

# Development of A Multi-Scheme Energy Management Strategy For A Hybrid Fuel Cell Driven Passenger Ship

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## Abstract

Hybrid fuel cell propulsion systems for marine applications are attracting widespread interest due to the need to reduce ship emissions. In order to increase the potential of these systems, the design of an efficient energy management strategy (EMS) is essential to distribute the required power properly between different components of the hybrid system. For a hybrid fuel cell/battery passenger ship, a multi-scheme energy managements strategy is proposed. This strategy is developed using four schemes which are: state-based EMS, equivalent fuel consumption minimization strategy (ECMS), charge-depleting charge-sustaining (CDCS) EMS, the classical proportional-integral (PI) controller based EMS, in addition to a code that chooses the suitable scheme according to the simulation inputs. The main objective of the proposed multi-scheme EMS is to minimize the total consumed energy of the hybrid system in order to increase the energy efficiency of the ship.

The world's first fuel cell passenger ship *FCS Alsterwasser* is considered and its hybrid propulsion system is modelled in MATLAB/Simulink environment. The performance of the developed multi-scheme EMS is compared to the four studied strategies in terms of total consumed energy, hydrogen consumption, total cost and the stresses seen by the hybrid fuel cell/battery system components considering a daily ship operation of 8 hours. Results indicate that a maximum energy and hydrogen consumption savings of 8% and 16.7% respectively can be achieved using the proposed multi-scheme strategy.

**Keywords:** Multi-Scheme Energy Management Strategy, Hybrid Power System, Fuel Cell, PEMFC, MATLAB, Simulink

## 1. Introduction

The minimization of the negative environmental impacts of shipping and improving ships energy efficiency have generated considerable recent research interest. This concern is enhanced by the introduction of more stringent environmental regulations by the International Maritime Organization (IMO) to control ship emissions. Hybrid electric power and propulsion concepts have been suggested as an energy efficiency design index (EEDI) reduction measure adopted by the IMO to help ships to comply with the new international regulations [1, 2]. In order to make hybrid propulsion systems greener, fuel cells can be used in these systems as a main source of power [3].

Proton exchange membrane fuel cell (PEMFC) has the advantages of zero emissions, quick start-up, high efficiency, high power density, low operating temperature, solid electrolyte, and low noise which promote the application of PEMFC in the transportation sector [4, 5]. A battery system is usually used as an energy storage technology

to hybridize the fuel cell propulsion system in transportation applications in order to improve the efficiency of the fuel cell system and its dynamics [6]. The presence of the fuel cell and battery systems together requires an energy management strategy (EMS) to improve the electrical integration of the system.

Development of a suitable EMS is a basic issue for hybrid fuel cell propulsion systems to properly split the required power between the fuel cell and battery systems. EMS controls the dynamic behaviour of the hybrid system, its fuel consumption, and affects the system efficiency, weight, size, and lifetime of its components [7, 8]. Therefore, efforts have been made to investigate different EMS. These strategies may aim to minimize hydrogen consumption [9], maximize fuel cell efficiency or overall efficiency [10], reduce stresses on the hybrid system components [11], maintain battery state of charge (SOC) or the bus voltage at a certain level [9, 12, 13], minimize the operational cost [14] or minimize the hybrid system weight and size [8]. Whilst most of the studies about EMS give their attention to the hydrogen consumption, which is certainly important, in this paper more focus is concentrated on the total consumed energy taking into consideration the bat-

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tery depleted energy and the required energy to recharge the battery back to its initial SOC for the purpose of improving the energy efficiency of the examined ship. By taking the battery discharge energy during the voyage and the required energy to recharge it back to its initial SOC into account, the total consumed energy can be accurately obtained and different energy management strategies are fairly compared.

The literature review in the area of power distribution of hybrid fuel cell propulsion systems is dominated by automotive industry applications; however, there have been a few studies that investigated this problem for marine applications. In hybrid fuel cell propulsion systems, the fuel cell system can be used to supply the average required power in a load-levelling mode as suggested for small ships and underwater vehicles in [15, 16]. An alternative approach was proposed in [3] for a Korean tourist boat to use the fuel cell system in a load-following mode to provide the required power. Meanwhile, the battery system is used as a supplement to the fuel cell system and charged or discharged when the required load power is lower or higher than the available fuel cell power. For the hybrid fuel cell/battery passenger ship *FCS Alsterwasser*, a state-based EMS was developed in order to maximize the hybrid system efficiency [10]. Also, an improvement to the classical PI controller based EMS was presented in [17] for the *FCS Alsterwasser* that takes into account the fuel cell efficiency as an input to the EMS which results in reducing the fuel cell operational stress and its hydrogen consumption. A fuel cell/battery/ultra-capacitor hybrid power system was proposed for the same ship with a fuzzy logic EMS with an objective of enhancing the hybrid system performance [18].

