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# Simulation of Multi-source Electric Production and Energy Transfers in Sailing

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**Abstract:** The exclusive use of renewable energies is today an essential nautical concern. Nowadays, the onboard energy generation comes mainly from diesel oil, which is in user mind the simplest way. Our objective is to develop a self-adaptive management system of the onboard energy in order to change the user mind. We introduce models for energy production, storage and consumption that fit with the yachting environment, which is mobile and not as predictable as the home automation case. These models are combined within a configurable simulator. This simulator can handle user's boat equipment, reproduce sailing conditions and so help to validate the models and to study different management strategies. This first step is necessary to develop a smart system able to manage sailing energy in order to answer the main issue: assuring safety and optimizing comfort according to user demands.

**Key words:** Renewable energy sources, power system simulation, marine navigation.

## 1. Introduction

Nowadays, the boats are built with heat-hardening composites strengthened with glass and carbon. These materials are absolutely not recyclable. They cannot be restructured, they are crushed and burnt. It is the same situation concerning the topic of this paper, the energy generation on board. Power comes mainly from diesel oil. The navigators run the motor, which starts an alternator to produce electricity. *Voilier du Futur* is a project in collaboration with different key economic players of the sailing industry and academics. The aim is to develop an eco-friendly sailboat reflected using innovative material (bio-composites + aluminum), the wastewater management and the exclusive use of renewable energies on board. It is today an essential nautical concern. Actually, the yachting of tomorrow will be a sailing in keeping with nature. Questions did not come up a few years ago: How to supply the engines? How to reduce the carbon emissions, which contribute to climate change and oceans acidification [1]? They encourage producing and consuming differently. Despite the considerable energy transfers on board (consumptions from 4 to 50 kWh/day), size of production and electricity storage systems are currently made in a rough way, relying on the user experience and past sailings. A simulation of energy transfers on board could allow to better proportion the equipment. So, it could increase the energy performances and the sailing conditions by choosing, among several options, the safest voyage according to the wished comfort throughout the route. So, the objective of this study is to develop a system for the self-adaptive management of the onboard energy coming from the whole available renewable power sources: wind, solar and hydraulic energy (Fig. 1).

Unlike a home, sailboats are mobile systems subject to more intense and variable weather conditions with an intermittent and hardly predictable production. Furthermore, the energy self-sufficiency is equivalent to user safety. At any time, the user must get out of any danger without being able to connect to the grid just like in the home automation case [2]. Now, models fitted for the yachting environment are not available. So, our first contribution is the development of energy production, storage and consumptions models. The second

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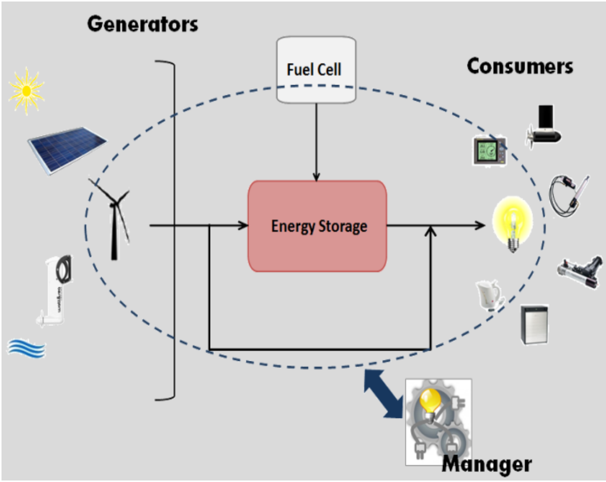


**Fig. 1 System representation.**

contribution is a simulator that reproduces the sailing conditions. It is used to validate the models and study strategies. Given that these two challenges are taken up, the next step of our work will be the development of an embedded intelligence able to perform a sailing energy management. This paper addresses these first challenges, namely the energy models and the simulator design. A Simulink model in Matlab environment is proposed. It includes an equipment model detailed in section 2 as well as a simulation of the sailing conditions explained in section 3. In section 4, these elements allow to highlight the factors influence on energy transfers and to compare different sailing scenarios to opt for the best compromise as possible relating to comfort and sailing performances.

