06
2	2	C	1860	2400	12.3	0.12
3	9	A	4000	6000	12.7	0.21
4	2	B	1860	450	12.1	0.03

7.4 Reflection on the tool

A tool has been developed which is intended for use by boat designers. This tool has been integrated in Rhinoceros. Rhinoceros itself has a user interface for which some experience is required. For example, many commands or actions can be done with shortcuts or with commands in a CLI. This means that the Rhinoceros user has some skills to work in a 3D environment and knows his way around with keyboard commands. Other tools and environments exist to design boats, but the choice for Rhinoceros has been explained in Section 5.3.

This tool easily integrates in the Rhinoceros environment. It runs in the background, but creates a visible menu button. Important output is visualized in the CLI. Some input has to be entered in the CLI as well. After the execution of simulations, reports are generated which holds information on energy balances for different scenarios and circumstances.



```
Create a new one
no_PVMs: 2
Number of PV modules: 2
Creating meshes... Press Esc to cancel
a534896f-e86e-4db2-9f2f-f76769f5d998
PVM array number: 0
PVM array UUID: b99e5ebb-705e-4592-905b-73ce827d83bf
PVM array number: 1
PVM array UUID: 2d2e0eb7-286b-4e84-9115-2218bc640989
PVM array number: 2
PVM array UUID: a534896f-e86e-4db2-9f2f-f76769f5d998
1 polysurface added to selection.
1 polysurface added to selection.
1 polysurface added to selection.
1 polysurface added to selection.
Command:
```

Figure 7.2: A screenshot of the tool.

7.4.1 Usability

A possible boat designer, asked to use the tool as it is in it current form, will not understand how to work with the tool. Although the placing and editing of PV system components is ‘click-and-drag’ and the executing of simulations can be accessed from the menu, some commands still need to be given in the CLI. A GUI which pops-up could be more clear when implemented. Once a simulation is selected and started, first the simulation routine will be initialized. This initialization requires information from the user, such as the location of the boat or its sailing route. Momentarily, these options need to be entered in the CLI, but a visual menu with options and buttons will drastically improve the effectiveness of gathering this information. Figure 7.2 shows a screen shot of the tool and some of its features.

The selection of components, is done from a list of components. However, these lists are made by hand and loaded every time a selection needs to be made. The user would be greatly helped if a database exist with an overview of existing components with their properties. Furthermore, if this database would hold up-to-date components and their properties, which the user can connect to online, that would be even a larger benefit.

Sailing routes are collections of GPS coordinates. Predefined sailing routes for different geographical areas for selection would be of convenience for the user. In that way, the user does not need to generate sailing routes themselves. An other alternative is to link this tool with open world maps, available on the Internet.

The output is in the form of files containing data representing boat design parameters, such as speeds, cost and generated energy. These files are in its rawest form and not clear to unexperienced users. Once imported in visualization tools to present graphs, the data can make sense. However, it would be of much more convenience if the tool itself can represent the data in a way that the user immediately can visualize the results from simulation.

An automated link between the determination of the hull resistance plug-in and the tool described in this research does not exist yet. Momentarily, if the user wants to run a simulation for a boat equipped with PV, first the hull resistance needs to be determined. The resulting data is then transferred manually into the tool, which uses that data to simulate the energy balance of the boat. The next step in development would be to acquire the hull resistance data automatically once the 3D model is ready and simulations on the energy balance need to be executed.

7.4.2 Perspective of use

Basically every boat designer can use this tool, once it reaches a state of easy usability with a good GUI. However, this tool is not only suitable for moving objects. Other applications, such as Building Integrated Photovoltaics (BIPV), can benefit from this tool since it easily integrates in a general 3D design environment. The framework to do so is available. The use of this tool to simulate the energy balance on boats, but also other moving objects equipped with PV, can be made available to the public after minor alterations, of which the implementation of a GUI is one. Better performing PV boats can be developed. Cars which run on PV can be developed which can meet the energy availability.

Besides being a tool for designers, other parties might have interest and benefit from this tool. This tool can be used for educational purposes. For example students can get easier insights in PV systems and the availability of energy with certain system configurations. PV systems can be easily dimensioned according to the needs of the user and energy balances can be simulated. In product design, this tool can be of great help to design better performing products which entirely or partly run on PV.

7.5 Discussion and conclusions

What can be learned from the case demonstrated in this chapter? It shows that, depending on the wishes and the needs of the designer and the end-user of the boat, various topologies can be chosen to equip a PV boat with a PV system. A fast overview can be generated with various system components to optimize the design of a PV boat with respect to a number of performance indicators.

This tool is an aid for boat designers, who can, as a result, implement electrical and mechanical components more easily in their PV boat designs. The tool comprises models with which the performance of PV boats can be determined.

With this tool, various types of simulations can be done which can help boat designers to make three key decisions:

1. The boat can sail on PV entirely. This includes propulsion and HEP loads.
2. The boat can sail partly on PV. This usually means that HEP loads are powered with PV, but propulsion is not.
3. It is not feasible to propel or power HEP loads with PV.

Such knowledge in an early design stage could lead to different boat designs, better planning of the energy system or even rejection of initial designs. That makes this tool an asset for boat designers. New technologies, such as PV, are not the standard system components boat designer have to work with and their knowledge.

The existing boat which was used to compare simulated data with, showed that the performance with respect to cost, autonomy and speed can be improved when using different PV modules and battery combinations.

Following from the cases shown in this chapter, the existing PV boat configuration can be optimized with respect to cost, speed and autonomy based on the assumptions described in Section 7.2. For comparable maximum speed (12.1 km/h instead of 12.2 km/h) and a little lower autonomy (0.03 instead of 0.06), the total cost of the system can be lowered with 70% (€ 2310 instead of € 7600). Another option exists, which shows a higher autonomy (0.12 instead of 0.06), a comparable maximum speed (difference $< 1\%$) and a reduction of system cost of 44%.

In the simulations in the case presented in this chapter, the capacities of the batteries were not matched: in some cases, the capacity was under 1800 Wh, which can have a negative influence on the end results. A better approach would be to determine the cost or weight per kWh. The values can then be extrapolated to the desired battery capacity for more accurate results.

Depending on the environmental conditions such as wind speed and water current, accuracy of boat speed calculations can differ significantly. Water currents of 4 km/h or more are not unusual on rivers, although the currents on Frisian canals and lakes can be considered 0 km/h.

For this demonstration, a variety of commercial available PV modules and batteries were used. When this tool would be linked with a database with up-to-date component prices and specifications, it can help designers to make decisions on system components much earlier in their design stage, resulting in better performing PV products.

It is impossible to compare synthesized irradiance data with monitored data in short time intervals, since synthesized data will never correspond with monitoring data. This is the result from the always changing atmospheric conditions which can only be described with average measurements.

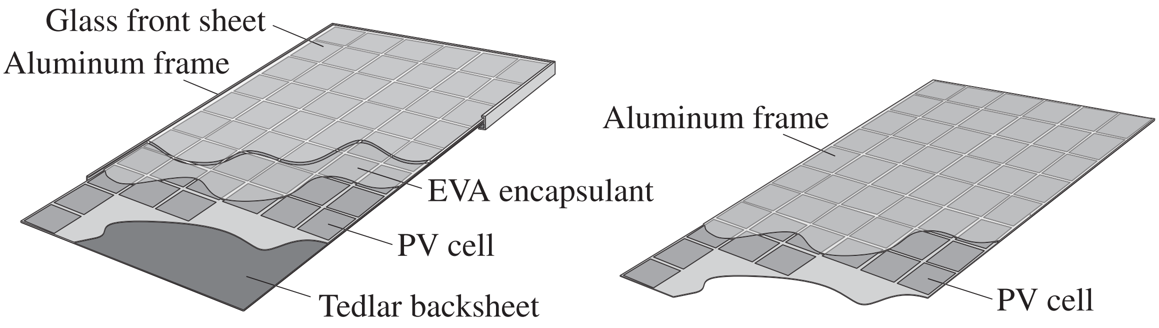
To make the solar boat performance model and its implementation in Rhinoceros available for boat designers, a good GUI should be added to the plug-in. Momentarily, the tool works only with a CLI, which might be too difficult for less-experienced users to work with practically. Furthermore, input from boat designers should be used to further develop this tool and its models meeting the demands and wishes of boat designers who want to add PV in their designs.

Further development of this tool should include various irradiation conditions, or a range of irradiation conditions as well as a better integration of various system components. More components and their descriptive models should be included in this tool, so that the performance of PV boats can be determined by just adding and simulating components.

Chapter 8

Encapsulants

This chapter has been published in the Journal of Applied Energy, Volume 92, pages 286–297 in 2012. T. Gorter and A. Reinders, entitled ‘A comparison of 15 Polymers for application in photovoltaic modules in PV-powered boats’.



(a) PV cells in a conventional glass laminate.
(b) PV cells in a polymer.

Figure 8.1: PV integration into boats.

8.1 Introduction

This chapter describes an opportunity to equip PV boats with low-weight, high-efficient PV modules. This might increase the performance of PV boats with respect to the energy balance. Autonomous electric propulsion in boats by PV-power is an upcoming technology which sets specific requirements to the integration of c-Si cells in boat surfaces, such as the deck. Light weight and flexibility of shape as well as endurance are required for successful PV-powered boat design.

In order to find alternative materials for common glass and Ethylenevinylacetate (EVA)[1] laminates, 15 polymers were evaluated, of which some are Glass Fiber Reinforced (GFR), which might be suitable for use as a replacement of glass in PV modules for recreational PV boats. The mechanical and optical properties and specific demands due to application in boats have been listed for these 15 polymers.

Within the yachting and boating sector, the need for integrating PV in boat surfaces is growing. Therefore, this chapter address the sub-research question ‘Which opportunities exist in developing better performing PV technology for PV boats?’ In Section 8.2 the problems of integration of PV into boats is discussed, followed by a research proposal in Section 8.3 to find PV modules which are better fit for use in PV boats. The results of a research in materials which might be fit for encapsulation of PV without using heavy weight glass plates is shown in Section 8.4.

8.2 PV integration into boats

One of the key problems of electric propulsion and boats is the amount of electrical energy needed to sail a distance with a certain average speed. Efficiency in the electrical system together with low boat weight plays an important role to achieve higher boat speeds, as described in Sections 5.3 to 5.5. This is of influence of considerations for the placement of PV. Among the considerations are the preferred PV technology, choice of electrical components and battery capacity. Furthermore, structural choices of boat design are relevant.

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[1] EVA is a polymer commonly used to encapsulate PV cells between glass sheets.

This includes the hull material and shape and the requirements of PV-integration into boat surfaces.

Because of the light weight requirement, arbitrarily shapes of boat surfaces and the use in a wet environment, the design of boat-integrated PV systems will be rather different from the design of conventional PV modules based on glass sheets and the integration of PV cells in for example aircrafts [107]. Conventional key research into PV technologies (cells, modules) is normally about cost-effectiveness and performance or cell efficiency [108].

However, this research emphasizes on another important factor, which is weight reduction for high efficient c-Si modules. Not much research into the integration of PV in mobility is being conducted and described, such as PV boats [108–110]. Therefore, to successfully integrate PV into dynamic objects, research into cost-effectiveness and energy efficiency performance are not the only key factors. PV module weight and endurance are examples of important factors described in this chapter, which are of importance if PV modules are successfully integrated into PV boats.

Conventional PV modules exist out of an aluminum frame which holds a laminate containing a glass front sheet, usually EVA as PV cell encapsulant and a backsheet, for example Tedlar. This is illustrated in Figure 8.1(a). PV cells need to be directly embedded into a polymer or GFR polymer, which provides for all the protection PV cells need without using glass in a PV module. This is illustrated in Figure 8.1(b). Such a polymer could be reinforced with glass fibers at the front and back side to enhance the strength of the module [111]. From a survey of almost 183 existing PV boats it was concluded that to equip boats with PV cells, the following interrelated boat features are relevant:

1. Light Weight
   The lower the total weight of a boat, the less the energy is needed to electrically propulse it [18, 112].

2. High Electrical Energy Efficiency
   To optimally use solar irradiance available, a high electrical efficiency of the electrical system from PV modules to electrical propulsion and HEP load is necessary.

3. Low Water Resistance
   Efficient or streamlined hull design ensures lower water resistance and reduces the energy need to travel at a certain speed for a certain period of time.

4. Large PV Surface Area
   A well designed boat deck should provide for a large surface area suitable for PV and as such allow for sufficient electricity generation for electric propulsion.

5. Sufficient Structural PV Support
   Because of the sensitivity of PV cells to impact and potential damage due to endured mechanical stress, PV cells integrated in a boat's deck must have sufficient support for

placement and fixation without stressing the PV cells.

Conclusion: in this research, the focus will be on the weight and cost of glassless PV modules for use on boats.

8.2.1 Functions of PV cell encapsulation

PV cells need protection against the environment. Without protection, they are exposed to a hostile environment which include Ultraviolet (UV)-radiation, humidity, mechanical stress and pollutants. One approach to provide protection is encapsulation. Czanderna and Pern stated the five primary functions of PV module encapsulation which also apply to PV-integration into boats, which are:

1. Providing structural support to the PV cells.
2. Ensure the maximum optical coupling between PV cells and solar irradiation.
3. To keep the electrical components electrically isolated.
4. To keep the PV cells and circuitry physically isolated.
5. To contain auxiliary connections within a module.

Therefore, conventional glass based PV modules contain various material layers to protect PV cells to fulfill these functions [113]. However, in PV-powered boats a sixth function is added, which would be “being 100% waterproof and salt resistant”.

8.2.2 Preferable PV technology

Commercial PV modules can be categorized into two technologies. First, the conventional PV modules which exist out of c-Si PV cells embedded in a laminate of glass, encapsulation material (usually EVA) and a backsheet (usually Tedlar). Secondly, Thin film PV module technologies that are either produced on glass, metal or plastic substrates and that can have a variety of forms. The use of PV on boats is only feasible when the limited surface area available on board would be efficiently used to generate electrical energy. Therefore, for this application, PV cells with high efficiencies are required. The best affordable candidates to be used on boats are c-Si PV cells with efficiencies around 20%. Although various multijunction PV cells offer efficiencies well above 40% [114], price per wattpeak (unconcentrated) is above € 100/Wp [115] compared to € 2.00/Wp to € 4.00/Wp for c-Si PV cells [116]. The high price of multijunction technology is only feasible for non-commercial applications or Concentrating Photovoltaics (CPV). It is therefore safe to say that PV on boats for recreational purposes should be of the c-Si type to provide as much energy as possible with a minimum of available surface area and at reasonable cost and weight. The total cost of a PV module can be depicted as € x/kg. A glass front sheet holds a part of x, let’s say y of the cost of the module, which can be depicted as € y/kg.

8.2.3 PV weight ratio and boat weight

Conventional PV modules based on glass, can weigh up to 130 g/Wp. Therefore it is assumed that a large size module with 175 Wp weighs 17.5 kg. When considering a 6 m long, 1.5 m wide boat, with a 6.3 m^2 deck area for placing PV, five 175 Wp modules can be placed with 87.5 kg of total weight. An example of such a boat is shown in Figure 8.2. A boat with these dimensions and configuration would weigh around 200 kg. In this case, the PV modules account for 44% of the total boat weight, including PV modules. This is illustrated in Figure 8.3, which shows a glass based PV module weight share with a weight per wattpeak ratio of 100 g/Wp on total boat weight (boat 1) compared to an arbitrary polymer or GFR polymer used in PV modules (boat 2). In the second case, an estimated PV module's weight ratio of 10 g/Wp was used, which could be achieved with c-Si PV cells embedded in a polymer or GFR polymer instead of using a laminate with glass.

Figure 8.2: PV boat of 6 m long and 1.5 m wide with five conventional 175 Wp glass-based PV modules placed on its deck (picture taken by author).

This research shows polymers and GFR polymers which could be used to embed PV cells and which might be suitable as replacement of rather heavy glass sheets while still providing the protection PV cells require; protection which is conventionally provided for by glass covers. With the purpose to reduce weight of a PV-powered boat, our research question is: what polymer or GFR polymer is best suitable for use to form a PV module which can be used in PV boats while maintaining similar mechanical and optical properties as glass and being resistant to water and salt. On boats, mechanical stiffness in combination with low weight is desired. Matching the mechanical properties of an alternative polymer or GFR polymer with glass is of importance. However, glass' ideal properties like transmittance, surface finish and protection against the hostile environment, need to be considered also. Another factor that

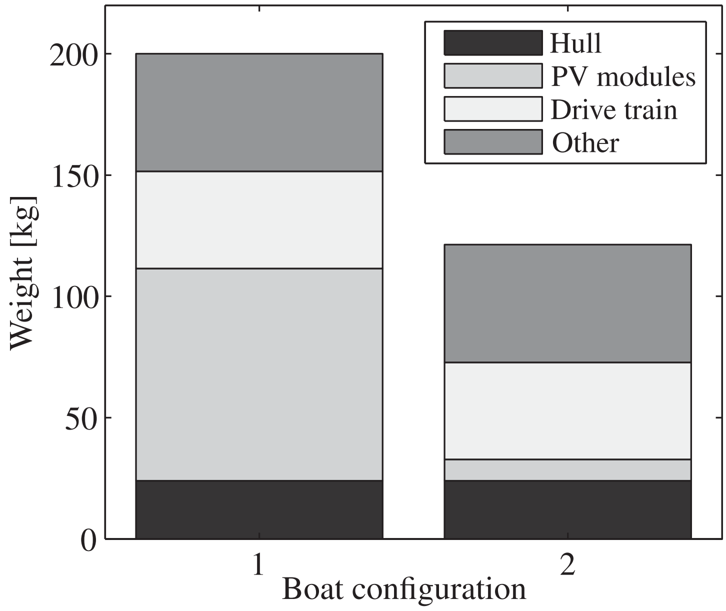


Figure 8.3: Weight bar chart for a 6 m long boat with 100 g/Wp (boat 1) and 10 g/Wp (boat 2) PV modules.

matters is the cost of a polymer or GFR polymer. Because the costs of integration of PV in boats cumulate in the total production costs of the boat, a one to one comparison of production costs of a glass sheet based PV module can not be made in one study. However it is assumed that costs should stay in a range that is acceptable for customers that purchase a recreational PV boat. The application of polymers and GFR polymers to embed PV cells in boat's surfaces should not necessarily lead to equal or lower cost compared to glass based PV laminates but to a better boat performance; that is to say a lighter weight and as such a higher average speed and better maneuverability.

Encapsulating PV cells in a polymer or GFR polymer which offers the protection needed by the cells should result in lower weight PV modules with lower thickness. This is illustrated in Figure 8.4. In this image, the three basic layers of a conventional PV module consisting out of a front sheet, glass, encapsulant, EVA and backsheet, Tedlar, are shown in configuration 1. Configuration 2 shows a PV module consisting out of only a polymer or GFR polymer, which ideally should replace glass. Such PV modules, existing out of c-Si PV cells laminated in a polymer, do exist [117] and show high energy conversion performance with respect to efficiency. However, it is assumed that endurance and application on boats has not been developed well yet. For other applications than boats, for example large surface roof mounted PV modules, reducing PV module weight has also advantages, including easier installation [118].