Due to the fact that each EMS has its main objective, there remains a need for using a multi-scheme EMS to improve the performance of hybrid fuel cell systems [11]. This study represents a new approach to design an efficient multi-scheme EMS for hybrid fuel cell/battery propulsion systems of ships that have significant variation in its power demand. The approach used in this study aims to compare different energy management strategies at different battery SOC and different load levels for a hybrid fuel cell/battery passenger ship. This comparison is then used to develop a multi-scheme EMS for the first time that switches between different strategies during the voyage of the examined ship based on the battery SOC and the required load power in order to reduce the energy consumption of the hybrid fuel cell system and improve its energy efficiency. Four different EMS are implemented for the comparison which are: state-based EMS, equivalent fuel consumption minimization strategy (ECMS), charge-depleting charge-sustaining (CDCS) EMS, and the classical proportional-integral (PI) controller based EMS. These strategies are the most common and they are chosen for their simplicity and ease of realizability while other strategies are more complex and require longer computational time [11]. The four strategies are combined to develop a multi-scheme EMS with an ob-

jective of minimizing the total consumed energy. Considering a daily operation of the ship of 8 hours, the five EMS are compared in terms of the consumed energy, hydrogen consumption, operational cost, and the stresses seen by the fuel cell and battery systems. Sensitivity analysis of different initial battery SOC as well as different energy prices are made to assess its effects on the results of the developed multi-scheme EMS.

The ship hybrid fuel cell propulsion system as well as different different energy management strategies are modelled in MATLAB/Simulink environment which is a flexible environment using the Simscape Power Systems (SPS) toolbox [19]. The paper is organized as follows. Section 2 introduces the examined ship and voyage. Section 3 describes different EMS while Section 4 illustrates the simulation implementation of the hybrid fuel cell propulsion system and different EMS. Section 5 shows the simulation results and discussion. Finally, Section 6 presents the work conclusions.

## 2. Description of the ship & voyage

The world's first hydrogen fuel cell passenger ship *FCS Alsterwasser* was developed in Germany as a part of the *Zemship* (Zero Emission Ship) project [3, 20]. The total project budget was €5.5 million, of which €2.4 million was co-funded by the European Union life program [21]. A hydrogen fuelling station has been also built for this ship as a part of the project. This ship is used as a case study in this paper and its main specifications are shown in Table 1.

Table 1: Specifications of the FCS Alsterwasser passenger vessel

Capacity	100 passengers
Length	25.5 m
Breadth	5.36 m
Depth	2.65 m
Draft	1.33 m
Displacement	72 tonnes
Top speed	8 kn
Powering	2 PEMFC of 48 kW each 360 Ah/560 V lead-gel battery

This ship is equipped with two PEMFC systems and a DC-DC converter to stabilise the fuel cell voltage. The fuel cell system is hybridized with a lead-gel battery system to deliver the propulsion power to an electric motor as shown in Figure 1 without producing any harmful emissions proving to be a highly reliable power system. Twelve tanks of 50 kg of hydrogen are installed onboard the ship at a pressure of 350 bar which is sufficient for about three operational days without refuelling [3]. The required time of the refuelling operation is about 12 minutes [21].

The operational area of *FCS Alsterwasser* includes the River Elbe, inner city waterways, Hafen City and Lake Alster in Hamburg, Germany for round and charter trips [20].

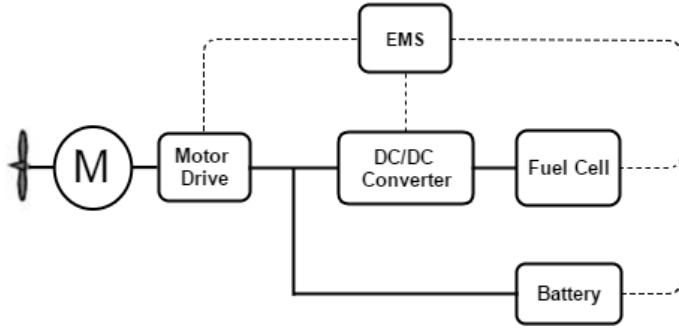


Figure 1: FCS Alsterwasser fuel cell/battery hybrid system

142 Therefore, its operational profile has considerable variation  
 143 in power requirement as shown in Figure 2. Part of the  
 144 real typical power requirement of the ship during its voyage  
 145 on the Alster, Hamburg has been measured as shown  
 146 in Figure 2 and it is available in [20, 10]. This power re-  
 147 quirements includes propulsion and auxiliary power and it  
 148 shows power requirements during cruising, docking, stop-  
 149 ping, and acceleration phases of the ship journey.