## 2. Equipment Models

The simulator is based on a components library. It includes generator, storage models and consumption profiles, which are presented hereafter. Thus, a configurable system is obtained in order to be consistent with every user's boat.

### *2.1 Generator Models*

In this work, we consider four types of electricity generators and develop one production model for each of them. The aim of these models is not to study the accurate performances of each equipment but rather to have a realistic estimation of the overall electricity production.

Solar Panels

The production from solar panels is estimated using the surface power coming from sun radiations. So the panel power model relies on a simple calculation of yield. The temperature of cells is an influential factor on panel yield [3], it is estimated using outside temperature. As soon as the rated temperature is reached, the cells become less efficient. So, the current yield can be estimated knowing the initial yield of the panel and the value of this loss by degree. Different use conditions are implemented in the simulator: (1) a continuous utilization, the panels are directly fixed on the boat deck; (2) a utilization at anchor, in calm sea, the panels are deployed on a kind of air mattress behind the sailboat.

Wind Turbine

The wind production only occurs when the boat is at anchor. In fact, it is not much efficient when the boat is sailing downwind because of the weak apparent wind and when it is sailing upwind, the resistance of the wind turbine is not negligible. Subsequently, it is more interesting to feather it while sailing. At anchor, the wind turbine is put in rotation for limited values of wind. This interval allows us to consider the minimum start speed due to the torque of the wind turbine and the maximum speed to acceptable mechanical pressures [4]. Then, the maximal retrievable power, $P_{\max}$, is determined by the Betz formula:

$$P_{\max} = \frac{16}{27} P_{kinetic} = \frac{8}{23} \rho S v^3 \qquad (1)$$

Where $\rho$ represents the air density, $S$ denotes the wind turbine surface and finally $v$ represents the incident speed of the air.

Hydrogenerator

It is a hydrokinetic turbine especially designed for sailing. Like a bike dynamo, which rubs on the wheel, or a turbine in a water current, the hydrogenerator propeller turns and produces electricity when the sailboat is moving. The output power of this generator is a function of the boat apparent speed. This function is called performance curve (Fig. 2) and it is provided by the “Watt & Sea” company, a reference in this domain. It designs, produces and commercializes hydrogenerators. In brief, there is no production when the boat speed is too weak and it is saturated when the speed exceeds some threshold. The power is also function of the sea state. In rough sea, the pitch of the boat can degrade the production.

Fuel Cell

A fuel cell is also modeled. Indeed, nowadays, it is difficult to plan to only equip a boat with producers like wind turbine, solar panels without adding an emergency producer in case of power cut. Users mind still has to evolve. The setting up of a diesel generator does not match the project requirements, so the fuel cell is selected. The choice among a hydrogen or methyl alcohol technology is not defined yet but the best solution would be hydrogen, which is non-carbon and can be produced onboard. However, in a first phase, we model a methyl cell, which is a product available on the shelf, already used in the sailing world. We use tables to represent it. They are based on the manufacturers’ datasheets.

The electricity production is now modeled. However, it always can not be consumed instantaneously, it must be stored.

### *2.2 Model of Storage System*

The performance of an entire battery pack is modeled. This pack is represented by one capacitor with variable capacitance and one resistor which allows representing the batteries self-discharge when they are not in use (Fig. 3). The potential VSOC varies between 0 and 1 V and represents the battery charge level [5].

$$\frac{dx}{dt} = \frac{-1}{R_{SD}C_{CAP}}x - 1\frac{1}{C_{CAP}}u \qquad (2)$$

Where $x$ denotes the voltage that represents the state of the charge and $u$ denotes the current $I_{BATT}$.

The capacitance is function of the number of performed cycles, the measured depth of discharge during every cycle and the temperature [6]. Its losses due to current peaks are not represented, since it is a complex phenomenon to identify that implies specific studies for every battery technology.