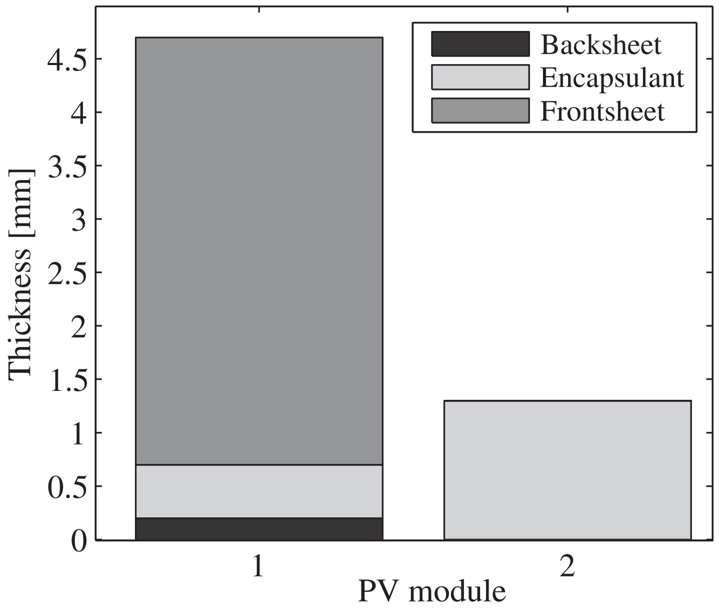


Figure 8.4: Thickness in PV modules for a conventional PV module (1) and a polymer or GFR polymer PV module (2).

8.3 Research approach

To categorize polymers and GFR polymers fit for use in PV modules and simultaneously offering satisfying properties to make glass covers obsolete, a literature research has been executed in 2009 and 2010. An evaluation of DeBergalis [118], Jorgenson et al. [119], Ketola [120], Norris [121], Sanchez-Illescas et al. [122], Warnet and Akkerman [123], WACKER [124], Kempe [125] and French et al. [126] led to a list of polymers which are already being used or currently being introduced in PV modules. Next, mechanical, chemical and optical properties of these polymers and GFR polymers were evaluated in order to compare polymers and GFR polymers amongst each other and with glass, see Section 8.3. The polymers and their properties are presented in Tables A.3 to A.5. Adding to this list, some of these polymers are presented with GFR. The polymers and GFR polymers evaluated in this paper are shown in Table 8.1

Most of the polymers' properties were found in producers' datasheets [124, 127, 128]. Values in datasheets are usually applicable to a family of products, resulting in a property's value range. When values could not be found in datasheets, other resources like material properties software were used to fill in the gaps [129–131].

To be able to compare various polymers and GFR polymers, relevant properties (mechanical, optical and boat specific) of glass used in conventional PV modules have been identified and listed [18, 113]. Below, these properties are listed and described:

Table 8.1: Overview of the evaluated polymers.

Index	Polymer	Application
1.	epoxies	other
2.	GFR epoxies	other
3.	Ethyltetrafluorethylene (ETFE)	frontsheet
4.	GFR ETFE	other
5.	Fluoroethylenepropylene (FEP)	frontsheet backsheet
6.	FEP	other
7.	Polyetherimide (PEI)	other
8.	GFR PEI	other
9.	Polyimide (PI)	backsheet
10.	GFR PI	other
11.	Polytetrafluorethylene (PTFE)	frontsheet
12.	GFR PTFE	other
13.	Polyethylene (PE)	other
14.	GFR PE	other
15.	Polypropylene (PP)	other
16.	GFR PP	other
17.	Polymethylpentene (PMP)	other
18.	GFR PMP	other
19.	Thermoplastic Polyurethane (TPU)	other
20.	GFR TPU	other
21.	Polyvinylideenfluoride (PVDF)	frontsheet backsheet
22.	Silicones	frontsheet
23.	Polyethylene naphthalate (PEN)	frontsheet
24.	Polyvinyl butyral (PVB)	frontsheet
25.	Polybutene (PB)	other

1. Tensile strength R_m $[MPa]$
   The maximum force a material can withstand just before breaking or deforming such that the material is considered broken. Various tensile strength testing methods exist and depending on the method used, tensile strength values for a material can differ [132, 133].

2. Impact strength K_v $[MPa]$
   Impact strength is the maximum force needed to break a clamped material. Various impact tests exist however values used in this research refer to the notched, Izod test at 23°C [132].

3. Density ρ [kg/m^3]
   Material's mass per unit of volume [132].

4. Laminate Thickness D [μm]
   In this research, a laminate thickness is defined as the film-thickness which can be used for lamination, given in literature or datasheets from producers.

5. Service Temperature T_s [°C]
   The service temperature for a material indicates in which a temperature range of a material can be used without resulting in breakage or other undesirable effects [132].

6. Glass Temperature T_g [°C]
   The glass temperature is a measure for a material which indicates the transition from solid state to a rubber state. This transition can be a temperature range depending on material and heating or cooling down rate [132].

7. Transmittance τ_λ
   Transmittance is the amount of irradiance transmitted by the material. This value is wavelength and research method dependent [133, 134].

8. Given Spectrum for Transmittance λ [nm]
   The given spectrum for transmittance is an indication in what spectrum EM transmittance is achieved [133, 134].

9. UV Stability
   UV stability is an indication for a material at which level it can withstand UV-radiation. The rating method is adapted from Granta Design Limited [130], which categorizes the values from poor to excellent according to Table 8.2.

Table 8.2: UV stability categories adapted from Granta Design [130].

Category	**Time before UV-degradation sets in**
Poor	Several weeks up to a month
Fair	Several months up to a year
Good	Several years up to ten year
Excellent	Tens of years

10. Refraction Index n
    Refraction index is a measure to determine angle shift in ingoing and outgoing Electromagnetic (EM)-radiation, dependent on the material's composition [134].

11. Cost p [€/kg]
    Cost gives the price per kilogram for bulk materials, bought in high volumes [130].

Table 8.3: Salt water categories adapted from Granta Design [130].

Category	**Salt water resistance**
Acceptable	The polymer may need additional protection against salt water
Excellent	The polymer is not influenced in a salt water environment

12. Embodied Energy [MJ/kg]
    Energy needed to convert polymer-feedstock materials into 1 kg of a polymer [130].

13. CO_2 [kg/kg]
    The carbondioxide emission (in kg) to convert polymer-feedstock materials into 1 kg of a polymer [130].

14. Water Footprint [l/kg]
    The Water Footprint is the use of fresh water needed to convert polymer-feedstock materials into 1 kg of a polymer [130].

15. Salt Water Resistance
    Salt water resistance is a measure for the salt water resistance of a polymer indicated by acceptable or excellent, see Table 8.3 [130].

8.4 Results

This section shows the results from the evaluated polymers and GFR polymers which might be suitable to be used as glass replacement in PV modules for integration into PV boats. The polymers and GFR polymers presented have one or more properties which fit the constraints mentioned in Section 8.3. By using the most suitable polymer or GFR polymer to embed PV cells in while simultaneously providing satisfying protection for PV cells, the aim is to design better PV boats for recreational purposes. The results are shown per property and per polymer-group, since per group similar results per property are found, see Section 8.3. The properties of polymers and GFR polymers which are compared with glass are considered to act as glass replacement in conventional PV modules. In such modules, PV cells are encapsulated with a thin layer of a polymer such as EVA and covered with one or two glass plates. These glass plates are the largest contributer to weight and price, therefore it is sufficient to compare polymers and GFR polymers only with glass. Glass used for PV modules has a density in a range between 2000 kg/m^3 and 3000 kg/m^3, see Table A.3. To compare polymers and GFR polymers with glass, graphs are plotted which show the thickness of the polymer in relation to the cost per square meter, in Figure 8.6(a) and 8.6(b) and Figures A.5(a) to A.12(a).

In this study, cost P has been defined as the price per square meter. These values for minimum and maximum cost and thickness can be calculated from Tables A.3 to A.5. Looking at Figure 8.6(a) as an example, glass starts at a minimum thickness of 4000 μm, with a minimum price of € 10/m^2. The maximum at 6000 μm is a range between the minimum density times minimum price per square meter times maximum thickness P$_{6000,\mathrm{min}}$ and the maximum density times maximum price per square meter times maximum thickness P$_{6000,\mathrm{max}}$, see Equations 8.1a and 8.1b. The maximum price of glass per square meter would be € 25/m^2. The minimum and maximum thickness for polymers can be calculated as follows:

$$P_{6000,min} = \rho(min) \cdot p(min) \cdot L_t(max) \tag{8.1a}$$

$$P_{6000,max} = \rho(max) \cdot p(max) \cdot L_t(max) \tag{8.1b}$$

With:

P = Cost per square meter [€ /m^2]
ρ = Polymer density [kg/m^3]
p = Cost per kilogram [€ /kg]
L_t = Laminate thickness [m]

In order to compare various polymers and GFR polymers with glass and with each other, polymers with similar properties are grouped together:

Table 8.4: Grouping of polymers.

Group	Polymers
Fluorides	ETFE, PTFE, PVDF, FEP
Polyimides	PEI, PI
Polyolefins	PP, PE, PMB, PB
Silicones	Silicones
Others	Epoxies, PEN, PVB, TPU
Conventional encapsulants (with glass-sheet)	EVA

8.4.1 Price comparison

Polymer price depends on the thickness of the polymer in which the PV cells are embedded. Prices given in tables are in cost per kilogram. The results are also shown in Figures 8.6(a) and 8.6(b) and Figures A.5(a) to A.12(a). Polymers were grouped in a price range to get an overview of their cost per kilogram. Pricegroups are as follows:

Fluorides are high priced polymers, except PTFE, which starts at € $8.00/kg$. Polyimides are also high priced polymers, except GFR PEI, which is middle priced. Polyolefins are low priced polymers, except PMP and GFR PMP, which are middle priced. Silicones are middle and high priced. Polymers in the group ‘other’ are low priced, except TPU, which is middle priced.

Table 8.5: Polymer price range (2010).

Category	**Pricerange [€/kg]**
Low	< 5.00
Middle	5.00–10.00
High	> 10.00

Table 8.6: Polymer per price range (2010).

Category	**Polymer**
Low priced	Epoxies, GFR Epoxies, PE, GFR PE, PP, GFR PP, PEN, EVA, PB
Middle priced	GFR PEI, PTFE, PMP, GFR PMP, TPU, silicones
High priced	ETFE, GFR ETFE, FEP, GFR FEP, PTFE, GFR PTFE, PVDF

Maximum polymer thickness compared to glass in relation to price

For a polymer to be cost effective with glass, maximum cost should be under the minimum cost for glass. Ergo, maximum price for a polymer should not exceed € 10/m^2 to be cost effective with glass. With the minimum cost for glass, the maximum thickness of a polymer can be found.

To illustrate these results, epoxy is used as an example. This means for Figure 8.6(a) that the maximum epoxy thickness should be between 4100 μm and 4500 μm. With the density value for epoxy from Table A.3 it can be calculated that epoxy with a thickness between 4100 μm and 4500 μm weighs between 4.6 kg/m^2 and 5.0 kg/m^2. This is compared to glass with a weight between 6.0 kg/m^2 and 18.0 kg/m^2, a reduction of more than 25% when using epoxy only to embed PV cells in. This thickness between 4100 μm and 4500 μm is not a fixed value. It is to be determined what minimum thickness is required to match the properties of epoxy with glass. Preferably, it should be under 4100 μm to be cost competitive.

Price development

Not only current pricing for polymers are used to compare polymers and GFR polymers for embedding of PV cells, price development examples over the last 5 years are shown in Figure 8.6(b) and Figures A.5(b) to A.12(a). As an example, GFR epoxy shows a large decrease in price over the last 5 years, from approximately € 7/kg to € 4/kg. Although this trend does not seem linear, it cuts its kilogram price over 5 years with 43%. However, price for the polymers evaluated in this research are under influence by customer demand and commercial influence of companies, together with availability. But, if the reasons for price developments are ignored, trends show a reasonable decrease for most polymers' prices so far. These price developments are the result of recorded data from 2005 up to 2010 for polymer price per kilogram.

8.4.2 Polymer Strength

Just like cost, a grouping was made for polymer and glass strengths, shown in Table 8.7.

Table 8.7: Strengths range.

Category	**Tensile strength [MPa]**	**Impact strength [kJ/m^2]**
Low	< 50	< 50
Medium	50–150	50–150
High	> 150	> 150

Most polymers show low tensile strength. However, polyimides show medium tensile strength and GFR polyimides and GFR epoxy show high tensile strength, see Table 8.8. GFR epoxy shows higher tensile strength compared with glass: respectively a range between 138 MPa to 241 MPa against a range of 10 MPa to 180 MPa for glass. Fluorides and polyimides show similar data as glass, in a range between 47 MPa and 174 MPa.

Table 8.8: Polymer tensile strength.

Category	**Polymer**
Low tensile strength	Epoxy, ETFE, FEP, GFR FEP, PTFE, GFR PTFE, PE, GFR PE, PP, GFR PP, PMP, GFR PMP, TPU, PVDF, silicones, PEN, EVA, PVB, PB, *glass*
Medium tensile strength	GFR epoxy, GFR ETFE, PEI, PI, GFR PP, GFR TPU, *glass*
High tensile strength	GFR epoxy, GFR PEI, GFR PI, *glass*

Most polymers show low impact strength. Fluorides, except PTFE, show medium impact strength, see Table 8.9.

Table 8.9: Polymer impact strength.

Category	**Polymer**
Low impact strength	Epoxy, ETFE, GFR ETFE, FEP, GFR FEP, PEI, GFR PEI, PI, GFR PI, PTFE, PE, GFR PE, PP, GFR PP, PMP, GFR PMP, GFR TPU, PVDF, PEN, PB
Medium impact strength	ETFE, GFR ETFE, FEP, PE, PVDF
High impact strength	GFR Epoxy, ETFE, FEP, PE, TPU, PB

8.4.3 Thermal expansion coefficient

Since the evaluated polymers in this paper will encapsulate PV cells consisting mainly out of Silicon, it is important to match the thermal expansion coefficient from Silicon with the polymer, to avoid unnecessary stresses on the PV cells. The thermal expansion coefficient

of PV cells lies between 2.5 and 3.2 in a 0°C to 100°C temperature range [135]. It can be said that most polymers have a ten times or even hundred times higher expansion coefficient compared to PV cells.
Polyolefins show a large range of thermal expansion coefficient, varying from $20 \cdot 10^{-6} \cdot {}^{\circ}C$ to $3960 \cdot 10^{-6} \cdot {}^{\circ}C$. Fluorides and Polyimides show lesser thermal expansion, ranging between $11 \cdot 10^{-6} \cdot {}^{\circ}C$ and $108 \cdot 10^{-6} \cdot {}^{\circ}C$, except for PTFE, GFR PTFE and PVDF.

8.4.4 Salt water resistance

All polymers as well as glass, except PE, show excellent resistance to salt water.

8.4.5 Energy conversion performance

The energy conversion performance for PV cells encapsulated within a polymer depends on many factors, including cell temperature, in coupling of solar radiation and cell technology [136]. However, it is in our opinion that two key factors, namely UV stability and transmittance, are of most concern to ensure high durability and endurance for a long period of time such as 10 years. The usable electrical energy efficiency depends mainly on the transmittance of the polymer and GFR polymer under standard test conditions [137]. The energy conversion performance will decrease when the transmittance of the polymer is lower, see Equation 8.2. To function properly over longer periods of time, PV cells need protection for the environment.

The efficiency of the PV module is dependent on the efficiency of the PV cell and the transmittance of the cover sheets:

$$\eta_{\text{module}} = \eta_{\text{cell}} \cdot \tau_{\text{polymer}} \tag{8.2}$$

With:

η_{module} = Efficiency of the PV module [-]
η_{cell} = Efficiency of a bare PV cell [-]
τ_{polymer} = Transmittance of a polymer [-]

UV-stability

Polymers which show ‘good’ to ‘excellent’ UV stability are the fluorides (ETFE, PTFE, PVDF, FEP), polyimides (PEI, PI) and silicones. Polyolefins (PP, PE, PMP, PB) show less UV stability, ranging from ‘poor’ to ‘good’ and the remaining polymers (Epoxies, PEN, EVA, PVB, TPU) also show ‘fair‘ to ‘good’ UV-stability, see Table 8.10.

Table 8.10: Polymer UV-stability.

Category	Polymer
Poor UV-stability	PE, PP, GFR PP, PMP, GFR PMP, PB
Fair UV-stability	GFR Epoxy, PE, GFR PE, PP, TPU, GFR TPU, EVA
Good UV-stability	Epoxy, FEP, GFR FEP, PTFE, GFR PTFE, PE, PP
Excellent UV-stability	ETFE, GFR ETFE, PEI, GFR PEI, PI, GFR PI, PVDF, PEN, *glass*

Transmittance

To achieve the highest in coupling, transmittance has to be near 100% over the total spectrum of the PV cell. In Table 8.11 are transmittance values given for the polymers. Transmittance of polymers has been grouped according to [130]. However, literature describes contradicting cases when it comes to polymers and their transmittance [111, 130]. This is probably due to the high variety of existing polymers nowadays, which can not be classified easily with one value for a single property. We stated that polymers with transmittance $> 95\%$ belong to the group *optical quality*. Polymers with $90\% <$ transmittance $< 95\%$ belong to the group *transparent* and polymers with transmittance $< 90\%$ belong to groups *translucent* and *opaque*.

Table 8.11: Polymer transmittance.

Category	Polymer
Opaque	GFR Epoxies, GFR ETFE, GFR FEP, GFR PEI, PI, GFR PI, PTFE, GFR PTFE, GFR PE, GFR PP, GFR TPU, *glass*
Translucent	PE, PP, GFR PMP, PVDF, *glass*
Transparent	Epoxy, PEI, PP, TPU, PVB, PB, *glass*
Optical quality	ETFE, FEP, PMP, PEN, EVA, *glass*

Endurance

Polymers which show to be good candidates are shown in Figure 8.5. This Figure shows categories for UV stability versus transparency. The numbers in Figure 8.5 correspond with the index numbers given to the polymers shown in Table 8.1.

Four areas have been identified, which are:

1. Very interesting.

2. Interesting.

3. Less interesting.

4. Not interesting.

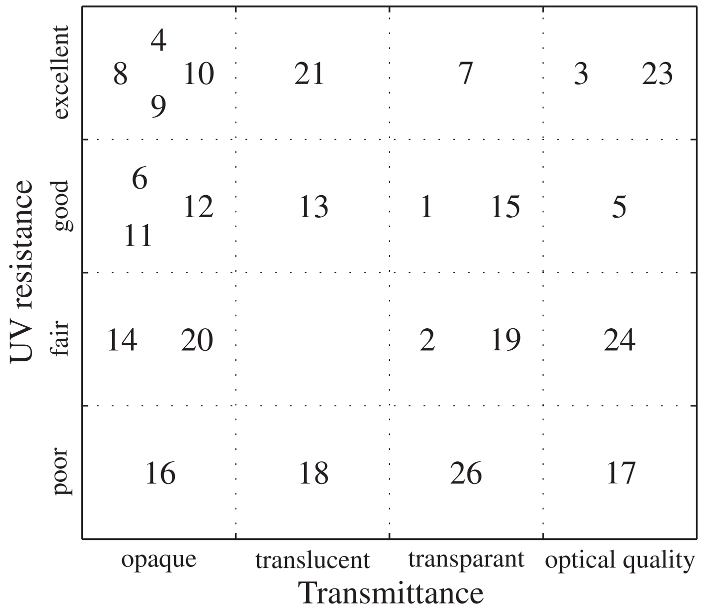


Figure 8.5: Performance of polymers for UV resistance versus transmittance. Numbers correspond to the index numbers from Table 8.1.

(1) Very interesting contains the polymers which show high UV resistance and high transmittance. (2) Interesting contains polymers which show high transmittance, but lesser UV resistance. These polymers might be of use when high efficient PV cells are to be used, but when lifetime is not of importance. (3) Less interesting contains polymers which show high UV resistance, but lower transmittance. Finally, area (4) not interesting contains the polymers which show bad UV stability and transmittance.

Table 8.12: Interesting polymer groups.

Category	**Polymer**
Very interesting	PEI, ETFE, PEN, epoxies, PP, FEP
interesting	TPU, EVA, PB, PMP
less interesting	GFR PEI, GFR ETFE, PI, GFR PI, PVDF, GFR FEP, PTFE, GFR PTFE, PE
not interesting	GFR PE, GFR TPU, GFR Epoxies, GFR PP, GFR PMP

8.4.6 Polymers' strengths and weaknesses overview

Table 8.13 shows all polymers with their strengths and weaknesses.

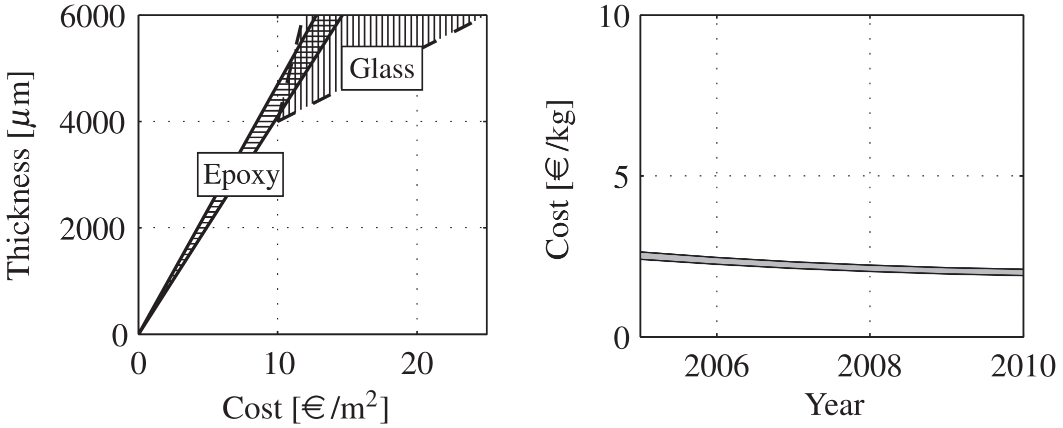
Table 8.13: Comparison of alternative encapsulants and their strengths and weaknesses.

	Strengths	**Weaknesses**
Epoxies		
PEN		
EVA	Lower cost	Higher density
PVB		Lower UV stability
TPU		
fluorides		
ETFE		More expensive
PTFE	Good UV stability	Lower tensile / impact strength
PVDF		Higher densities
FEP		
polyimides		
PEI	Higher tensile strength	Lower impact strength
PI	Good UV stability	Lower transmittance
polyolefins		
PP		
PE	Lower cost	Lower tensile / impact strength
PMP		Lower UV stability
PB		
silicones	Good UV stability	Lower tensile / impact strength

8.4.7 Weight per wattpeak ratio

When the findings are applied to a 6 m long, 1.5 m wide recreational PV boat, this would result in a lower boat weight. PV cell integration based on epoxy should have a maximum thickness of 4 mm. This thickness results in a weight of 4.6 kg/m^2 when considering epoxy's density, see Table A.3. For a PV surface area of 6.3 m^2, this would result in a weight of 29 kg. Dividing this weight over the total amount of 875 Wp, this leads to a weight per wattpeak ratio of 33 g/Wp. Considering GFR Epoxy as polymer, the maximum thickness to be cost effective with glass is 1.8 mm. It is expected that this value might be lower in practice. From the fluorides, ETFE shows good results when considering barrier properties. Structural properties however are less than other polymers presented in this research. Ignoring this, ETFEs and GFR ETFEs density is also around 1800 kg/m^3, resulting in the same weight ratio as GFR epoxy, when considering a thickness of 1.8 mm. GFR PI has a lower weight per wattpeak ratio of 20 g/Wp considering a 1.8 mm thickness and Silicones have an even lower weight per wattpeak ratio between 12 g/Wp to 18 g/Wp considering a 1.8 mm thickness. In the last three examples of polymer thickness, the highest density for a polymer found was used in the calculations of the weight per wattpeak.

A complete overview of all polymers and their properties which are compared with glass are shown in Tables A.3 to A.6. These polymers can be analyzed the same way as epoxy was in Section 8.4, resulting in a maximum thickness which is cost-effective to be used as glass replacement in PV modules. Tables A.3 to A.5 hold data of the polymers which are composed from various sources: Reinders et al. [111], Czanderna and Pern [113], Norris



(a) Cost per square meter for epoxy compared to glass.

(b) Epoxy price development.

Figure 8.6: Polymer properties for Epoxy.

[121], Sanchez-Illescas et al. [122], Warnet and Akkerman [123], WACKER [124], Kempe [125], DuPont [127], Granta Design Limited [130], Omnexus [131], Kang et al. [138] and Stockton [139].

8.5 Discussion and conclusions

We evaluated 15 polymers of which some with glass fiber reinforcement, which might be used as glass replacement for c-Si PV modules on PV boats. In the case of costs per square meter being important, epoxy is an affordable polymer between € 1.96 and € 2.15, good UV resistance and tensile strength between 45 Mpa and 90 Mpa. In the case of cost per gained speed being important, more expensive polymers such as the fluorides, polyimides and silicones show good properties to be used in PV-powered boats. These polymers have excellent UV stability but have higher cost, between € 8.00 and € 35.00. Silicones show very low tensile strength: between 0.4 MPa and 12 MPa. As conclusion, silicon-based PV modules for use on recreational PV boats need structural support. UV stability varies a lot per polymer compared with glass. Fluorides and polyimides seem to be the best candidates considering UV stability. The polymers and GFR polymers evaluated in this research to embed PV cells for PV boats reduce the total boat-weight significantly. Especially Silicones can reduce PV module's weight between 79% and 91%. When considering the energy conversion performance, ETFE and PEN seem good candidates with high UV stability and transmittance. This should ensure a long lifetime for the PV cells when these materials are used to embed PV cells. GFR fluorides should be tested for their transmittance and might provide enough structural support to act as glass replacement in PV modules and thereby reducing the weight per wattpeak ratio. When the price for fluorides would decrease, it could be an economical attractive alternative, not only to increase the maximum speed of PV boats, but also as price per wattpeak for PV modules, placed in PV boats.

Not all polymers show reliable data for transmittance. This should be subject of further research.

Chapter 9

Conclusions and Discussion

Conclusions and discussion

The result of this research demonstrates a tool which comprises models and algorithms to determine the energy balance of PV boats, with special focus on the integration of PV into these boats. The novelty of this research is that existing models are linked together into one environment. Boat building tools and models exist, but are usually stand alone. PV system tools exist, with which the energy balance, power output or energy yield can be determined. However, when it comes to specific loads in combination with moving objects, these tools are not sufficient to calculate the energy balance of PV boats. Another very important result from this research is that by determining physical properties of the PV system, including the batteries and auxiliary equipment, the impact of the system components on the energy balance can be determined. In the case of a PV boat, the weight of the batteries and PV modules can have negative impact on the end-performance of the PV boat.

The tool which has been developed has been integrated in Rhinoceros, a 3D environment used by boat designers. The tool comprises models with which the performance of PV boats can be determined. In the form of a plug-in, a boat designer can easily design their boat and add a PV system. After that, simulations can be executed to determine the energy balance for various sailing scenarios. Furthermore, the user is able to simulate a sailing boat over a specific trajectory, anywhere in the world. Especially for boats equipped with tilted PV modules, such a tool to determine the energy balance of PV systems in combination with moving object is new, since the orientation of the modules is dependent on the bearing of the boat. This can lead to several conclusions, of which the three most important are:

1. The boat can sail on PV entirely. This includes propulsion and HEP loads.
2. The boat can sail partly on PV. This usually means that HEP loads are powered with PV, but propulsion is not.
3. It is not feasible to propel or power HEP loads with PV.

Such knowledge in an early design stage could lead to different boat designs, better planning of the energy system or even rejection of initial designs. That makes this tool an asset for boat designers. New technologies, such as PV, are not the standard system components a boat designer has to work with and as a result not part of their knowledge. Although experts are able to ‘predict’ the performance of boats, even equipped with PV, at forehand based on experience, the limits of use of PV power on boats can now be proven mathematically.

Besides being a tool for designers, other parties might have interest and benefit from this tool. This tool can be used for educational purposes. For example students can get easier insights in PV systems and the availability of energy with certain system configurations. PV systems can be easily dimensioned according to the needs of the user and energy balances can be simulated. In product design, this tool can be of great help to design better performing products which entirely or partly run on PV.

As such, a framework has been developed which enables boat designers to determine the performance of PV boats, before they are even built. This framework has been developed in a modular way and uses generic models. Research which applies to specific topics, can be integrated in the framework, which is part of the tool described in this dissertation. In that way, this tool can easily be upgraded if necessary in the upcoming years.

A second results from this research is the identification of various materials to replace glass in conventional PV modules with as aim to reduce the weight of PV modules for better integration into boats. Replacing glass with polymers can decrease the overall weight of PV modules which has a positive impact on the performance of (especially smaller) PV boats.

In general, this dissertation demonstrates the opportunities of transport with renewable energies on the water as a new development. The research question of this dissertation therefore is: ‘How to aid boat designers to design well-performing PV boats, with the focus on choosing optimal PV system components?’ In order to answer this question, five sub-questions have been formulated.

1. ‘What are the design criteria of PV boats?’

Two design methods and design aids can be identified which can be helpful for the design of PV boats. These two methodes, the systematic design approach by Pahl and Beitz and the ship design spiral by Hollister, can complement each other in such a way that better performing PV boats can be designed. It is expected that the design and building of PV boats will be in low numbers and as such, the design does not need to be perfect.

2. ‘What are the design features of existing PV boats?’

During this research, certain design features for different boats were unknown. To conclude, design features for PV boats need to be standardized. Certain design variables are important, such as length, width, motor power and a particular sailing speed with corresponding sailing autonomy. However, not all data for all 183 boats was available making it difficult to compare all PV boats’ design features.

Existing PV boats show the potential of sailing with solar power. Especially boats up to 10 m show good performance with respect to maximum speed. Larger boats are able to transport a relatively large amount of persons with solar power. However in general most PV boats show relatively low performance with respect to maximum speed (in a range between 10 km/h and 15 km/h) compared to PV boats which participate in the DSC (with the maximum speeds in a range between 15 km/h and 40 km/h).

The DSC is a good example of relatively high efficient, well-performing PV boats. These PV boats are characterized by a low weight design and a relatively large surface area available for PV modules and a relatively small battery capacity and small electrical motor. This indicates that PV boats participating in the DSC sail more efficiently. Other PV boats show lesser performance, partly because not all available surface area on these boats is used for PV modules.

3. ‘How is PV boat performance defined?’

In a design process, the success of a design is determined by comparing the end-result with initial demands. By determining performance indicators of PV boats, measuring and comparing performance values can be enabled. Therefore, a PV boat has been monitored and analyzed in 2010 and an upgraded version of that boat has been monitored and analyzed in 2012 and 2013.

The tool presented in this dissertation is an aid to evaluate the performance with respect to the aforementioned issue. In practice, it is impossible to determine one value for the performance of PV boats. However, the tool presented in this dissertation can be an aid to determine the performance of PV powered boats, by comparing various PV boat designs under the same conditions.

It is fairly easy to determine the energy yield of stationary PV systems, whereas boats are dynamic systems. However, it is impossible to compare PV systems which are installed onshore with PV systems on boats. Obstructions such as bridges and trees have a negative impact on the energy balance of PV boats. Therefore, the energy yield of PV boats is always lower compared to stationary systems.

4. ‘Which models and their algorithms are needed to simulate the behavior of a PV boat’ To understand how to improve PV boats as a whole, knowledge of the interrelationship between the individual components will lead to better performing PV boats. The PV boat designer is offered an aid which fills the knowledge gap with PV power in the ship design spiral. In that way, a PV boat designer can design his PV without having the need for expertise knowledge of PV systems and energy balance calculations. Therefore as a result, the focus is on a tool with models to simulate the impact of the PV system on the technical and financial performance of PV boats.

Solar trajectory algorithms were used, which have a maximum error of 0.2°. By using the Perez diffuse irradiation model, diffuse irradiation on tilted PV modules can be estimated. However, large errors of up to 33% can be introduced when this model is used on tilted surfaces, requiring careful consideration of the results by the user.

An alternative albedo ρ fit for water surroundings is used to determine the reflectance on PV modules which are in a water environment. Some work can be done to increase the accuracy of the models to determine the reflectance on water surfaces.

PV modules in this tool are described with a model from Phang et al. which shows an accuracy of 95%. The model from Phang et al. has been implemented in C++ and integrated in the tool. With the Newton-Raphson method, IV curves can be determined to find the MPP of PV modules.

Currently, not all electrical and mechanical components are integrated in this model. Reliable models for PV modules and the solar positions are integrated. However, reliable generic models for battery packs and other electrical components have not yet been used. The battery models show low accuracy when high power is demanded from the battery. For the case of PV boats, power demand can occasionally be high. These components which are not modeled in detail, are considered as a source of losses which is constant. The same is the case for mechanical losses, such as seen in the drive train.

To determine the hull resistance for a boat model, ORCA can been used. However, the error in the results from the hydrodynamic calculations is unknown. Furthermore, it is likely that the error can be different for different boat hulls.

The validation of monitoring and simulation data for five specific cases and one boat shows RMSE and MAE values in the range of 1.9% to 32.3% . When comparing the power which goes into the battery for monitoring and simulation data, the RMSE and MAE values are respectively 21.4% and 19.7%. The RMSE and MAE values for the power which goes out of the battery are respectively 32.3% and 27.5%. For battery SOC, the RMSE and MAE values are respectively 3.1% and 1.9%.

To conclude, when comparing values for in- and outgoing power between monitoring and simulation data, the RMSE and MAE errors are relatively large. This is not the case for RMSE and MAE values for battery SOC. The range for The RMSE and MAE values decreases when summing the energy values for an increasing number *n* of timestamps. This suggests that with a number of timestamps which is large enough, a more accurate estimate of the maximum error can be made, when considering energy values instead of power values.

The models used in this tool are related with each other in a way that it is possible to determine the performance of PV boats numerically. The key models are for solar irradiation, hydrodynamics, the PV system and the drive-train. Not all models have been implemented in full detail. This dissertation mainly focuses on the modeling of solar irradiation and the PV system of PV boats. The hydrodynamics of boats can be determined with another tool, such as ORCA, for Rhinoceros. The drive-train has been modeled with constant resistances. The results from simulation show that these four key models are an aid to determine the performance of PV boats in an early design stage.

A simulation tool which has been implemented in C++ for Rhinoceros has been developed as aid to boat designers to integrate PV into boats. A demonstration of that tool shows that, depending on the wishes and the needs of the designer and the end-user of the boat, various topologies can be chosen to equip a PV boat with a PV system and how that choice affects the performance of a PV boat. A fast overview can be generated with various system components to optimize the design of a PV boat with respect to a number of performance indicators. The existing boat which was used to compare simulated data with, showed that for a marginal reduction in autonomy, a large reduction in vessel cost can be achieved.

5. ‘Which opportunities exist in developing better performing PV technology for PV boats?’ In some areas of PV, opportunities exist to increase the performance of PV system components, in order to increase the overall performance of PV boats. For example, from an aesthetic and energetic point of view, conventional PV modules are not fit for use on smaller PV boats. Therefore, 15 polymers were evaluated of which some with glass fiber reinforcement, which might be used as glass replacement for c-Si PV modules on PV boats.

It was concluded that silicon-based PV modules for use on recreational PV boats need structural support. UV stability varies a lot per polymer compared with glass.

GFR fluorides should be tested for their transmittance and might provide enough structural support to act as glass replacement in PV modules and thereby reducing the weight per Wattpeak ratio. When the price for fluorides would decrease, it could be an economically attractive alternative, not only to increase the maximum speed of PV boats, but also as price per Wattpeak for PV modules, placed in PV boats.

The PV systems of two boats have been monitored for a relatively short period τ. For future research, more periods of monitoring can lead to more accurate results. It might also lead to better insights in PV boat behavior with respect to the performance ratio in relation to the PV boat’s power-speed relationship. More monitoring should be done on PV boats. This might lead to better insights on how these boats are used and in what way the energy balance of these boats can be optimized.

Since PV boats are not continuously used, it is better to compare the available irradiance with the used power during the time of use. This will result in a measure for the PV system efficiency instead of a measure of how much solar energy is effectively used.

More boat hulls and configurations should be simulated in the tool described in Chapter 5. The results can either conclude that the models used in this tool are either specific or generic. If the models used in this chapter are specific for the boat used in validation, steps have to be taken to create a more generic model.

To make the model and its implementation as a plug-in for Rhinoceros available for boat designers, a good GUI should be added to the plug-in. Momentarily, the tool only works with a CLI, which might be too difficult to work with practically for less-experienced users. Furthermore, input from boat designers should be used to further develop this tool and its models meeting the demands and wishes of boat designers who want to add PV in their designs.

Further development of this tool should include various irradiation conditions, or a range of irradiation conditions as well as a better integration of various system components. More components and their descriptive models should be included in this tool, so that the performance of PV boats can be determined by just adding and simulating components. Research and validation of irradiance on open waters is needed to optimize the models used in the tool.

A more in-depth research into various tools to determine the hull's hydrodynamics should be done, since a number of experts working in the field of CAD boat design do not share a common opinion on which tool fits best purpose or shows best results to determine a boat's hydrodynamics.

Depending on the environmental conditions such as wind speed and water current, accuracy of boat speed calculations can differ significantly. More research can be done in this area to find the effects of water currents and waves and the impact of these effects on the performance of PV boats in simulation.

An important factor to increase the success of PV boats is the human factor, which can also be observed for other forms of electric transportation. Future research should address the aesthetics and user willingness to sail with PV boats. Results from such research could lead to alternative design constraints, which can help to increase the performance of PV boats.