The temperature factor is estimated by a piecewise linear function built from three points extracted from datasheets. The cycle factor is calculated as function of the number of performed cycles which allows dating the battery. The maximal cycle number is calculated from the measured depth of discharge. Then with the datasheet references, a linear function allows us to estimate the battery lifespan from the average value of the depths of discharge.

$$C_{CAP} = Capacity \quad f_1(cycle)\ f_2(Temp) \qquad (3)$$

So, the battery pack is modeled by a discrete state-space representation whose parameters change during the simulation. The system stops the simulation when the batteries are flat. Because, this means that the chosen configuration is not appropriate. Furthermore, the battery charge stops when they reach a 100% estimated level in order to avoid the overcharge. In reality, this action is performed by the BMS (Battery Management System) [7].

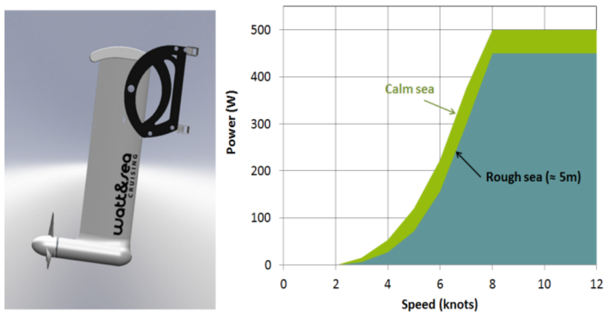


**Fig. 2 Hydrogenerator performance curves [Watt&Sea].**

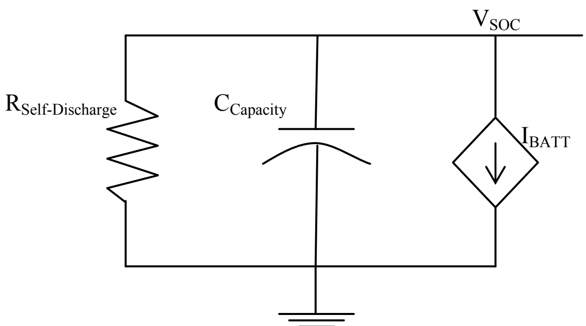


**Fig. 3 Battery lifetime model.**

Storage and production models are now created. We can move on to consumers.

*2.3 Energy Consumers*

A boat is equipped with six large families of consumers that are almost essential for seafaring sailboat:

(a) Sailing assistance devices inform about the sailor environment, they bring together the data coming from the sensors in order to give the boat speed, the position (navigation system, GPS (Global Positioning System), etc.) and dangers in the vicinity (radar, radar detector, AIS (Automatic Identification System), etc.). Some equipment can take control of the boat helm (automatic pilot); all this equipment consumes ≈ 85 W in running, on average on a 40-feets boat in standard sea conditions.

(b) Communication elements keep a link with the external world to rescue or be rescued, to get weather data and hit the road or for entertainment (VHF (Very High Frequency), radio receiver, etc.) ≈ 30 W in running, on average.

(c) Lightings allow to be seen, to signal the boat state, in sailing or at anchorage, they make the life on board easier (anchorage light, navigation light, cabin lighting, etc.) ≈ 30 W in running, on average.

(d) Engines allow bursting out of a danger in case of wind lack. They make the mooring easier too and weigh anchor (electric motor, windlass, brow thruster, etc.) ≈ 17,500 W in running, on average.

(e) Pumps and water circuit bail out the boat if needed be, supply the shower room or the kitchenette (bilge pump, freshwater pump, water pump unit, etc.) ≈ 240 W in running, on average.

(f) Comfort elements make the life on board easier and are equivalent to home equipment (charger, refrigerator, etc.) ≈ 140 W in running mode (average value).

*2.4 Consumption Profiles*

Consumers are diverse and variable. It is impossible to make an exhaustive list of them. Subsequently, they are coarsely modeled for a first approximation. We build profiles which depict at best the whole seafaring panel. A profile is a combination of several consumers which are described using manufacturer datasheets. These datasheets are weighted according to the comfort level and the different use rates. For example, the use rate parameter of the satellite communication can be fixed to ten minutes a day to have an Internet access, get the weather data, and talk to relatives. Some components are activated only under certain sailing conditions, temperature or luminosity like the heating or the lights. The profiles represent three different seafaring categories.