Chapter 10

Epilogue

10.1 Introduction

The purpose of this chapter is to communicate experiences with PV boats, in order to support the research question in this dissertation. Furthermore, the experiences I had in PV boat design and building PV boats seems sometimes as stating the obvious. This chapter describes tacit knowledge, with the idea that professionals with experience can have an important role in developing knowledge [140]. However, this chapter is not set up in a scientific way, but it describes my personal experiences and as a result, holds my personal opinions.

I participated in two world championships and I also helped building several PV boats. This was an amazing experience for me. Firstly I had the chance to do my work theoretically and experience it immediately after in practice. Secondly I had the opportunity to meet very interesting people during my PhD, that are connected to PV boats. Especially meeting the people who bring the innovation in solar boats to practice was a real pleasure. Thirdly, during my participation in two world championships I have learned many lessons to improve the performance of PV boats. These lessons are however not explained with the models in this research. Last but not least, my PhD took for the larger part place in Friesland. The province of Friesland funded for a large part my research, and at NHL University of Applied Sciences I worked at the Maritime Center of Expertise. A total different setting for a PhD student, far away from a university setting like the University of Twente. I have no doubt that I walked a different path to reach my research goals compared to other PhD-students that carry out their projects alone.

In November 2009 I started with my PhD at the university of Twente. In the beginning I worked mainly at the University since I was doing preparations for the course Introduction into Sustainable Design, also given at the University. I visited NHL University of Applied Sciences several times. But at that time, we worked in the previous educational building (which does not exist anymore) and it was suggested to fully start my PhD in the new building in January.

10.2 2010

A new year and a new start in a new building and a new environment. Almost immediately I was asked to participate in the already formed team of NHL University of Applied Sciences. I knew something about PV, and the team knew something about boats. The Maritime Center of Expertise had already made plans on how to build the best performing PV boat for the Frisian Solar Challenge (which in 2012 was called the Dong Energy Solar Challenge). It felt like a challenge to join so I accepted.

As the race approached (somewhere in July), a complete boat was built. A hull was made from carbon-epoxy, conventional PV modules were placed on the deck, MPPTs from DriveTek were installed, batteries from MG Electronics were bought, a deck was built, propellers were milled and stern drives partly made by hand. This turned out to be my first experience in building a boat from scratch. According to the Maritime Center of Expertise, it had to be the fastest and quickest boat in the field.

And it was! We first encountered the incredible potential of our boat Scylla[1] during the

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[1] Her name was Scylla, after the Greek mythical creature with 6 heads which terrorized the seas. Our team

sprint, a mandatory event of the Frisian Solar Challenge. During the sprint, we could classify for start positions for the race. Our Scylla reached a top speed of 28 km/h and finished second overall. In our class by far the fastest. In total around 45 boats participated in the sprint, of which at least 8 had twice the power installed we had on board (different class). In my euphoria during that sprint event, I fell and broke a toe.

Although I was a bit disabled (walking did not go so well), it did not stop me from contributing ideas. In the approach to the race, I had developed a model with which the energy balance of the boat could be determined. A simple set up in a spreadsheet program, not particularly accurate, but I thought it could be helpful as guidance during the race. Especially questions such as how fast to sail to reach the finish with an empty battery but with a constant average speed were the drive to develop that model. Of course, the variable in that model is solar irradiation which was always the tricky part.

I stayed behind at NHL University of Applied Sciences together with Marco Roorda, another team member, and we guided the race from there. This led to the setting up of the 'command center'. During the race, we monitored the boat, followed its location, followed the stand-by team[2], monitored the weather, the irradiation and the energy balance.

That in itself was a very exciting experience. Imagine tracking a boat during a race while simultaneously tracking other boats on a computer screen. This is comparable to watching a game without having influence on the end-result. Some races took several hours, so we sat for 3 or 4 hours, gazing at computer monitors to see tiny boat sprites moving pixel by pixel from start to finish. In my opinion, that was and extremely exciting experience.

If everything went well during the race, then I could conclude this section with the championship on our name. But in those five days during the race a lot happened! As said before, we had an extremely fast boat and we were well ahead of other teams. But having a fast and quick boat, does not necessarily mean that it is a reliable boat. When we sailed from Sloten to Stavoren and crossed the Slotenlake[3], a lot of water got trapped in our boat. Waves were reasonably high and some water entered the boat at the driver's position. At that time we did not consider it to be a big issue, since a bilge pump was installed in the boat.

However, some time later the boat started falling back. The weather conditions were too good to accept the low output of solar energy. But we were unable to explain what the cause was. This led to other teams overtaking us. At that time still not really a problem, since we had a strong position in the overall ranking. Furthermore, we did not had a reference cell onboard, so there was no way to estimate the performance of the PV system. However, according to the driver it was hot, the skies were clear and there were hardly any clouds. But the solar output was 150 W with a 875 Wp PV system. The conclusion was that we were running on 1 PV module!

In that boat, we installed per PV module an MPPT[4]. We figured out in our command center that 4 out of 5 PV modules were not operating and that it might be connected with the water which entered the boat. How it happened was not clear, since all MPPTs were in watertight compartments.

Our stand-by team was asked to take a look. They discovered that the watertight com-

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consisted out of 6 people (Later 8, but that is a different story)

[2] The stand-by team followed the boat on shore with cars as close as possible to give aid if there were problems.

[3] Some people pronounce this as the Slaughterlake, since it is a difficult crossing.

[4] MPPTs make the PV modules work in their best performance point.

(a) MPPTs in a watertight compartment.

(b) The command center.

(c) Pole position during FSC 2010.

(d) A-boat Scylla during FSC 2010.

Figure 10.1: Photo's during the Frisian Solar Challenge 2010.

partment was flooded with water and our MPPTs were all under water. That confirmed our guess that 4 out of 5 MPPTs were not working was correct... The fact that the watertight compartment was flooded and the presumed loss of our MPPTs demotivated us. We figured we could never win the race without MPPTs. So the boat set off and continued its slow-speed race. If I remember correctly, we did something like 7 km/h whereas other teams did 13 km/h or thereabouts.

After some time and consideration, we instructed our stand-by team to stop the boat once more. Perhaps we could pierce the bottom of the watertight compartment and drain the water. Perhaps the MPPTs would still work? And so it was decided. The boat was stopped once again, the team removed the PV module, drained the water, and... we had full working MPPTs again! So the boat went of with its incredible speed and fortunately most was not lost for us. We only lost our gained position time. I think we were about equal with others, but we were still at pole position.

At the end of the race we evaluated how the watertight compartment could be flooded. It turned out that one of the team-members had drilled holes in the bottom to position the compartment with tie-wraps. Then tacky tape was used to ‘close’ the holes.

Although we lost considerable time, the championship was not lost yet. The next day we started off very good and sailed at pole position in our class. We were well prepared and I directed the race from the command center. Before the race, I analyzed areal maps from Google earth, to ensure the driver of our boat would not make any mistakes such as wrong turns: a feared mistake among all teams. But how much I analyzed and prepared with our areal maps, I never participated that these maps might be outdated. This made us pay a huge prize.

Somewhere along the route, the driver approached an ɥ-junction. According to my map, the main route was a wide canal originating from the south going up north with a left turn followed by a right turn. Where the route turned left, a small canal, hardly 2 or 3 meters wide, went straight ahead. However, a new housing project was realized in that area and for some reason the width of that small canal was extended and matched with the wider canal. Not taking this into account, it appeared as if we could sail straight ahead. We did and we got stuck! The canal was widened, but not deepened. The new canal brought so much confusion to the other teams too, that the team who sailed at second position got stuck next to us. The third contender realized it in time, seeing two boats stuck in the water. Although they sailed into the new canal, they were able to reverse and take the left turn. And so did the other teams.

In the meanwhile the alarm bells in our command center were ringing and we organized a rescue party and send out the stand-by team. After a quick inventory of the problem, we first helped the other team on its way, which was just a simple push in the right direction. Then we concentrated on our own boat. Unfortunately our stern drive was bent. We sent the boat on its way but after a couple of hundred meters, it turned out that more work needed to be done to fix the stern. Of course we did it on site, but it took too much time and that day, the race was lost. We finished, but we lost our pole position.

A complaint was lodged at the race jury, stating that the maps were not clear that they had given us[5]. Since we were sailing at pole position and after the race having the knowledge that other teams found it also unclear how to sail, we wanted to have a compensation for our lost time. And so we did! They rewarded us with a 2 minutes bonus (2 minutes were subtracted from our end time). However, these 2 minutes did not make up the time we lost, which was over 1 hour.

In the succeeding days, we sailed with average results. Sometimes we encountered problems in our boat which delayed our aim for pole position. As a result, on the last day, there was no chance for us to finish first in our class. But we could reach a second place! It meant we had to do the last sprint with full power. Something we were best at. After calculations with my model, we had to sail with a speed of around 25 km/h over a distance of several kilometers. Our battery was full, the sun was shining, so it was feasible.

Sailing with those speeds meant also we had to draw high currents of around 120 amps from our battery pack for a period of about 20 minutes. One of the most important things we had to monitor was the temperature of the battery, which should not exceed 65 degrees centigrade. Otherwise, the BMS would disconnect the entire battery until it reached a temper-

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[5] The race direction handed out route maps to guide the drivers and normally, at difficult, or unclear locations, they place arrows or send people out to provide for directions.

ature within its limits. And so we went off and we kept an eye on the batteries temperature. Everything went well so far.

The finish of that day's race was also the finish of the entire Frisian Solar Challenge. The last leg was a sprint so it was an amazing event for spectators. The finish was in the Prinsentuin in Leeuwarden and the boats had to pass NHL University of Applied Sciences. We set up our command center in the Prinsentuin and we waited, with the other team members from the stand-by cars, for our boat to arrive. What could go wrong? We were all watching our boat's sprite, progressing pixel by pixel to our current location.

Suddenly the sprite on the screen stopped and it was just in front of the NHL University of Applied Sciences building! Contact with the driver revealed that 'all electric systems shut down suddenly and nothing is working anymore'. Our driver remained calm and went through all the steps to get the boat going again. Nothing worked. In the meanwhile, team members rushed to the boat for help. After 15 minutes (other boats were passing us and finishing), it turned out that the main circuit breaker cut the power from the battery. No clue how that could happen. Besides that, the worst thing was that that breaker was in the back of the boat: out of reach of the driver. Talking about design errors! I had pleaded for rocker switch circuit breakers. If they go, they are easily put back in their original position. Something which is much more difficult with glass fuses. But we never thought of the reachability of the fuses. Especially that one, which was the mains. If there should be a short circuit, the smaller ones would have gone first.

After a delay of 15 minutes, we got to the circuit breaker and we finished the race. But why did that circuit breaker cut the power? We were not exceeding the maximum current at all.

That particular type of circuit breaker was regulated by heat. Around 60 degrees centigrade, it would cut the power. And it was positioned next to the battery. Copper is a great conductor, so most probably the heat of the battery heated up the circuit breaker. After 15 minutes of cooling down, the temperature was within the limits and we could sail further and finished with what we started with in the first place. Our overall position: 3$^{\text{rd}}$ place.

My first experience with the Frisian Solar Challenge: what a rush! It was amazingly exciting and fun to do. We had stress, especially in the command center where you see everything happen, but where you are without power to really do something.

The Maritime Center of Expertise showed that we were able to build a fast and quick solar boat. But we suffered from so many human errors, that we lost our pole position. The boat was simply the best in our class, but we were not able to sail the race without breakdowns. And it did not only happen to us, other teams with innovative PV boats encountered serious problems. For example team Andela, which introduced sailing with hydrofoils and showed a fast boat, but encountered so many problems that he had to drop out of the race. We would see him back in 2012 with an even more daring hydrofoil design.

Innovation and technology is one thing, but reliability is the other. And we needed plenty of that.

10.3 2011

The year 2011 was not a very exciting year when it comes to solarboat racing. However, it was the year in which I had some participation in building the PV-sportsboat and the Liyang-boat. Furthermore, with my experiences during the Frisian Solar Challenge 2010, I suggested some changes at NHL to create a better team with an improved organizational structure and more continuity. Furthermore, a centralized command center had proven to be very effective. Taking responsibility out of the hands of the driver when it comes to race strategy and directing stand-by cars in case of emergencies is better commanded externally.

At the end of 2010, the beginning of 2011, the PV-sportsboat was realized. The PV-sportsboat was a commercial spin-off of our 2010 racer. The PV-sportsboat was a nicely designed boat based on the hull of our racing boat. The weight was a bit increased for usability and stability and more batteries were added to increase the action radius. Lightweight, semi-flexible PV cells were integrated in the deck.

During the building of the PV-sportsboat I was actively involved in the shaping of the hull. For a whole week, a group of enthusiasts and me used filler to get the proper shape into the deck of that boat. Although the boat was built as light weight as possible, adding around 25 cans of filler does add up to the total weight. It shows that when building these kind of boats, where weight is of utmost importance, at the end of the building process the boat needs to be perfect. Every adjustment in the form of filler or paint is an addition of weight to the boat and therefore an addition of the total hull resistance (basically...; some exceptions exist).

Mid 2011, I started to develop ideas on how to give the solarboat racing at NHL an impulse. In previous years, boats were build with great efforts and creativity of my colleagues at the Maritime Center of Expertise. However, they felt a bit alone in that process. Something that I also identified during the building of the boat in 2010. So we started thinking up ideas on how to create a more NHL-wide awareness of our solarboat mission and to promote solarboat racing. I talked with many people at NHL and after a long period of time, NHL Solarboat Racing was conceived. A fully continues, multidisciplinary team which developed solar racing boats, not only from engineering studies, but also with students Communication, Communication Multimedia Design and even students from another University of Applied Sciences: Stenden Leeuwarden. We created our own brand, website and corporate design. We thought big and effective.

At that time Bjorn Harink, from the University of Twente, was helping me to set up a marketing plan with goals and mission. We visited some companies which might be interested in sponsoring us. Some of them, we still cooperate with. We created a large team, with over 30 people and the aim was to participate with two boats in the Dong Energy Solar Challenge in 2012.

Since we were a solar team from the Maritime Center of Expertise, many schools and companies came to us with questions about solar boats. But we never had the question before if we could actually build a boat for a team. We were asked by a city in the Province of Liyang in China if we could build a boat for them, so that they could participate in the solar challenge. And we accepted. Partly from the Maritime Center of Expertise, but also partly from NHL Solarboat Racing, we worked together to build that boat. From my point of view, building first that Liyang-boat was a great opportunity (for me, and the students) to get experience in building a solar boat. Basically, it was the same boat as our solar racer, but we built it more

(a) The PV sportsboat spray-painted.

(b) Driver’s spot of the PV sportsboat.

(c) The PV sportsboat finished.

(d) The PV sportsboat in the water.

Figure 10.2: Photo’s during the building of the PV-sportsboat.

reliable and cheaper (since we considered it to be a commercial product). For me, building that boat was great fun and a good experience.

We made the Liyang-boat shiny red and around the front PV module, we placed stars with decreasing size. It was a wink to communism and their flag. However, we felt a bit insecure: how would they respond to it? We truly hoped the Chinese team would not be insulted by it.

10.4 2012

We started 2012 ambitious: our[6] plan was to participate in the Dong Energy Solar Challenge with 2 solar boats. A newly built replica of our 2010 boat and a newly designed T-class boat: the best of the best.

The lay out and the plans for our A-boat were more simple then the new T-boat. We had the experience from 2010 and the experience from the Liyang-boat. But the T-class boat had

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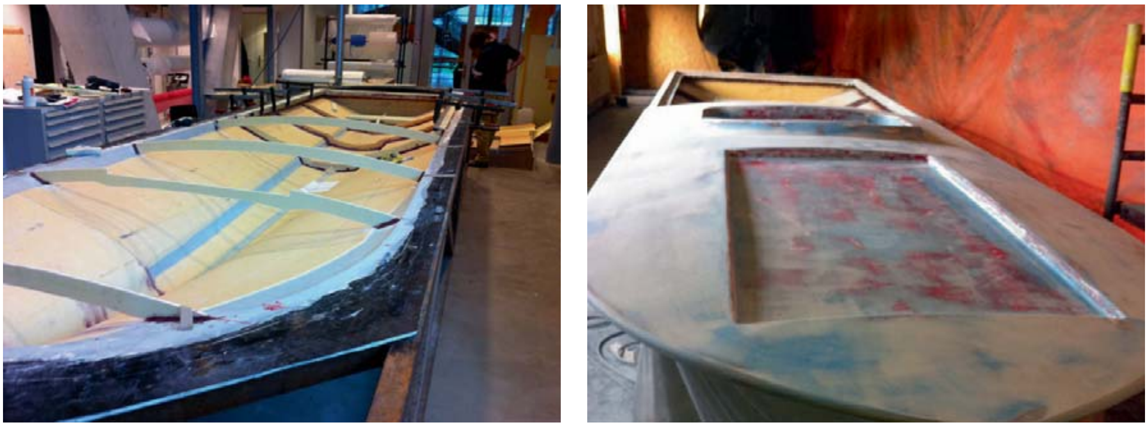
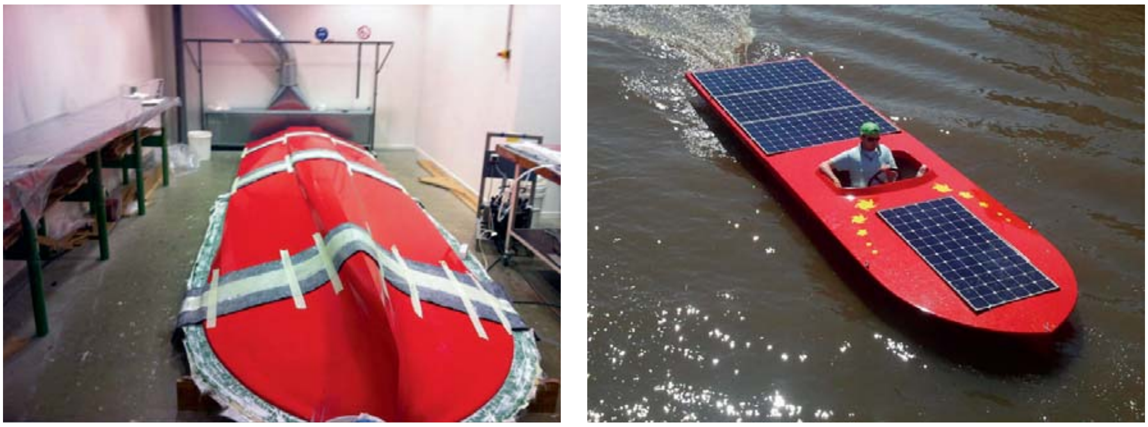
[6] The team consisted out of the members of the Maritime Center of Expertise, many students from all kinds of studies, students from Stenden University of Applied Sciences Leeuwarden and even volunteers, and hired experts.

(a) Lamination of the Liyang boat's hull. (b) Vacuum injection of the hull.



(c) Supports for the deck of the Liyang-boat. (d) Final fillings of the deck of the Liyang-boat.



(e) Creating trailer supports for the Liyang-boat. (f) The Liyang-boat in the water.

Figure 10.3: Photos during the building of the Liyang-boat.

to be a new design. We wanted to integrate hydrofoils in the design and we had to develop our own PV modules. Both expertises we did not had. Jan van der Zee, student Maritime Engineering, convinced us that he had good plans for a great hydrofoil design. Furthermore, we had contacts with ECN[7] and a lector solar energy and mobility just started in his position. So we thought we had it all worked out. Build a winning A-boat, replica from 2010, to win the Dong Energy Solar Challenge and build a T-boat, not necessarily to win, but at least to practice and get the experience with hydrofoiling.

I suggested to monitor the energy balance, temperatures and so on, of both boats. But to do so, we had to develop a telemetric system. With Timo Schraa and 2 students electrical engineering, Max van Kessel and Casper Kloppenburg, we developed such a system, which is still in use. Furthermore, we developed a GUI to visualize our readings.

I was truly enthusiastic about this race and the building of both boats, but due to my other work (I still had to do a PhD) private circumstances and the pressure to be teamcaptain of both teams, I had to bail out one month before the race. Stress had caught me and I needed to focus on my priorities.

One week before the race, I picked up where I had left and in the meanwhile our A-boat was finished and the T-boat was still under construction. The team who was responsible for the T-boat had done a great job: in such a short time building a boat from scratch.

At the beginning of the race in 2012 we had one finished A-boat. It sailed well and everything was working. The T-boat however was another story. The monitoring and telemetric system was not working. Even worse, the driver did not have a monitoring system on board (except for a rudimentary voltage indicator). Although the PV system was built and installed on the boat, it was not working. Under all circumstances, ingoing power was 0 watts. For a race on solar energy, that is problematic.

To prove that a participant can sail the race, every contender has to show that they can sail a distance of 10 km with an average speed of 12 km/h. For our A-boat that was no problem, but for the T-boat it was! First of all, to sail an average speed, one needs to know the speed of the boat. From the organization every participant got a transponder, which showed all boats on their website. With that device we could estimate the speed of our boat. That was one problem solved.

Once the speed of the boat is known, it is important to know how much power is needed to reach that speed. That relationship we did not know. Furthermore, we had no clue of the SOC of the battery. We knew that is was full when we started, but we had no idea how much we drained at 12 km/h. The only parameter we could read was the voltage of the battery. With data from 2010 (we used that same battery in the 2010 boat), we could relate the voltage readings to state-of-charge. So basically, during the first race to prove our capability of racing, we also developed simultaneously the models to estimate energy levels, outgoing power and speed relationships for the T-boat.

Keeping in mind that we still did not had working PV modules on our T-boat, we entered the race. If we finished (a big IF), we still had one night to fix the PV system. Without PV system all was lost, since then we had no means of charging our batteries. We told the driver to sail at the minimum speed, 12 km/h, to finish in time and to make it over the total distance. We crossed our fingers and off we went. Sitting in our mobile command center, a

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[7] ECN is the Dutch Centre for Research into Energy.

(a) The T-boat from NHL Solarboat Racing.
(b) The A-boat from NHL Solarboat Racing.

(c) The A-boat for repairs on shore.
(d) The command center in 2012.

Figure 10.4: Photos during the Dong Energy Solar Challenge 2012.

nice idea developed by students from Stenden, we looked at the screen and watched our boat going slowly. It took a bit less than 1 hour, but we managed to cross the finish line, within time! We celebrated, of course, but almost immediately we received a phone call from the driver. He needed assistance, since his battery was depleted at the very moment he crossed the finish line and now he was at drift.

Excitement while tracking the T-boat. In the meanwhile, we evaluated other teams in the A-class and we soon discovered that we had heavy competition. Later it turned out that one team was better then us on all fronts. Another team was sailing more efficiently, but was not a match during sprints. Two or three other teams were heavy competitors on sprints and endurance. It was going to be an exciting week.

We returned to the paddock to do the last work on our T-boat and to make it race-ready. By systematically excluding all components between battery and PV module, I found out why the PV system was not working. Firstly, the modules needed a main switch which can connect or disconnect the modules in case of an emergency. The main switch regulated 2 relays which could break the left and right group of modules. I discovered that the relays were connected in series instead of parallel. An error which can overcome the best engineer, so with that discovery we thought we solved the problem of the PV modules which were not functioning.

We connected the relays in the right way and... nothing. Still the power output was 0 watts. It took us a while to find the second cause of the problem. PV modules are equipped with a bypass diode, in case the cells are overshadowed. I found out that most of the bypass diodes were connected wrongly (anode and cathode reversed), causing the PV modules being short-circuited. It was already turning dark so we needed lights and electricity to solve that problem. No way we could find other diodes at that time, so we had to use the old ones, hoping they were not damaged by the high currents. We reversed all diodes which needed reversal and once we were finished it was already around midnight.

We realized that it was late and the next day the first race would start. And our battery was still depleted, so we had to charge it, which was still allowed for that evening. Basically Bjorn and I sat there with the boat, waiting until the battery was charged. We borrowed a power supply which was rather expensive from another team under the condition that we kept an eye on it at all times. It only took 4 hours...

During that race week, we did not encounter so much trouble with both boats. The only large disappointment was that the PV system of the T-boat was not working optimal. We estimated that around a third of the maximum power was being generated. Two occasions are worth mentioning during the race. First, we encountered bad luck with our A-boat and secondly the presumed loss of our T-boat.

We had accepted that at least 2 teams were our superiors. But we could still make it for third place. And that was extremely exciting, since race strategy became amazingly important and we had to sail very sharp. However, bad fortune struck us during one of the last days. Just a few kilometers from the start, our steering system failed. It turned out that the steering cable cut through a support beam, which was there to keep tension on the cable. No tension meant no steering capabilities.

Disappointed with that event and knowing that a third place was lost, we did not gave up. I was sitting in the command center and I talked to the driver. The driver was so frustrated that he wanted to quit immediately. So my first job was to convince him to stay in the race. That we could solve it. Then, I needed an evaluation of the problem. In the meanwhile I had instructed the stand-by team to aid and do repairs. Of course, the location was very difficult to reach, which took some time. While talking to the driver, I analyzed the problem and I came up with a replacement part which the stand-by team could construct on-site. I made a drawing and sent it to the team. Once the team arrived, they could easily construct the new part and position it in the boat. And the boat went of again and joined the race.

Another problem we encountered during the race is worth mentioning. Firstly, because it was really exciting. Secondly, because we had a real laugh about it (afterwards, of course). During one of the worst days during the race, since we had terrible irradiation conditions, we lost our T-boat for 45 minutes. The weather was bad and somewhere along the route, cell phone coverage was poor. This had effect on the transponders from the organization, but also on the cell phone of the driver. We could not reach the driver, our stand-by team had no visual on the boat and the organization claimed that their follow-up boat[8] had already crossed the

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[8] The follow-up boat makes sure no boats are left behind during a race. In case of a breaking down, the follow-up

finish line.

So nobody had seen our T-boat, we could not get into contact so we feared the worst! May be the boat had sunk and so what happened to the driver? We called other teams to ask if they had seen something and our stand-by team was still on the look-out. But nobody had seen our T-boat and the minutes past by slowly. The organization was not as worried as we were, but as time passed by, more people started to realize that something might be wrong. In the meanwhile, I tried continuously to call the driver. Suddenly, from one moment to the other, the call was excepted and I was talking to the driver. According to him, the follow-up boat was behind him and he was slowly progressing but getting there. No need to worry.

After five days, we were running sixth with our A-boat, another team had bad luck. They took a lot of water and had to drop out of the race for safety. That event increased our position to fifth. That was also the overall qualification for our A-boat. Our T-boat reached eight place: out of eight, not really an achievement, however we had shown that with dedication we could at least sail the race. In our T-boat, nothing broke down seriously, only the PV system was not working optimal. In general, in moments of trouble-shooting we really showed what a good team can do. A small failure in our A-boat caused us our good time and thus position, but with respect to strategy, we did great things. While sailing ‘blind’ with our T-boat, we managed to interpret data in such a way that we could make sense out of it. Experience and common sense.

What happened to the Liyang-boat? We built it and we gave it to the Chinese team which had no experience at all. But we built it good and they had not problems whatsoever. Their boat did not brake down once and they placed ninth in the A-class at the end of the race. We were a bit proud of that result, because it was also ‘our’ boat which made it and keeping in mind that the team who sailed it had not experience on the water, their ninth place out of 35 was not bad at all.

10.5 2013

As a result from the hard work in 2012, I focused in 2013 more on my PhD to finish it. We participated in the Open Dutch championship for solar boats and finished third (out of third) with our A-boat. Not a good result either. However, firstly it was bad weather, secondly we did not start with a full battery, since the day before we were invited on a television show where we demonstrated our boat. It was not planned and we were not able to charge out battery manually. But that championship was more for fun then for racing anyway.

In November 2013 my contract at the University of Twente was officially ended, but immediately after I was offered a new contract at NHL University of Applied Sciences were I was bombarded as project-leader of NHL Solarboat Racing. Besides sailing with our A-boat in 2014, we decided to design a new T-boat.

10.6 2014

Momentarily I am in the final stage of writing my dissertation. The A-boat is getting a new drive-train and the new T-boat is being designed by Jacob Blom and Van Oossanen Yacht

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boat drags teams to the finish.

Designers using CFD techniques. Furthermore, this new T-boat is going to be equipped with hydrofoils, which are also designed by Jacob and Van Oossanen. Momentarily, I can not say so much about the progress of both boats, but I am looking forward to the new Dong Energy Solar Challenge, which will hold two new classes: the V10 and V20. The V10 is for youngsters from secondary school to create awareness and enthusiasm. V20 is a standard class with one standard boat which participants can buy and tune to their wishes.

10.7 The five rules in solarboat design

What have I learned during the races, the preparations for the race and all the other events with which we played with our solar boats? The next five rules are needed to build successful PV boats at NHL University of Applies Sciences:

1. Plan well.
2. Create a good team.
3. Balance your team.
4. At the same time and same place, money, means and (wo)men should be together.
5. Build light.

Planning is crucial. Without good planning, too much has to be done near the end. And when time is running out, mistakes are being made.

Good engineering and experts can increase the reliability of boats. It should be said that at a University of Applied Sciences, it is always difficult to get the best students to do the job. Some students can do their work perfectly by themselves and feel responsible for the end result. Others do not care about it. It is sometimes difficult to estimate which students are like what and that can lead to bad designs. It is of utmost importance to evoke interest with young students for PV boats, or any other high-tech engineering matters. It should be cool to be involved in races and to build racing equipment which deals with high currents and (potentially) dangerous technologies. A team does not win with students which have to participate. A team wins with students which want to participate.

A multidisciplinary team is necessary to design and build a well-performing PV boat. Without the interaction between, and the working together of engineers from various disciplines, the change of building a well designed PV boat is smaller. And to add to that, it does not only bring engineers for the success of a well-performing PV boat. Recently I experienced an increase in promotional output with our PV boat. Our boats are not the best in their classes, however, we are continuously asked by other teams how to build well-performing PV-boats and we had many publications. And I believe that is caused by our promotional activities.

Five requirements are needed to build well performing PV boats. If all five conditions are met, it is more likely that a PV boat can be realized: at the same time and the same place, money, means and (wo)men should be together. If one of these five requirements fail, it is less likely that the success and performance of a PV boat will be good.

Finally, once building a solar boat and not only for racing, remember that the less weight the boat has, the better it will perform. Water has a much higher density compared to air. The less hull is in the water and the more it is in the air, the more efficient your boat will sail.

10.8 To conclude...

In general the Dong Energy Solar Challenge shows what can be done with PV on boats. Lightweight boats with less than 2 kWp of PV power installed and a relatively small battery pack of 1.5 kWh can reach top speeds of over 44 km/h and average speeds of over 25 km/h for hours (see for example Private Energy Solar Boat Team with their FuriaIII). Lightweight, reliable and fast with the least amount of electrical power. Large steps are being taken in this race on the water and technologies developed for this Frisian race are transferred to other areas, such as the World Solar Challenge for cars, electric sailing and other appliances which depend on electric power with or without the sun.

A problem that needs to be tackled is the anxiety of people for electric sailing. However, with the boat races which I described in my research and in this chapter, we show that we can sail larger distances electric only. Sailing with PV is feasible, especially for smaller recreational boats. And we are not finished developing new, fast and efficient boats. I would not be surprised if in one or two years, solar boats as seen in the Dong Energy Solar Challenge reach top speeds over 50 km/h. Such fast boats imply that their efficiency is increasing, thus their action radius is increasing and thus being more attractive for the general public.

In my research I partly try to prove that it is also feasible to develop PV boats which are not that expensive. We do not need high-tech PV system components to create a well performing boat. In that way we can reduce the cost of PV boats and make them more attractive for the public. The V10 class, developed by Jeroen Veenema and others, shows that with standard components, 2 PV modules and a wood construction set, a PV boat can be realized under € 10 000.

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Mei mooglik makke troch de provinsje Fryslân
provinsje fryslân
provincie fryslân

Biography

Tim Gorter is an industrial design engineer who was born in 1982. During his study at the University of Twente, he was active in a high number of committees for different study associations including dance association 4 Happy Feet. Furthermore, he worked as a student assistant for various courses and he did two internships abroad; in Cambodia and in Italy. In Cambodia he researched the opportunities of LED lighting in rural areas of Cambodia, with specific interest in cost and acceptable illumination levels and quality of illumination. In Italy, he worked on an LED-PV lighting combination as replacement of office lighting which fulfills all legislation requirements for offices.

After receiving his master degree in Industrial Design Engineering at the University of Twente in 2009, he started his PhD at the same university in collaboration with the Cartesis Institute and the NHL University of Applied Sciences in Leeuwarden in The Netherlands. During the startup of his PhD, the Cartesis Institute was terminated and the Province of Friesland took over the funding of the PhD research.

During his PhD research in Leeuwarden, Tim participated with various PV racing boats in the Frisian Solar Challenge 2010, the Dong Energy Solar Challenge 2012 and the Dutch Open championships for solarboats in 2013. As a result from his participation, he established a more continues group of solar boat enthusiastics at NHL University of Applied Sciences. Important developments such as a reliable telemetric system with visualization capabilities for monitoring and analyzing solar boat data, continuation of the solarboat team and solar boats, preservation of knowledge and publishing the knowledge, as well as communication of the capabilities of solar boats to the outer world, were the result from his participation and input during his PhD. For his PhD he lectured at the University of Twente for the course ‘Introduction in Sustainable Design’. Furthermore, he was invited for numerous guest lectures, mostly regarding the topic of integration of PV into boats.

Besides his PhD research, he identified that PhD conditions at NHL University of Applied Sciences can be improved and together with a few other PhD-students he initiated a PhD network in 2012 at NHL University of Applied Sciences to increase the quality of the PhD work.

After his contract ended at the University of Twente, Tim was offered a position as senior researcher at NHL University of Applied Sciences at the department of sustainable energy. He also became project leader of NHL Solarboat Racing to prepare for the Dong Energy Solar Challenge 2014.

Scientific appendix

Journal papers

- T. Gorter and A. Reinders, A comparison of 15 Polymers for application in photovoltaic modules in PV-powered boats, Journal of Applied Energy, Volume 92, pages 286–297, 2012.

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- T. Gorter, E. Voerman, P. Joore, A. Reinders, and F. Van Houten, PV boats: design issues in the realization of PV-powered boats. In Proceedings of the 25th European Photovoltaic Solar Energy Conference / 5th World Conference on Photovoltaic Energy Conversion, Hamburg, Germany, 2010.

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- T. Gorter, E. Voerman, P. Joore, A. Reinders, and F. Van Houten, PV-powered boats: evaluation of design parameters. In Proceedings of the 37th PVSC, Seattle, Washington, USA, 2011.

- T. Gorter, E. Voerman, P. Joore, A. Reinders, and F. Van Houten, Development of a Synthesis Tool for PV Boats. In Proceedings of the 26th EUPVSEC, Valencia, Spain, 2011

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- T. Gorter, A. Reinders and F. Van Houten, A new approach In Numerical Simulation of PV Systems for PV Boats. In Proceedings of the 27th EUPVSEC 2012, Frankfurt, Germany, 2012.

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- T. Gorter, E. Voerman, P. Joore, A. Reinders, and F. Van Houten, Scenario-based simulation of PV boats in an early design stage. In Proceedings of the 39th PVSC, Tampa, Florida, USA, 2013.
- T. Gorter, P. Joore, A. Reinders, and F. Van Houten. Results from numerical simulations to determine the performance of PV boats in an early design stage. In Proceedings of the PlugBoat World Electric & Hybrid Boat Summit, Nice, France 2013.

A.1 PV boat research overview

Table A.1: Evaluated design features of PV-powered boats.

	Research features	**Dimension**	**Range**	**amount of boats**
1	Producer		*various*	96
2	Year of production		1984–2012	122
3	Length	[m]	2.1–33.0	160
4	Width	[m]	0.9–22.8	101
5	Maximum draft	[m]	0.1–1.2	45
6	Empty weight	[kg]	200–115 000	60
7	Full weight	[kg]	200–35 000	32
8	PV surface	[m^2]	1.0–536.0	75
9	PV power	[kWp]	0.2–93.5	137
10	PV technology		mono-crystalline, multi-crystalline, multi-junction, thin film	91
11	PV module orientation		*various*	158
12	Engine power	[kW]	0.1–162.0	102
13	Number of engines		1–2	47
14	Engine technology		*various*	28
15	Battery technology		lead-acid, lead-gel, lithium-ion, lithium-polymer, nickel-hydrogen, nickel-cadmium	30
16	Battery Capacity	[kWh]	0.6–230.4	78
17	Cruise speed	[km/h]	3–20	56
18	Max speed	[km/h]	4–55	64
19	Person capacity		1–150	108
20	Price		*various*	27
21	Category		private/research, humans transport, recreation, racing	175
22	Hull type		monohull, catamaran, trimaran, hydrofoils	140

Table A.2: Comparison of PV boat categories.