The first profile is only equipped with basic consumers, it uses around 4 kWh/day. It includes classic sailing assistances (navigation system, GPS, automatic pilot), mandatory communication elements (VHF, radio receiver), essential lightings (anchorage light, navigation light, cabin lighting, deck lighting), engines necessary for the boat functioning (electric motor, brow thruster, windlass), pumps (bilge pump, shower pump, freshwater pump, water pump unit) and a minimum of comfort elements (refrigerator, chargers).

The second profile, better equipped, consumes around 20 kWh/day. It includes all the equipment of the previous profile to which comfort elements are added (heating, water heater, desalinator, kettle, electric cooker, and microwave) plus radar.

The last profile includes all the home comfort and sailing facilities, it consumes about 35 kWh/day. It is equipped with the previous consumers and an air conditioning, a washing machine, a dishwasher to get back to the home elements. A satellite communication is added as well as electric winches for sailing assistances.

Some equipment, like the water heater, requires a converter use. In that case, converter consumption and the yield of this one are included to the equipment description. Finally, it is possible to select among these three predefined profiles (small, medium and big consumer) or a profile to be completely defined by the user to fit with specific equipment and behavior.

Weather conditions are parameters that influence both energy production and consumption.

## 3. Simulation of Sailing Conditions

### *3.1 Objectives*

The objective of the simulation of sailing conditions is to define a boat route in order to have realistic data. They are equivalent to choice the sailing strategies in relation to the weather. They correspond to different boat configurations and sailing performances.

### *3.2 Boat Routing*

A boat routing is computed in order to obtain a realistic trajectory. To define this route, there are two solutions. The user can directly enter a real boat route with GPS coordinates. The route can be calculated with professional routing software like MaxSea or Adrena [8, 9]. Routing software optimizes the route between two points but requires an expensive license. We want to open our simulation tool, so the choice made by default is a manual option. The user has just to enter the waypoints coordinates where the boat must pass.

### *3.3 Tracking Law*

The route is now defined. There are two existing solutions to determine the boat behavior between two points. (1) The boat behavior is a manual one corresponding to a sailor who takes the helm. It is very complex to reproduce since it must learn from real observations a law that depends on multiple parameters. (2) The boat behavior is controlled by an automatic pilot. It can also be really complex like the industrial pilots, which are used by amateur and professional sailors, or, it can be simplified like the one used in robotic sailing. This last option produces a realistic behavior. It is selected and explained below.

The simulation of the behavior is based on the estimation of the speed and the course. Tracking lines are determined by waypoints defined during initialization. Each line is defined by two points [A, B] (Fig. 4). A line is validated as soon as the boat is within a radius of 20 nautical miles from the point B. Then, a new line is calculated from the boat position to optimize its displacement. The different line angles, which will be exploited by the tracking law, are calculated (Fig. 5) [10].

$$\sin \alpha = \frac{\lfloor (b_x - a_x)(m_y - a_y) - (b_y - a_y)(m_x - a_x) \rfloor}{\| m - a \| \times \| b - a \|} \quad (4)$$

$$\cos \gamma = \frac{\lfloor (b_x - a_x)\cos \vartheta - (b_y - a_y)\sin \vartheta \rfloor}{\| b - a \|} \quad (5)$$

$$\sin \gamma = \frac{\lfloor (b_x - a_x)\sin \vartheta - (b_y - a_y)\cos \vartheta \rfloor}{\| b - a \|} \quad (6)$$