	Hull type				**LB ratio**				
	Monohull	Catamaran	Trimaran	Other	1:1	2:1	3:1	4:1	5:1
Human transport	15	**33**	0	1	1	8	**17**	**9**	5
Recreation	3	6	1	1	0	6	2	1	1
Private/research	**37**	15	8	1	0	**10**	**13**	8	5
Racing	8	1	6	**36**	0	1	5	2	2
Other	3	1	0	3	0	0	1	2	0

	Maximum speed [km/h]					**Cruise speed [km/h]**				
	$[0,10\rangle$	$[10,20\rangle$	$[20,30\rangle$	$[30,40\rangle$	>40	$[0,3\rangle$	$[3,6\rangle$	$[6,9\rangle$	$[9,12\rangle$	>12
Human transport	**17**	**10**	0	0	0	2	6	**15**	4	0
Recreation	7	1	0	0	0	1	2	1	0	0
Private/research	**12**	2	3	0	1	0	2	**9**	2	2
Racing	3	4	2	0	0	0	0	2	2	5
Other	0	1	0	0	0	0	0	1	0	0

	PV power [kWp]					**Engine power [kW]**				
	$[0,1\rangle$	$[1,2\rangle$	$[2,3\rangle$	$[3,4\rangle$	>4	$[0,5\rangle$	$[5,10\rangle$	$[10,15\rangle$	$[15,20\rangle$	>20
Human transport	17	7	1	4	6	**17**	7	3	4	8
Recreation	8	0	0	0	0	4	1	0	0	1
Private/research	**29**	5	0	2	5	**31**	3	4	2	1
Racing	**40**	9	0	0	0	8	3	0	0	0
Other	1	1	0	0	0	1	0	0	0	1

A.2 PV boat database

Boat	Solar Craft 1	Solar Glisseur	Basilisk 1 (T550)	Korona
Producer	Alan Freeman	Roger Martire	Artisolar	Prof. Dr. Christian Schaffrin mit Studierenden der Hochschule Konstanz (HTWG)
Year of production	1975	1984	1987	1988
Length [m]				7.2
Width [m]				
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]				9
PV power [kWp]				1
PV technology				
Engine power [kW]				2.2
Number of engines				1
Engine technology				
Battery technology				
Battery Capacity [kWh]				
Cruise speed [km/h]				
Max speed [km/h]				12
Person capacity				6
Price				100 000 DM

Boat	Solist	Anna	Yamaha Sanyo Amorton Flower	Solar Gajner
Producer	Firma Systec in Spay am Rhein	Bootsbaufirma Adlung und Kaiser auf Kiel	Sanyo Electric, Yamaha Motor	Moss Solar
Year of production	1989	1989	1990	1992
Length [m]	7	7		
Width [m]				
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]	9	9		
PV power [kWp]		1		0.4
PV technology			a-Si	8×50Wp
Engine power [kW]	2.2			
Number of engines	1			
Engine technology				Minn Kota trolling motor
Battery technology				12V, 60Ah
Battery Capacity [kWh]				0.72
Cruise speed [km/h]	10			
Max speed [km/h]			4	
Person capacity	6	12		
Price	140 000 DM	100 000 DM		

Boat	Carl	Sunboat II	Solifleur - Chlorophylle	Wasser häx TC 750
Producer	Thomas Meyer	students and staff at Prince Alfred College in Adelaide	MW Line im schweizerischen Yverdon	Artisolar
Year of production	1993	1995	1995	1995
Length [m]		11.82	8.5	
Width [m]		5.49	2.5	
maximum draft [m]			0.6	
Empty weight [×1000 kg]			1.2	
Full weight [×1000 kg]			2	
PV surface [m^2]				
PV power [kWp]			0.842	
PV technology		1728 cells		
Engine power [kW]			4	
Number of engines			1	
Engine technology		36V		
Battery technology	lead-acid		24V, 400Ah	
Battery Capacity [kWh]			9.6	
Cruise speed [km/h]			8	
Max speed [km/h]			10	
Person capacity	1		12	
Price				

Boat	Ra II	Malt's Mermaid	Marjorie K	SB Collinda
Producer		Kenichi Horie		Collinda
Year of production	1995	1996	1996	1997
Length [m]				6.7
Width [m]				2.3
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]				
PV power [kWp]	0.98	1.5		1.4
PV technology	14×70Wp			20 panels
Engine power [kW]				1.32
Number of engines				
Engine technology	Torqeedo 2000			
Battery technology	8×12V deep cycle, 65Ah	Nickel Hydrogen		
Battery Capacity [kWh]	6.24			
Cruise speed [km/h]				10
Max speed [km/h]				
Person capacity		1		
Price				25 000 GBP

Boat	Sonnenschein	Hirondelle	De Blaustirns	Aurinokvene
Producer	SUEK GmbH	Artisolar	Hager bv, NHL hogeschool	Jorma Ponkala
Year of production	1997	1997	1997	1997
Length [m]	15	11	16.5	7.75
Width [m]	3.9		3.5	2.35
maximum draft [m]	0.6		0.6	0.25
Empty weight [×1000 kg]				0.9
Full weight [×1000 kg]				
PV surface [m^2]	38.5			
PV power [kWp]	5		4.5	1.2
PV technology			108	
Engine power [kW]	12		14	1
Number of engines	2		2	
Engine technology				
Battery technology	130V, 214Ah		lead gel, 4.2 ton	
Battery Capacity [kWh]	27.82			
Cruise speed [km/h]	12		4	9.3
Max speed [km/h]	16		10	
Person capacity	58		25	
Price			€ 1 500 000	

Boat	Passeur de La Rochelle	Source Solar	Ra31	Lestrol
Producer		University's Sustainable Energy Research Group (SERG) of the Civil and Environmental Engineering Department	Kopf Solarschiff GmbH	
Year of production	1998	1998	1998	1999
Length [m]	10	7	9.4	6.47
Width [m]	3.5			1.67
maximum draft [m]	0.9			
Empty weight [×1000 kg]	4.1			
Full weight [×1000 kg]	6.5			
PV surface [m^2]	9			
PV power [kWp]	1.2		1.8	
PV technology		12 panels, 26A		
Engine power [kW]	20	0.8	4.7	
Number of engines	2		2	
Engine technology				
Battery technology	Nickel Cadmium, 660kg	24V		
Battery Capacity [kWh]	20			
Cruise speed [km/h]	12		7	
Max speed [km/h]			13	
Person capacity	50		12	
Price			37 000 DM	

Boat	Zonnepont	Aquabus 1050 - 1050T	Ra66	Ra72
Producer	hager bv	MW-Line		KOPF
Year of production	1999	2000	2000	2000
Length [m]	7.8	10.5	20	22
Width [m]	2.3	2.5	4.6	4.3
maximum draft [m]		0.76	0.7	0.6
Empty weight [×1000 kg]	2	2.6	12	25
Full weight [×1000 kg]		4.4		
PV surface [m^2]		14		
PV power [kWp]	2.28		3.8	4.2
PV technology	32.190Wp			
Engine power [kW]	6	8.2	20	24
Number of engines	2	1	2	2
Engine technology	48V	EE2		
Battery technology	2×48V, 205Ah	48V	2×96V, 560Ah	2×80V, 1800Ah
Battery Capacity [kWh]	1.64		53.76	144
Cruise speed [km/h]		10	8	8
Max speed [km/h]		16	13	13
Person capacity		24	50	68
Price		300 000 DM		

Boat	Ra82	SOL 10	Solar Sailor	Voyager 780
Producer	KOPF	KOPF	Robert Dane	Das Yachtcenter / Artisolar
Year of production	2000	2000	2000	2000
Length [m]	27	4.05	21	8.5
Width [m]	4.3	1.9		2.5
maximum draft [m]	0.95	0.4		0.6
Empty weight [×1000 kg]	34	0.42		1.6
Full weight [×1000 kg]				2.5
PV surface [m^2]				4
PV power [kWp]	7.4	0.21		0.5
PV technology				monocristalline
Engine power [kW]	24	0.6		2.5
Number of engines	2			
Engine technology				Agni-Lynch
Battery technology	2×Lead-Acid, 80V, 1800Ah	4×6V lead gel, 400Ah		Lead AGM
Battery Capacity [kWh]	144	2.4		10
Cruise speed [km/h]	8	3	9	8
Max speed [km/h]	13	5		12
Person capacity	120	4	100	6
Price	1 300 000 DM			€ 65 000

Boat	Mobicat	Vél’eau 12	Zholar	Capitaine Soleil
Producer	BKW FMB Energie AG	Artisolar		
Year of production	2001	2001	2001	2001
Length [m]	33	12	6.1	33
Width [m]	22.83	1.6	2.7	12
maximum draft [m]		0.6	0.5	
Empty weight [×1000 kg]		0.6	0.65	115
Full weight [×1000 kg]		2	1.1	
PV surface [m^2]	180	6		180
PV power [kWp]		0.7	0.734	
PV technology		monocristalline	Microcrystalline Apex/Astropower thin film silicium in Glas Tedlar laminated	
Engine power [kW]	16.2	2	2.6	162
Number of engines	2			2
Engine technology		Agni-Lynch		
Battery technology		Lead AGM	8× compact power lead (acid?), 24V, 270Ah	
Battery Capacity [kWh]		5	6.48	
Cruise speed [km/h]		10		
Max speed [km/h]		13		
Person capacity	150	12	6	150
Price	2 000 000 CHF	€ 50 000		

Boat	Aquabus C60 standard - C60+	Chassalli Solar	Mimbi	Nomad 3
Producer	MW line			
Year of production	2002	2003	2004	2005
Length [m]	14	10.16		10.6
Width [m]	6.6	2.35		2.5
maximum draft [m]	1	0.45		
Empty weight [×1000 kg]	10	1.8		3
Full weight [×1000 kg]	14			
PV surface [m^2]	20			
PV power [kWp]		0.8		1.1
PV technology		15× Siemens SM 55		6×185W Monocrystalline
Engine power [kW]	8	30		8
Number of engines	2			
Engine technology	EE2	Siemens 1PV5		ETEK Repm permanent magnet max 3200 rpm 3: 1 reduction belt drive to 16inch brass propeller
Battery technology	48V	Gel 108V, 160		8×6 volt Deep cell sealed (lead acid) gel batteries-300AH + 12V - 75AH for ‘house’ power
Battery Capacity [kWh]		17.28		2.7
Cruise speed [km/h]				7
Max speed [km/h]		12		9.5
Person capacity	60	12		
Price				

Boat	Aquabus 850T	Ra46	Ra82 (extended)	El Retiro
Producer	MW line	KOPF	KOPF	
Year of production	2006	2006	2006	2006
Length [m]	8.5	14.3	27	
Width [m]	2.5	3.5	5.3	
maximum draft [m]	0.48		0.95	
Empty weight [×1000 kg]	2	14	40	
Full weight [×1000 kg]				
PV surface [m^2]	5			
PV power [kWp]		1.9	9.6	
PV technology				10 modules
Engine power [kW]	8	20	36	4.8
Number of engines		2	2	2
Engine technology				
Battery technology	gel, 48V, 360	96V, 500Ah	2×80V, 1800Ah	gel
Battery Capacity [kWh]	17.28	48	144	
Cruise speed [km/h]	11	6	8	10
Max speed [km/h]		15	15	15
Person capacity	12	40	120	
Price	€ 78 900		1 300 000 DM	

Boat	Sun21	Basilisk 3	Czeers Mk1	SWAN
Producer	transatlantic21 (katamaran from MW-line Type C)	Artisolar	Nils Beers and David Czapp	Yacht Concept Solartechnology GmbH
Year of production	2007	2007	2007	2007
Length [m]	14	12	10	
Width [m]	6.6	2.5 / 4.5	2.7	
maximum draft [m]		0.6	0.4	
Empty weight [$\times 1000$ kg]		1.8	0.35	
Full weight [$\times 1000$ kg]		3	1	
PV surface [m^2]	65	10	14	
PV power [kWp]	10	2		5
PV technology		Sunpower	Silicon	
Engine power [kW]	16	5	30	16
Number of engines	2			2
Engine technology		Agni-Lynch	410V	
Battery technology	48V, C5, lead (acid?), 520Ah	Lead AGM	custom li-ion-polymer, 410V	200Ah
Battery Capacity [kWh]	24.96	20	38	
Cruise speed [km/h]	11	13	15	9
Max speed [km/h]	13	17	55	14
Person capacity		12	5	
Price		€ 150 000	€ 650 000	

Boat	SWAN 2	Hydrobot	Navette du Millenaire	ASV Roboat
Producer	Yacht Concept Solartechnology GmbH			Gesellschaft für innovative Computerwissenschaften
Year of production	2007	2008	2008	2008
Length [m]	11.2		15	3.75
Width [m]	3.2		5	
maximum draft [m]			1.2	
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]			21	1.5
PV power [kWp]	4		2.7	0.285
PV technology				
Engine power [kW]	12		44	
Number of engines	2		2	
Engine technology			Fischer Panda POD's	
Battery technology			NiCd	lead (acid?)
Battery Capacity [kWh]			110	
Cruise speed [km/h]				
Max speed [km/h]			14.4	
Person capacity	8		100	
Price				

Boat	Solar-Ferry 30	T1200	Frolic	Solarly
Producer	Yacht Concept	MW-Line Artisolar	Artisolar	Creative marine / Artisolar
Year of production	2008	2009	2009	2009
Length [m]		7	6.4	6.5
Width [m]		3.5		1.8
maximum draft [m]		0.6		0.6
Empty weight [×1000 kg]		1.5		1
Full weight [×1000 kg]		2.5		1.6
PV surface [m^2]		7	3.8	4
PV power [kWp]		1	0.7	0.8
PV technology		type Sunways, monocristalline, transparent roof integrated	4× monocristallyne (Sunpower), 144 cm × 66 cm, containing 55 cells	Sunpower
Engine power [kW]		3	2.4	2.5
Number of engines		2		
Engine technology		Agni Lynch	AGNI Lynch 2,4 KW / 24 V	Agni-Lynch
Battery technology		2×24V, lead AG	6V, Sonnenschein Gel, 180Ah	lead gel
Battery Capacity [kWh]		10	1.08	10
Cruise speed [km/h]		8	6	8
Max speed [km/h]	12	12	11	11
Person capacity	30	13		6
Price		€ 70 000		€ 20 000

Boat	Aequus 7.o	Bus de mer de la Rochelle	Aquabus SOLON C60	Buga
Producer	Aequus		SolarWaterWorld AG	J. Albrecht
Year of production	2009	2009	2009	2009
Length [m]	7	15	17.65	11.5
Width [m]		5	6.85	4.5
maximum draft [m]		1.2		
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]	6	26		
PV power [kWp]	0.8	4		
PV technology			24 modules	
Engine power [kW]	4.5	44		
Number of engines		2		
Engine technology		Fischer Panda 2ăPOD's		
Battery technology	AGM, 48V, 200Ah	Ni/CD		
Battery Capacity [kWh]	9.6	130		
Cruise speed [km/h]	10			
Max speed [km/h]	13	17.5		
Person capacity		75	50	30
Price				

Boat	Aquakart	SunCat 23	Solarwave	SunCat 46
Producer	J. Albrecht	SolarWaterWorld AG		SolarWaterWorld AG
Year of production	2009	2009	2009	2010
Length [m]	3.2	7		14
Width [m]	1.7	2.5		
maximum draft [m]		0.75		
Empty weight [×1000 kg]	0.15	1.3		
Full weight [×1000 kg]	0.65	2.3		
PV surface [m^2]				
PV power [kWp]		0.215		
PV technology		4× Solon SE, transparent mit Sunpowerzellen		
Engine power [kW]	8	2.8		
Number of engines	1			
Engine technology		Kräutler Elektromotor GPAV 2,8 / 48 V		
Battery technology		4× 12V, Mastervolt Gelbatterien , 200Ah		
Battery Capacity [kWh]		2.4		
Cruise speed [km/h]			8	
Max speed [km/h]		11		
Person capacity	5			
Price	€ 18 500	€ 69 000		

Boat	Electronemo	C700	PlanetSolar	SunTech Guosheng
Producer	Jan Hamza	original boat from unknown producer / Artisolar		Suntech / Solar Sailor
Year of production	2010	2010	2010	2010
Length [m]	10.2	25	31	31.5
Width [m]	3.2	4	15	
maximum draft [m]		0.8		
Empty weight [×1000 kg]		30	85	
Full weight [×1000 kg]		35		
PV surface [m^2]		25	536	
PV power [kWp]		4	93.5	
PV technology		Sanyo HIT	eff: 18,8%	
Engine power [kW]	2.2	20	20	
Number of engines		2		
Engine technology		AGNI Lynch		
Battery technology		48V, Lead gel HD, 1600Ah	200Ah	
Battery Capacity [kWh]		19.2		
Cruise speed [km/h]		8	14	
Max speed [km/h]		13	25	
Person capacity	30	6	50	
Price	150 000 USD	€ 250 000	€ 24 000 000	

Boat	GreenLine	GS4	Scylla	Solarboat HZ Engineering
Producer	Seaway		NHL Hogeschool	HZ engineering
Year of production	2010	2010	2010	2010
Length [m]	10	3.85	6	6
Width [m]	3.5	2.05	1.68	1.3
maximum draft [m]	0.7		0.14	0.14
Empty weight [$\times 1000\,$kg]		0.35	0.162	0.22
Full weight [$\times 1000\,$kg]		0.75	0.232	0.29
PV surface [m^2]	8	2.5	6	6
PV power [kWp]	1.3	0.36	0.875	0.875
PV technology			c-si 14%	c-si 14%
Engine power [kW]		2	8	1.7
Number of engines			1	1
Engine technology			Agni 143D	
Battery technology	240Ah		LiPo MG-Electronics	
Battery Capacity [kWh]		4.56	1	1
Cruise speed [km/h]			14	14
Max speed [km/h]		8	28	19
Person capacity			1	1
Price			€ 25 000	

Boat	Solarteam zeevaartschool Vlissingen	Graafschap College	Private Energy Solar Boat team / Furia 2	Team Sunrise
Producer	Zeevaartschool Vlissingen		MG Electronics	
Year of production	2010	2010	2010	2010
Length [m]	6	6	8	5
Width [m]	1.67	2.2	1.6	1.6
maximum draft [m]	0.1	0.17	0.1	
Empty weight [×1000 kg]	0.217	0.257	0.12	0.145
Full weight [×1000 kg]	0.287	0.327	0.19	0.215
PV surface [m^2]	6	6	9	6
PV power [kWp]	0.875	0.875	1.75	0.875
PV technology	c-si 14%	c-si 14%	c-Si A300 21%	c-si 14%
Engine power [kW]	2.2		8	2
Number of engines	1	1	1	1
Engine technology				
Battery technology				
Battery Capacity [kWh]	1	1	1	1
Cruise speed [km/h]	14	12	20	14
Max speed [km/h]	16	16.8	31	20.5
Person capacity	1	1	1	1
Price				

Boat	Artesis	Alustar	Us Boat	Vripack
Producer				
Year of production	2010	2010	2010	2010
Length [m]	5.7	6	5.8	
Width [m]	2.4	2.38	2	
maximum draft [m]	0.195	0.48	0.2	
Empty weight [×1000 kg]	0.335	0.27	0.33	0.16
Full weight [×1000 kg]	0.405	0.34	0.4	0.23
PV surface [m^2]	6	6	6	
PV power [kWp]	0.875	0.875	0.875	
PV technology	c-si 14%	c-si 14%	c-si 14%	c-si 14%
Engine power [kW]	0.68	2.4	2	
Number of engines	1	1	1	
Engine technology				
Battery technology				
Battery Capacity [kWh]	1	1	1	1
Cruise speed [km/h]	9.5	11.5	10	
Max speed [km/h]	11.5	14	14	
Person capacity	1	1	1	1
Price				