$$Line\ dist = \| m - a \| \sin \alpha \quad (7)$$

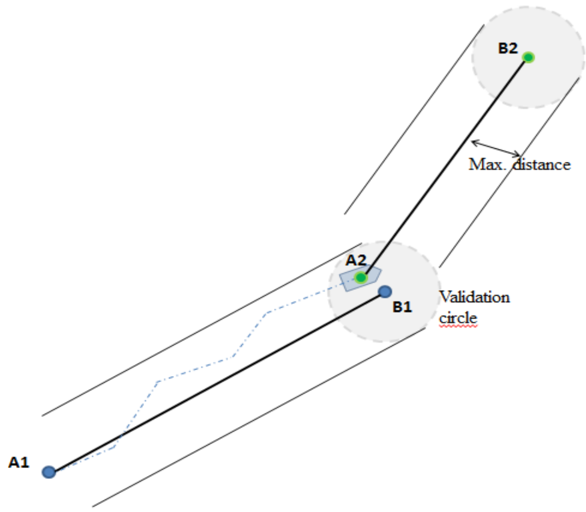


**Fig. 4 Tracking law illustration [10].**

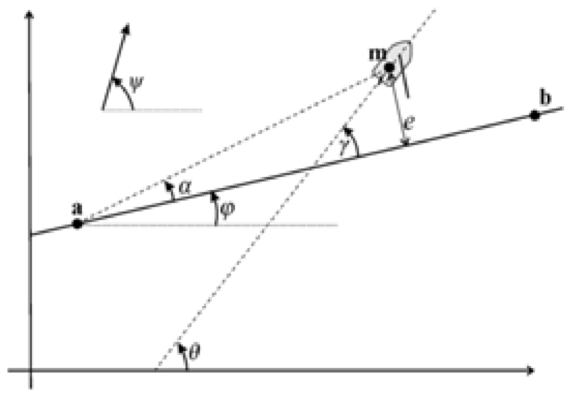


**Fig. 5 Angle definition [10].**

Where “a” denotes the coordinates of the point A, “m” the boat ones and θ denotes the boat heading.

Finally, the boat control is a weighted average between both a course and line distance control [10]:

$$\begin{aligned} \delta_g &= \delta_{g\max}\left(\lambda \sin\gamma + (1-\lambda)\times sign(\sin\alpha)\right) \textit{ if } \cos\gamma > 0 \\ \delta_g &= \delta_{g\max}\, sign(\sin\gamma) \textit{ else} \end{aligned} \quad (8)$$

Where $\delta g$ denotes the rudder angle.

The tracking law gives the course over ground, $Rf$ to follow and the surface course $Rs$ is deduced from the next expression [11]:

$$R_S = R_f + \arcsin\left[\frac{V_C}{V_S}\sin(R_f - Z_C)\right] \quad (9)$$

Where $V_C$ represents the current speed (knot) and $Z_C$ the current azimuth (°).

If the course requested by the tracking law is not appropriate, the sailboat adopts a sailing up strategy. A course is not appropriate when $\cos(\psi-\theta) < -\cos\delta_{\text{upwind}}$ where $\delta_{\text{upwind}}$ is the minimum upwind angle the boat can keep and ψ the wind angle. If the line distance is negative, the boat will sit upwind with starboard tack. If the distance is positive, the boat will sail up with a port tack. As soon as the line distance is too important or the boat pops by tailwind again, the tracking line is tried again. In the case of a strategy change to sail up the wind, the course over ground is not anymore the one which is initially determined by the control. So, it has to be recalculated according to the next formula [11]:

The GPS position of the boat is determined by calculating the travelled distance between every simulation time step. Knowing the course over ground, the new coordinates of the boat can be deduced. These coordinates allow exploiting the corresponding climate data.

$$\begin{aligned} R_f &= \frac{R_S + Z_C}{2} + \arctan\frac{V_S - V_C}{V_S + V_C}\tan\frac{R_S - Z_C}{2} \\ &+ \frac{sign\left[(V_S - V_C)(R_S - Z_C)\right]\left[1 + sign\left(\left|R_S - Z_C\right| - 180°\right)\right]}{2}\times 180° \end{aligned} \quad (10)$$

The apparent speed of the boat is computed with speed polar [12], which are specific to each boat with a specific set of sails, they are provided by marine architects. This speed is determined from the TWA (True Wind Angle) and the TWS (True Wind Speed). The TWA is the angle between the true wind and the boat. It is adjusted according to the sea state, which slows the boat. The speed over ground of the boat results from the sum of the current vector and the apparent speed vector of the boat [13]. The speed over ground is set to 0 knot when the boat is at anchor. The travelled distance is calculated from this speed. All it takes to sum the whole results; the time step is 1 hour (1 knot = 1 mile/hour).

*3.4 Generation of Climate Data*

Most climate data come from Grib files took from the American server NOAA (National Oceanic and Atmospheric Administration), which includes an archiving of wind (angle, speed), temperature, sea state (wave height, period and direction) and current data (angle, speed). These data are transcribed in the form of matrix and integrated to the simulator, which selects the data that fit the GPS coordinates of the boat and the date and time of simulation.

A sunshine model is also implemented to estimate the surface power of the sun radiations. It depends on the date and sailboat position on the globe. All the details can be found in the Piedallu’s article [14].

Concerning the cloudiness, it is determined in a statistical way [15]. The typical form of the probability density function of the cloud cover is known as given by Eq. (11). We collect the specific constants corresponding to some regions and typical months to have as much diversity as possible. Finally, we pick up cloudiness values for each crossing from these probability density functions thanks to a uniform distribution.

$$f(k_t) = \frac{C}{(k_{tu}\lambda\gamma)\left[e^{\lambda k_t}(1-\gamma k_t) - 1\right]} \quad (11)$$

Where $k_t$ represents *the* clearness index, $k_{tu}$ the upper bound of the clearness index and ($C$, $\lambda$) the specific constants fixed according to the average clearness.

## 4. Factor Influence and Scenario Comparison

### *4.1 Routes Comparison*

To validate the simulator and the chosen models, different scenarios of Atlantic crossing are compared. First, two different crossing routes are analyzed. They are performed exactly during the same period, in June. The hydrogenerator and the solar panels are the only producers. These two routes start from the same coordinates and arrive at the same GPS point. One passes more at the North than the other, as presented in Fig. 6. The route 1 (5,100 nautical miles) is slightly longer than the route 2 (4,800 nautical miles).

The cloudiness data, as explained in the previous section, are a random variable. Therefore, a draw is specific to each simulation. To fulfill all the comparison criterions, each simulation is performed about ten times. This gives several samples, which are valid to make the analysis. The results are given in Table 1.Taking the route 1 will produce 5.5% more than the route 2, being 658 Wh/day (Table 2). This can be equivalent to four extra hours of satellite communication or a half-day of heating per day. The difference of hydrogenerator production is explained by better wind and current conditions in route 1. On average, the wind blows 2 knots stronger which allows the boat to go 0.5 knots faster.

The hydrogenerator production is directly linked to the apparent speed. It explains the difference of 5.7%. The difference of solar panels production is explained by the period of the simulation, which is performed in June, around the summer solstice for the northern hemisphere. Therefore, the route 1 gets more intense radiations than the south route. The days at the north are longer which means a better amount of sunshine, whatever the cloudiness. On average, 3% more is produced. This first comparison highlights the consequence of the current and the wind on the boat speed, so, on the hydrogenerator production. Moreover, it highlights the geolocation consequence on sunshine, so on solar panels production. As a conclusion, taking a route slightly longer will waste almost one day of navigation but will guarantee much better comfort and security.


**Fig. 6 Boat routes used for the first comparison.**

**Table 1 Results of simulations.**

| Route | Time (h) | Hydrogenerator average (Wh/day) | Solar panels average (Wh/day) | Total (Wh/day) |
|---|---|---|---|---|
| N°1 | 586 | 11,461 | 1,241 | 12,702 |
| N°2 | 569 | 10,841 | 1,203 | 12,044 |
| Gap | 17 | | | |

**Table 2 Routes comparison.**

| | (Wh/day) | % |
|---|---|---|
| Difference of hydrogenator production | 620 | 5.7 |
| Difference of solar panels production | 38 | 3.1 |
| Difference of total production | 658 | 5.5 |

**Table 3 Results of simulations.**

| Period | Time (h) | Hydrogenerator average (Wh/day) | Solar panels average (Wh/day) | Total (Wh/day) |
|---|---|---|---|---|
| June | 586 | 11,243 | 1,234 | 12,477 |
| November | 579 | 10,541 | 272 | 10,813 |
| Gap | 7 | | | |