Boat	Tempress	ROC Friese Poort	De Wilgen	Port of Antwerp Solarboat team
Producer				
Year of production	2010	2010	2010	2010
Length [m]	6.25	6	6	6
Width [m]	1.8			
maximum draft [m]	0.1			
Empty weight [$\times 1000\,\mathrm{kg}$]	0.11			
Full weight [$\times 1000\,\mathrm{kg}$]	0.19			
PV surface [m^2]		6	6	6
PV power [kWp]	1.7	0.875	0.875	0.875
PV technology	N-type Silicon semi flexible encapsulated 20 modules containing 15 cells. 85Wp per panel with 9.4V	c-si 14%	c-si 14%	c-si 14%
Engine power [kW]				
Number of engines	1			
Engine technology				
Battery technology	Lithium Ion 24V			
Battery Capacity [kWh]	1	1	1	1
Cruise speed [km/h]	20			
Max speed [km/h]				
Person capacity	1	1	1	1
Price				

Boat	Yellow Sunsation III	Solarteam Zee-vaartschool Vlissingen	Ipanema	Prodeon Solarteam Windesheim
Producer				
Year of production	2010	2010	2010	2010
Length [m]	6	6	6	6
Width [m]				
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]	6	6	6	6
PV power [kWp]	0.875	0.875	0.875	0.875
PV technology	c-si 14%			
Engine power [kW]				
Number of engines				
Engine technology				
Battery technology				
Battery Capacity [kWh]	1	1	1	1
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity	1	1	1	1
Price				

Boat	Energa Solar I	Team Graafschap college	Universidate Federal do Rio de Janeiro: Catalao	Stille wateren
Producer				
Year of production	2010	2010	2010	2010
Length [m]	6	6	6	6
Width [m]				
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]	6	6	6	6
PV power [kWp]	0.875	0.875	0.875	0.875
PV technology				
Engine power [kW]				
Number of engines				
Engine technology				
Battery technology				
Battery Capacity [kWh]	1	1	1	1
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity	1	1	1	1
Price				

Boat	Solarteam HZ engineering	Swette Switter	SCM	Fiten Solar Team
Producer				
Year of production	2010	2010	2010	2010
Length [m]	6	6	6	6
Width [m]				
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]	6	6	6	6
PV power [kWp]	0.875	0.875	0.875	0.875
PV technology				
Engine power [kW]				
Number of engines				
Engine technology				
Battery technology				
Battery Capacity [kWh]	1			
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity	1	1	1	1
Price				

Boat	Ventu Sol	Solar team groningen	Copacabana	ROC Friese poort drachten
Producer				
Year of production	2010	2010	2010	2010
Length [m]	6	6	6	6
Width [m]				
maximum draft [m]				
Empty weight [$\times$1000 kg]				
Full weight [$\times$1000 kg]				
PV surface [m^2]	6	6	6	6
PV power [kWp]	0.875	0.875	0.875	0.875
PV technology				
Engine power [kW]				
Number of engines				
Engine technology				
Battery technology				
Battery Capacity [kWh]				
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity	1	1	1	1
Price				

Boat	ROC Zeeland: Tech.Know.Logy Solar Team	Marne College	De Griene Sinnefretter	HAN Solar boat
Producer				
Year of production	2010	2010	2010	2010
Length [m]	6	8	8	8
Width [m]				
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]	6	7.2	7.2	7.2
PV power [kWp]	0.875	1.05	1.05	1.05
PV technology				
Engine power [kW]				
Number of engines				
Engine technology				
Battery technology				
Battery Capacity [kWh]				
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity	1	2	2	2
Price				

Boat	Solarboat team Emden	Energa Solar II	ROC van Amsterdam	Marflex Redundancy
Producer				
Year of production	2010	2010	2010	2010
Length [m]	8	8	8	8
Width [m]				
maximum draft [m]				
Empty weight [$\times 1000\,\mathrm{kg}$]				
Full weight [$\times 1000\,\mathrm{kg}$]				
PV surface [m^2]	7.2	7.2	7.2	7.2
PV power [kWp]	1.05	1.05	1.05	1.05
PV technology				
Engine power [kW]				
Number of engines				
Engine technology				
Battery technology				
Battery Capacity [kWh]				
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity	2	2	2	2
Price				

Boat	Drenthe College	Sunseeker	Delta Loyd Solar Boat Team	Stichting Solar-boat Delft
Producer		Gowrings energy		Imtech
Year of production	2010	2010	2010	2010
Length [m]	8	8	8	8
Width [m]				
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]	7.2			
PV power [kWp]	1.05	1.75	1.75	1.75
PV technology				
Engine power [kW]				
Number of engines				
Engine technology				
Battery technology				
Battery Capacity [kWh]				
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity	2	1	1	1
Price				

Boat	Hogere Zeevaartschool Antwerpen	Team Tempress	Solar team Groningen	Feenstra’s Future
Producer	Antwerp Maritime Academy	Tempress Systems BV		Feenstra’s Installatiebedrijf / Noordenwind
Year of production	2010	2010	2010	2010
Length [m]	8	8	8	8
Width [m]				
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]				
PV power [kWp]	1.75	1.75	1.75	1.75
PV technology				
Engine power [kW]				
Number of engines				
Engine technology				
Battery technology				
Battery Capacity [kWh]				
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity	1	1	1	1
Price				

Boat	Andela Solarteam	PV Sportboot	Eco Slim	Polli Boat
Producer	Andela Scheepstechniek	Kenniscentrum Jachtbouw	Drassanes Dalmau	Miniwiz Sustainable Energy Private Ltd.
Year of production	2010	2011	2011	2011
Length [m]	8	6	24	7
Width [m]		1.66	10.5	
maximum draft [m]		0.25		
Empty weight [×1000 kg]		0.15		
Full weight [×1000 kg]		0.3		
PV surface [m^2]				
PV power [kWp]	1.75	1		0.432
PV technology		c-Si 21%	40× monocrystalline	
Engine power [kW]		8		
Number of engines		1	2	
Engine technology		Agni 143D		
Battery technology		LiPo MG-Electronics, 48V nominal		
Battery Capacity [kWh]		4		
Cruise speed [km/h]			11	
Max speed [km/h]		25	20	
Person capacity	1	2	150	
Price		€ 50 000		

Boat	Furia 3	Firefly	Aquabus C15 Scuba	Solemar
Producer	MG Electronics	Dan Baker	MW line	Seacleaner Trawler S.A.
Year of production	2012	2012		
Length [m]	7.3		11.8	12
Width [m]	1.6		4	5
maximum draft [m]	0.5		0.6	0.9
Empty weight [×1000 kg]	115		5	
Full weight [×1000 kg]	185		8	
PV surface [m^2]			20	
PV power [kWp]	1.75	0.14		4.625
PV technology	Sunpower 21% C60			
Engine power [kW]	6		16	9.6
Number of engines	1		2	2
Engine technology	1,5kg	2× brushless DC	EE2	
Battery technology	MG Electronics HD	Lead acid	48V	48×, 23520Ah
Battery Capacity [kWh]	1750			
Cruise speed [km/h]	20	6.5		7
Max speed [km/h]	38			11
Person capacity	1	4	30	60
Price	€ 100 000	2900 CAD		

Boat	ASMV	OASIS	SCOUT	SAUV
Producer		Center for Innovative Technology, the National Aeronautics and Space Administration Wallops Flight Facility and the National Oceanic and Atmospheric Administration		
Year of production				
Length [m]	2.13	6	3	2.3
Width [m]	0.91	2.6		1.1
maximum draft [m]	0.33			
Empty weight [×1000 kg]	0.176			0.2
Full weight [×1000 kg]				
PV surface [m^2]				1
PV power [kWp]				
PV technology				
Engine power [kW]				
Number of engines				
Engine technology	12V longitudinal trusters			
Battery technology	12V Deep discharge 50Ah gel			
Battery Capacity [kWh]	0.6			2
Cruise speed [km/h]		4.5		
Max speed [km/h]	4.5			3
Person capacity				
Price				

Boat	Princesse Alexandra	ECOSOL 28	ECOSOL 33	ECOSOL 42
Producer		KOPF	KOPF	KOPF
Year of production				
Length [m]		8.5	10	13
Width [m]		2.5	3	3.5
maximum draft [m]		0.55		
Empty weight [×1000 kg]		2.8	5.5	11
Full weight [×1000 kg]				
PV surface [m^2]				
PV power [kWp]		0.9	1.45	2.2
PV technology				
Engine power [kW]		10	20	36
Number of engines		2	2	2
Engine technology				
Battery technology		2× 48V, 560Ah	2×48V, 1120Ah	96V, 1000Ah
Battery Capacity [kWh]		26.88	53.76	96
Cruise speed [km/h]		7	8	8
Max speed [km/h]		10	12	16
Person capacity		12	25	25
Price				

Boat	SOL-CAP 370	Ra33-2	Ra82-17	Solar Gondola
Producer	KOPF	KOPF	KOPF	
Year of production				
Length [m]	3.7	9.95	25	5
Width [m]	1.7	2.95	5.4	1.85
maximum draft [m]				
Empty weight [×1000 kg]	0.28	4.3	43	
Full weight [×1000 kg]				
PV surface [m^2]				
PV power [kWp]	0.2	1.7	5.8	0.25
PV technology				
Engine power [kW]		10	50	0.5
Number of engines		2	2	
Engine technology				
Battery technology	360Ah	48V, 360Ah	2×96V, 2400Ah	140Ah
Battery Capacity [kWh]		17.28	230.4	
Cruise speed [km/h]	4	8	8	6
Max speed [km/h]	7	11	15	
Person capacity	5		110	4
Price				

Boat	SunCat 48	SunCat 58	SunCat 21	SunCat 12
Producer	SolarWaterWorld AG	SolarWaterWorld AG		SolarWaterWorld AG
Year of production				
Length [m]	14	17.8		3.6
Width [m]	5	6.85		1.7
maximum draft [m]				0.55
Empty weight [×1000 kg]	8.72	8.72		0.26
Full weight [×1000 kg]				0.54
PV surface [m^2]				
PV power [kWp]				0.2
PV technology				4 Leichtbaulaminate, im Bootsdeck integriert
Engine power [kW]				
Number of engines				
Engine technology				
Battery technology				200Ah
Battery Capacity [kWh]				
Cruise speed [km/h]				5
Max speed [km/h]	15	15		7
Person capacity				2
Price				9500 DM

Boat	SunCat 13	SolarCat LW 800	Solaris	Annie
Producer	SolarWaterWorld AG			
Year of production				
Length [m]	3.6	8.15	18.3	8.2
Width [m]	1.7	3.8	4	2.1
maximum draft [m]	0.55	0.3		
Empty weight [×1000 kg]	0.26			
Full weight [×1000 kg]	0.54			
PV surface [m^2]				
PV power [kWp]	0.2	1	2.4	0.45
PV technology	4 Leichtbaulaminate, im Bootsdeck integriert			
Engine power [kW]		6	6	0.9
Number of engines				
Engine technology				
Battery technology	200Ah			
Battery Capacity [kWh]				
Cruise speed [km/h]	5	8		
Max speed [km/h]	7	20		
Person capacity	3	29		
Price	9500 DM			

Boat	Corvelia	Sommerset Dream	Solar Flair	Solar Flair 2
Producer				
Year of production				
Length [m]	3.6	3.7	6.4	4
Width [m]	1.4	1.6	1.5	1.2
maximum draft [m]				
Empty weight [$\times 1000\,\mathrm{kg}$]				
Full weight [$\times 1000\,\mathrm{kg}$]				
PV surface [m^2]				
PV power [kWp]	0.32	0.3	0.3	0.15
PV technology				
Engine power [kW]	0.6	0.3	5.5	0.22
Number of engines				
Engine technology				
Battery technology				
Battery Capacity [kWh]				
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity				
Price				

Boat	Solar Flair 3	Cellcraft	Bata Greine	Solar Heritage
Producer				
Year of production				
Length [m]	6.4		13	14
Width [m]	1.8		3.3	6.6
maximum draft [m]				
Empty weight [$\times$1000 kg]				
Full weight [$\times$1000 kg]				
PV surface [m^2]				
PV power [kWp]	0.6		1.15	2
PV technology				
Engine power [kW]	0.43		3.2	3.8
Number of engines				
Engine technology				
Battery technology				
Battery Capacity [kWh]				
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity				
Price				

Boat	Ransome	New Era	Aquawatt 550	Frolic 21 Solar
Producer				
Year of production				
Length [m]	12.2	7.4	5.5	6.4
Width [m]	3.1	2.2	1.84	1.8
maximum draft [m]			0.4	
Empty weight [×1000 kg]			0.48	
Full weight [×1000 kg]			0.55	
PV surface [m^2]				
PV power [kWp]	2.28	0.48	0.34	0.575
PV technology	2.4			
Engine power [kW]		1.08	1.6	1
Number of engines				
Engine technology				
Battery technology			24V Lead-acid / AGM, 260Ah	
Battery Capacity [kWh]			6.24	
Cruise speed [km/h]				
Max speed [km/h]			11	
Person capacity				
Price				

Boat	Loon	Ra	Ruskin	Cedric’s Canoe
Producer				
Year of production				
Length [m]	6.1	8.8	12.2	5
Width [m]	2.5	2.7	2.9	1
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]				
PV power [kWp]	0.738	1.55	1.14	0.2
PV technology				
Engine power [kW]	1.2	1.7	2.5	0.14
Number of engines				
Engine technology				
Battery technology	8x6V			
Battery Capacity [kWh]				
Cruise speed [km/h]	9			
Max speed [km/h]	11			
Person capacity	8			
Price				

Boat	Kyknos	SolCat 3	Terrapin	Unity
Producer				
Year of production				
Length [m]	3.1	5	7.3	20.7
Width [m]	1.6	1.8	1.5	4
maximum draft [m]				
Empty weight [$\times 1000\,\mathrm{kg}$]				
Full weight [$\times 1000\,\mathrm{kg}$]				
PV surface [m^2]				
PV power [kWp]	0.15	0.32	0.21	1.2
PV technology				
Engine power [kW]	0.34	0.24	0.6	6
Number of engines				
Engine technology				
Battery technology				
Battery Capacity [kWh]				
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity				
Price				

Boat	DSE hybrid	Felix de Azara	Solar Star 22	SOL 20
Producer		MW Line		Kopf Solarshiffe
Year of production				
Length [m]			7.01	6
Width [m]			2.5	1.9
maximum draft [m]				0.4
Empty weight [$\times$1000 kg]			0.7	0.77
Full weight [$\times$1000 kg]				1.4
PV surface [m^2]		50		
PV power [kWp]	6	4	0.6	0.55
PV technology				
Engine power [kW]		32	3	0.9
Number of engines				1
Engine technology				
Battery technology		2x1080 Ah/C5, 48 V DC		96V, 125Ah
Battery Capacity [kWh]		51.84		12
Cruise speed [km/h]				
Max speed [km/h]			28	15
Person capacity		75	6	8
Price			45 000 USD	

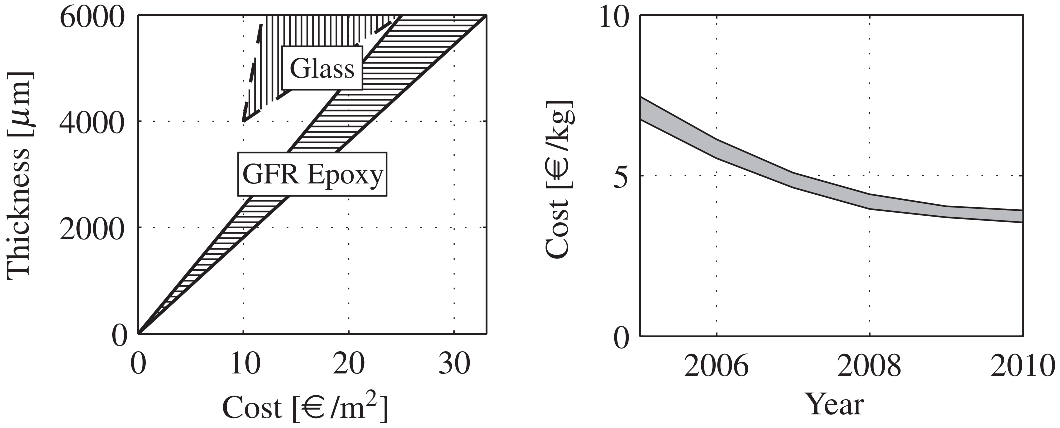
Boat	Solar Explorer	Davide	Ganni	CO2
Producer		Senofonte Ambrosini		
Year of production				
Length [m]	18	6.8	5.9	4.2
Width [m]	5.1			1.39
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]			4	1.2
PV power [kWp]	9.02		0.4	0.24
PV technology		14×24V	48V	24V
Engine power [kW]	15	2	8	2
Number of engines	2			
Engine technology	Watercooled synchronous engines			
Battery technology		4×lead acid 100A 12V	4x	24V
Battery Capacity [kWh]		1.2	0.076	0.2
Cruise speed [km/h]		9.26		
Max speed [km/h]		11		
Person capacity	48	4		
Price				

Boat	Alike	Girasole	Senofonte	Solo Sole
Producer	ITIS Majorana di Grugliasco			
Year of production				
Length [m]	3.8	7	5	4.4
Width [m]				
maximum draft [m]				
Empty weight [×1000 kg]				
Full weight [×1000 kg]				
PV surface [m^2]	0.6	4	1.5	
PV power [kWp]	0.05	0.24	0.05	0.07
PV technology	30V	24V	24V	
Engine power [kW]	0.18	0.65	2	0.25
Number of engines				
Engine technology		Minn Kota Traxxis 70		
Battery technology				
Battery Capacity [kWh]	0.324	1	2.1	0.96
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity				
Price				

Boat	Solone7	Electro Solar	Camilla	Friul
Producer				
Year of production				
Length [m]	8	5.5	4.4	5.7
Width [m]	4.5	2.5	1.6	2.2
maximum draft [m]				
Empty weight [$\times 1000\,$kg]	0.5	0.24	0.098	
Full weight [$\times 1000\,$kg]				
PV surface [m^2]	16	10	6	
PV power [kWp]	1.92	1.82	0.78	0.42
PV technology	72V	48V	4×195W 17,6V	6×
Engine power [kW]	16	4	2	0.38
Number of engines	2			
Engine technology				12V
Battery technology				2×100Ah
Battery Capacity [kWh]	6.48	3.84	4.32	
Cruise speed [km/h]				
Max speed [km/h]				
Person capacity				
Price				

Boat	Lilia	Argo	Enigma	Wilmi
Producer				
Year of production				
Length [m]	5.5	10.75	10	5.5
Width [m]		2.95	4.8	
maximum draft [m]			0.35	
Empty weight [$\times$1000 kg]			9.9	
Full weight [$\times$1000 kg]				
PV surface [m^2]				
PV power [kWp]			1.8	0.175
PV technology		18×	24× Isofoton I-75S/12 75Wp	24V
Engine power [kW]	1	2	16	2
Number of engines				
Engine technology			2x 48V	
Battery technology	60V	12V 42Ah 4×		
Battery Capacity [kWh]	2.2	2.016		2
Cruise speed [km/h]				
Max speed [km/h]			6.5	
Person capacity			57	
Price				

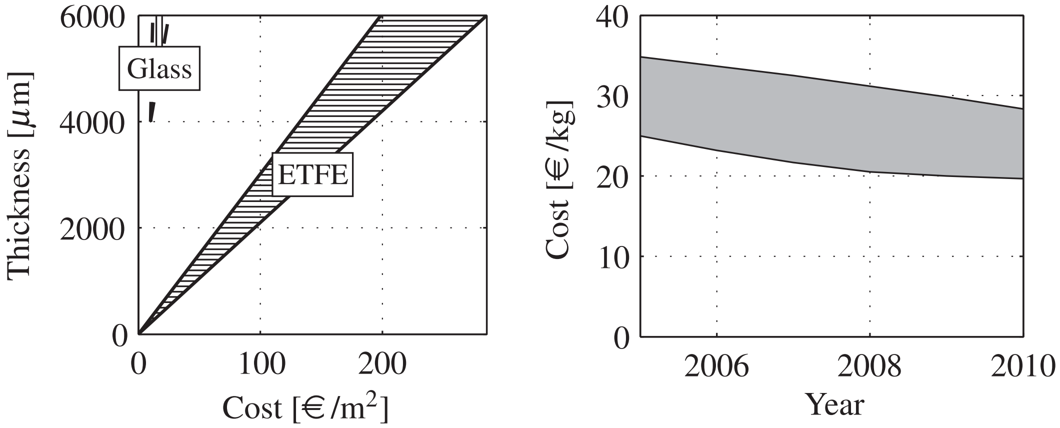
A.3 Properties of various polymers



(a) Cost per square meter for GFR Epoxy compared to glass+EVA.