**Table 4 Periods comparison.**

| | Wh/day | % |
|---|---|---|
| Difference of hydrogenator production | 702 | 6.7 |
| Difference of solar panels production | 962 | 354 |
| Difference of total production | 1,664 | 15 |

*4.2 Periods Comparison*

The second analysis is about the comparison of one route of Atlantic crossing performed during two distinct periods, in June and November (Tables 3 and 4). There are only 7 hours of interval between the two routes. However there is a difference of 15.4% of production, which makes 1.7 kWh/day. It is equivalent to 1 hour of water heater functioning or half an hour of electric cooker use per day. The route performed in November is faster but leads to a lower production of the hydrogenerator (7%). The wind conditions (> 4 knots on average), so the apparent speed of the boat is better on this route, the production should go hand in hand with it. But this conclusion excludes the sea state.

Actually, the sea is much rougher on this route (about 3 m) and leads to a less homogeneous production of the hydrogenerator, sometimes it can be out of water. The solar production is much more important in June. Such a difference confirms the model validity, the days are longer and the radiations more powerful around the summer solstice. This comparison points out the consequence of the chosen date of crossing on the amount of sunshine so on the solar production. It highlights the consequence of the sea conditions on the hydrogenerator too. The boat can go faster however it still can have a less good quality production. Then, it loses in both sailing and energy comfort. Therefore, the sailing period has to be chosen in function of what the navigator is looking for. The navigator can look for performance and sensation or for comfort and serenity on board, in medium measures evidently.

## 5. Conclusion

In this paper, we propose production, storage and consumptions models fitted for the yachting environment. They are combined within a configurable simulator that reproduces sailing conditions. This is the first step to reach our goal, namely the development of a self-adaptive management system of the onboard energy in order to assure safety and optimize comfort with the exclusive use of renewable energy sources. This simulator highlights the weather conditions influence (wind, sea state, etc.) over production, so the route effect. It helps to compare scenarios and opt for the best compromise as possible between comfort and performance. Now, we have to refine the influence of these parameters over the consumption (e.g. the routing over the automatic pilot). The next step, in the medium term, will be the development of energy management algorithms (e.g. selective power cut) to give to the final user a complete system from the production to the use. They will be tested with the simulator before being implanted in the real Voilier du Futur prototype.

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## The Introduction of the Authors

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She received her engineer's degree from Grenoble InP, ENSE3 in 2013. She is specialized in design, control and monitoring of smart energy systems. After her graduation, she joined the Lab-STICC, UBS in Lorient where she worked on the "Voilier du Futur" Project to develop the energy management system of the sailboat. Currently, as a research engineer, she is engaged in design interface for energy management at home.

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He received the M.Sc. degree in Electrical Engineering from Ecole Supérieure d'Electricité of Rennes in 1999 and the PhD. degree in Computer Sciences from the UBS University Lorient, in 2002. In 2005, he joined the Université de Bretagne Sud and CNRS laboratory Lab-STICC as an associate professor.

His research interests include: i) software/hardware consumption models and estimation for complex heterogeneous embedded systems, ii) Low power embedded systems for uncertain environments and iii) Low power communication systems for SoC.

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He is a CNRS director of research at Lab-STICC, Lorient/Brest, France. He received the Ph.D. degree from Rennes University (France) in 1996. In 1997, he has been a visitor researcher at IMEC (Belgium). He has been an associate professor at UBS University (France) until 2002. In 2003, he co-founded the dixip company in the domain of wireless embedded systems. Since 2004 he is a CNRS researcher at the Lab-STICC. He has been a visitor researcher at the University of Queensland, Australia in 2010 and an invited Prof. at Tohoku University, Japan in Nov. 2014. His current work focuses on various aspect of embedded system design: i) Self-adaptativity for uncertain environments, ii) CAD tools for heterogeneous system-on-chip synthesis iii) Dedicated hardware architectures including security and embedded vision and iv) Low power and open navigation units.