(b) GFR epoxy price development.

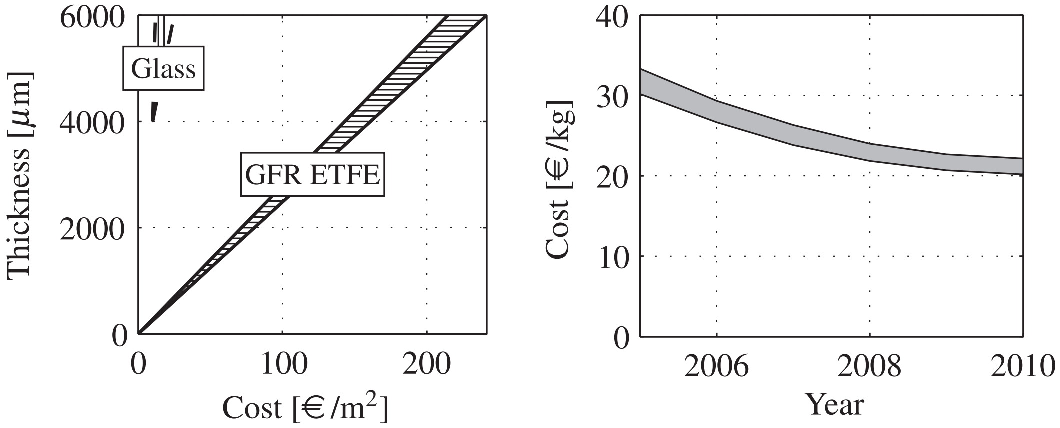
Figure A.5: Polymer properties for GFR epoxy.



(a) Cost per square meter for ETFE compared to glass+EVA.

(b) ETFE price development.

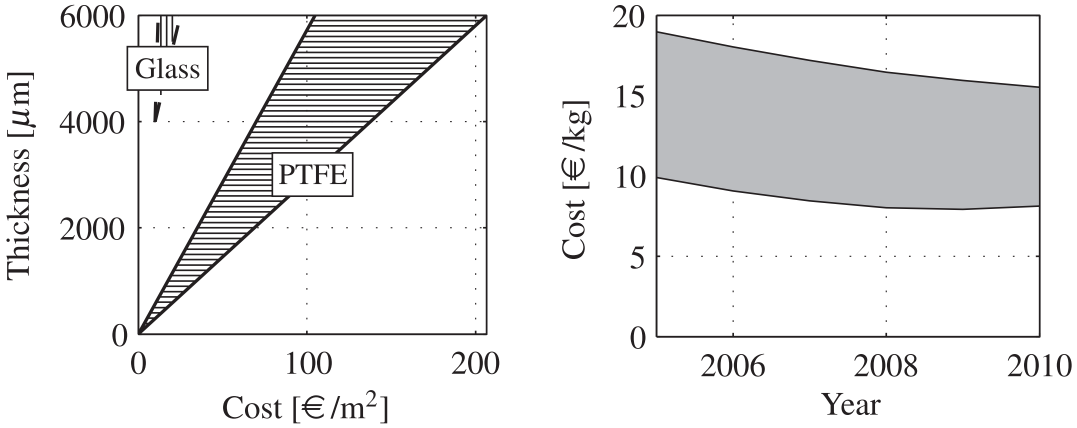
Figure A.6: Polymer properties for ETFE.



(a) Cost per square meter for GFR ETFE compared to glass+EVA.

(b) GFR ETFE price development.

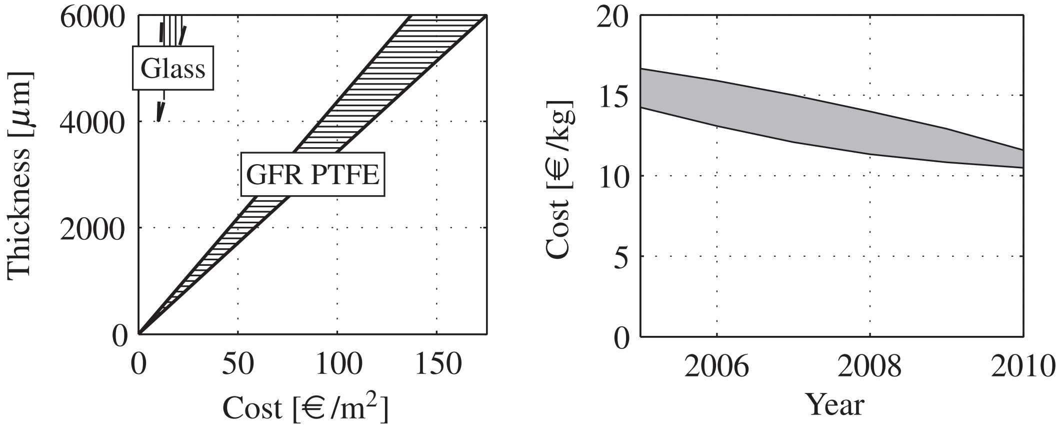
Figure A.7: Polymer properties for GFR ETFE.



(a) Cost per square meter for PTFE compared to glass+EVA.

(b) PTFE price development.

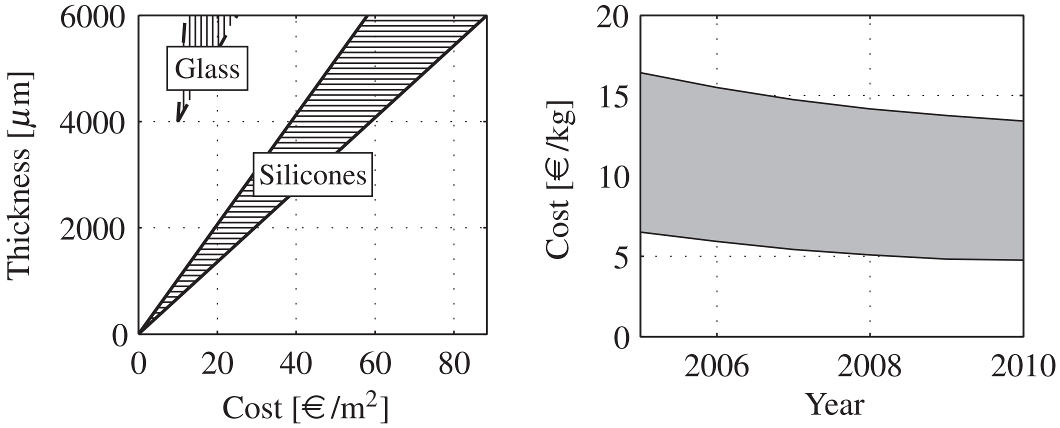
Figure A.8: Polymer properties for PTFE.



(a) Cost per square meter for GFR PTFE compared to glass+EVA.

(b) GFR PTFE price development.

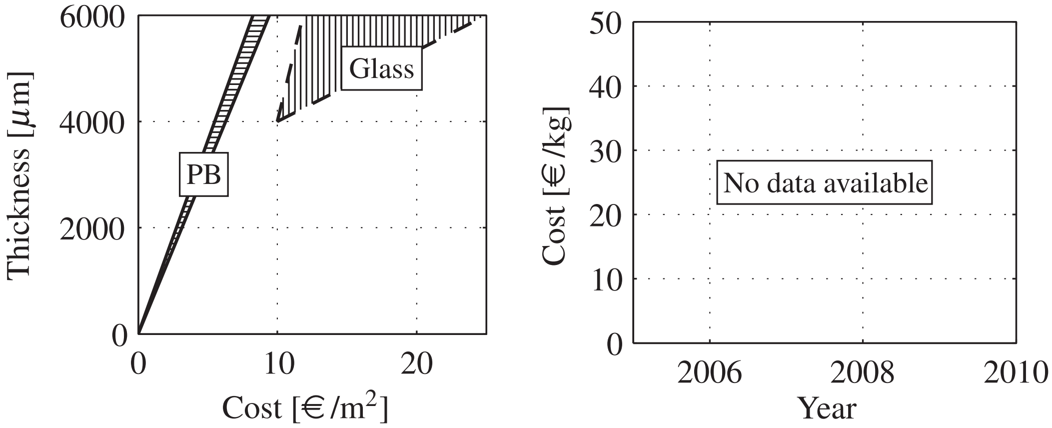
Figure A.9: Polymer properties for GFR PTFE.



(a) Cost per square meter for silicones compared to glass+EVA.

(b) Silicones price development.

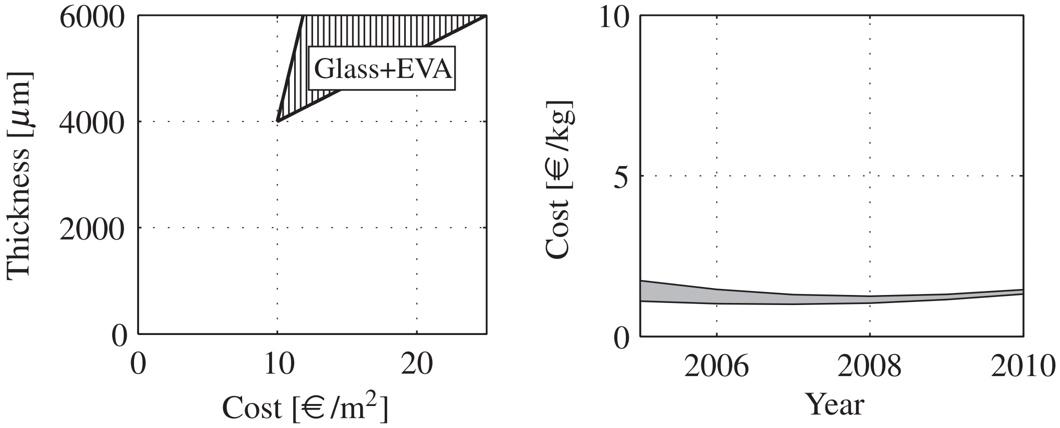
Figure A.10: Polymer properties for silicones.



(a) Cost per square meter for PB compared to glass+EVA.

(b) PB price development.

Figure A.11: Polymer properties for PB.



(a) Cost per square meter for Glass+EVA.

(b) EVA price development.

Figure A.12: Polymer properties for EVA.

Table A.3: Overview of encapsulant materials and their properties.

Material	**Tensile Strength** σ [MPa]	**Impact Strength** (notched at 23°C) K_v [kJ/m^2]	**Density** ρ [kg/m^3]	**Thickness** d [μm]
Epoxy	45–90	2–26	1120	
Epoxy with glass fiber (15%–50%)	138–241	160–200	1500–1800	
ETFE	42	45–200	1680	13–127
ETFE with glass fiber (25%)	79–87	45–50	1780–1820	
FEP	19–21	16–200	2120–2170	13–4750
FEP with glass fiber (20%)	16–17	16–18	2180–2260	
PEI	91	6–11	1260	
PEI with glass fiber (30%)	160–197	9–11	1490–1510	
PI	75–158	4–13	1340–1800	
PI with glass fiber (30%)	158–174	11–12	1540–1580	
PTFE	21–35	12–17	2140–2220	
PTFE with glass fiber (15%, 25%)	14–24		2180–2300	
PE	10–48	1–200	917–1240	
PE with glass fiber (20%–30%)	48–62	6–18	1090–1280	
PP	17–49	2–25	805–1160	
PP with glass fiber (10%–50%)	35–127	4–32	942–1500	
PMP	19–29	2–16	825–842	
PMP with glass fiber (10%–30%)	28–30	3–5	1000–1100	
TPU	37–43	190–200	1070–1100	460–500
TPU with glass fiber (40%)	128–134	36–44	1430–1550	
PVDF	24–50	8–115	1770	
Silicones	0.4–12		980–1350	180–700
PEN	46–49	3	1330–1390	
EVA	10–19		930–955	400–600
PVB	24–28		1060–1160	380–1520
PB	23–30	190–200	886–925	
Glass	10–180		2000–3000	4000–6000

Table A.4: Overview of encapsulant materials and their properties (continued).

Material	**Thermal expansion coefficient** α $[10^{-6}\cdot{}^{\circ}\mathrm{C}]$	**Transmittance** τ_λ [%]	**Transmittance spectrum** λ [nm]	**UV stability**
Epoxy	40–180	transparent		good
Epoxy with glass fiber (15%–50%)	21–22	transparant–translucent		fair
ETFE	18–108	$> 95\%$	380–780	excellent
ETFE with glass fiber (25%)	18–58	Opaque		excellent
FEP	39–51	96%	380–780	good
FEP with glass fiber (20%)	39–40	opaque		good
PEI	25–101	transparent		excellent
PEI with glass fiber (30%)	36–38	opaque		excellent
PI	11–101	opaque		excellent
PI with glass fiber (30%)	31–95	opaque		excellent
PTFE	120–215	opaque		good
PTFE with glass fiber (15%, 25%)	120–180	opaque		good
PE	106–396	translucent		poor–good
PE with glass fiber (20%–30%)	71–88	opaque		fair
PP	38–130	transparent–translucent		poor–good
PP with glass fiber (10%–50%)	20–57	opaque		poor
PMP	115–190	optical quality		poor
PMP with glass fiber (10%–30%)	138–141	translucent		poor
TPU	264–278	$> 93\%$		fair
TPU with glass fiber (40%)	27–27	opaque		fair
PVDF	21–258	translucent		excellent
Silicones	440–470			
PEN	22-210	optical quality		excellent
EVA	160–190	optical quality		fair
PVB		$> 91\%$		
PB	230–270	$> 94\%$		poor
Glass	-4–13	opaque–optical quality		excellent

Table A.5: Overview of encapsulant materials and their properties (continued).

Material	**Embodied energy** [MJ/kg]	**CO_2 footprint** [kg/kg]	**Water footprint** [l/kg]	**Salt water resistance**
Epoxy	99–141	4–5	107–322	excellent
Epoxy with glass fiber (15%–50%)	99–141	4–5	107–322	excellent
ETFE	161–177	8–9	585–646	excellent
ETFE with glass fiber (25%)	176–194	14–15		excellent
FEP	155–171	8–9	554–612	excellent
FEP with glass fiber (20%)	171–189	13–14		excellent
PEI	143–158	7–8		excellent
PEI with glass fiber (30%)	147–162	11–12		excellent
PI	173–191	9–10	652–720	excellent
PI with glass fiber (30%)	185–204	15–16		excellent
PTFE	145–160	7–8	283–850	excellent
PTFE with glass fiber (15%, 25%)	145–160	11–12		excellent
PE	104–114	4–5	277–306	acceptable
PE with glass fiber (20%–30%)	91–104	6–7		excellent
PP	87–108	3–4	189–271	excellent
PP with glass fiber (10%–50%)	91–107	6–7		excellent
PMP	127–141	6	405–448	excellent
PMP with glass fiber (10%–30%)	130–144	10–11		excellent
TPU	111–144	5–7	318–465	excellent
TPU with glass fiber (40%)	110–127	8–9		excellent
PVDF	140–155	7	472–524	excellent
Silicones	152–168	8–9	190–571	excellent
PEN	99–109	3–4	250–276	excellent
EVA	87–96	3	69–289	excellent
PVB				
PB	88–97	3	190–210	excellent
Glass	14–40	1–2	7–230	excellent

Table A.6: Overview of encapsulant materials and their properties (continued).

Material	**Service temperature** T_s [°C]	**Refractive index** n	**Glass temperature** T_g [°C]	**Cost per kilogram** [€ /kg]
Epoxy	-42–122		67–167	1.96–2.15
Epoxy with glass fiber (15%–50%)	-123–190		67–167	3.68–4.05
ETFE	-200–141	1.30–1.50	78–93	20.00–30.00
ETFE with glass fiber (25%)	-200–209		78–93	20.70–22.80
FEP	-240–205	1.34–1.35	81–96	16.30–24.70
FEP with glass fiber (20%)	-205–215		73–87	18.40–20.20
PEI	-42–160		215	10.80–11.90
PEI with glass fiber (30%)	-49–200		205–225	8.86–9.74
PI	-248–271	1.65–1.66	240–325	29.00–35.00
PI with glass fiber (30%)	-248–209		240–260	23.50–25.90
PTFE	-268–271	1.31–1.30	117–130	8.00–16.00
PTFE with glass fiber (15%, 25%)	-268–290		117–130	10.90–13.10
PE	-89–160	1.50–1.57	-125– -90	1.10–3.54
PE with glass fiber (20%–30%)	-82–150		-125– -90	2.18–2.61
PP	-26–124	1.48–1.50	-25– -6	1.12–2.37
PP with glass fiber (10%–50%)	-26 –139		-25– -6	1.90–2.92
PMP	-63–220	1.46	49–61	7.47–9.13
PMP with glass fiber (10%–30%)	-63–190		49–61	7.43–8.17
TPU	-47–76	1.49–1.50	-71– -63	8.67–9.54
TPU with glass fiber (40%)	-26–107		-16–0	4.30–4.73
PVDF	-25–175	1.40	-40– -27	12.30–18.50
Silicones	-60–180	1.40		9.88–10.90
PEN	-50–180	1.50	118–126	2.67–2.94
EVA	-85–47	1.48–1.49	-101–69	0.49–0.55
PVB				
PB	-34–97		-38– -24	1.55–1.70
Glass	-273–1400	1.44–1.88	100–2000	1.25–1.39

Boats equipped with photovoltaic modules to power the propulsion system are a means to reduce polluting emissions on the water. To develop well performing photovoltaic boats, new approaches are needed in the design of photovoltaic boats and the integration of solar energy systems. As a result, this research describes a 3D environment in which a boat can be designed in combination with a well-performing photovoltaic system.