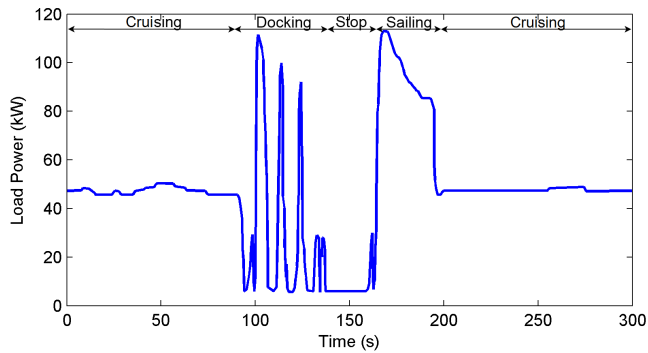


Figure 2: Typical load characteristics on the Alster

150 In order to have power requirements of the ship during  
 151 a full voyage, an extrapolation of the power requirements  
 152 shown in Figure 2 has been made considering a voyage  
 153 from Finkenwerder to Landungsbrücken as displayed in  
 154 Figure 3. Then, the developed power requirements shown  
 155 in Figure 3 is repeated for 8 times in order to cover the  
 156 daily operation of ship.

157 Each leg of the examined voyage contains 4 stops  
 158 between the two destinations as shown in Figure 4 and its  
 159 duration is about 1 hour as detailed in Table 2. The de-  
 160 veloped power requirements is then used as an input to the  
 161 simulations as will be discussed in the following sections.

### 162 3. Energy management strategies

#### 163 3.1. State-based EMS

164 For the same examined ship, a state-based EMS was  
 165 developed in [10] to split the required power between the

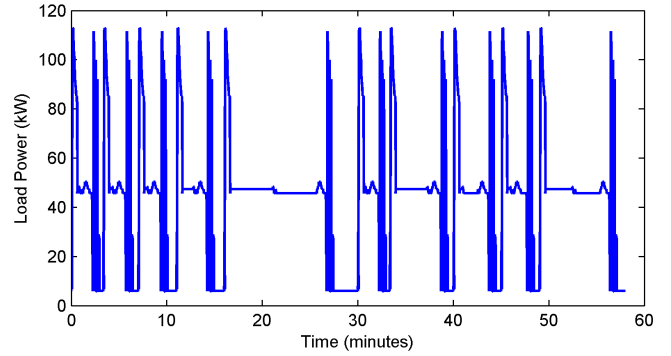


Figure 3: Developed power requirement of a real full voyage

Table 2: Finkenwerder - Landungsbrücken time table [22]

Landungsbrücken	19.15	Finkenwerder	19.45
Altona	19.18	Bubendey-Ufer	19.48
Dockland	19.22	Neumuhlen	19.55
Neumuhlen	19.26	Dockland	20.00
Bubendey-Ufer	19.31	Altona	20.04
Finkenwerder	19.43	Landungsbrücken	20.13

166 fuel cell and battery systems with an objective of max-  
 167 imizing the system efficiency. This control strategy is a  
 168 deterministic rule-based method which can contain many  
 169 operating states to control the energy flow between the  
 170 components of the hybrid fuel cell power systems [23].  
 171 These operating states is based on the operational lim-  
 172 its of the fuel cell and battery systems into consideration,  
 173 the required load power, and the battery SOC.

174 In this strategy, the ship required load power ( $P_{load}$ ) is  
 175 compared with different combinations of the fuel cell and  
 176 battery systems operating limits which are fuel cell min-  
 177 imum power ( $P_{FCmin}$ ), optimum fuel cell power ( $P_{FCopt}$ ),  
 178 maximum fuel cell power ( $P_{FCmax}$ ), battery optimum dis-  
 179 charge power ( $P_{optdis}$ ), battery optimum charge power ( $P_{optchar}$ )  
 180 and battery optimum power ( $P_{BATopt}$ ) taking into consid-  
 181 eration the battery SOC limits as shown in Table 3.

182 The values of the operating limits of the fuel cell and  
 183 battery systems are decided based on the voltage and cur-

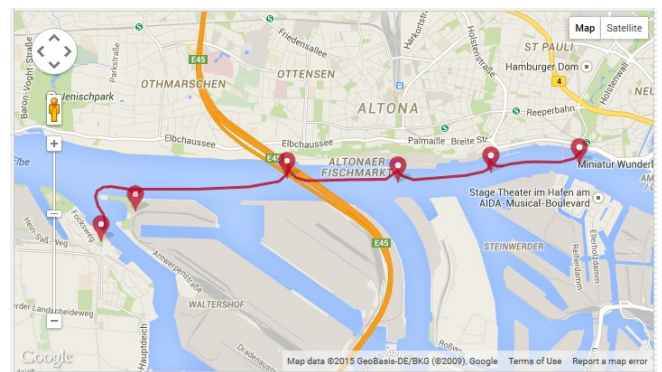


Figure 4: The examined vessel route [22]

Table 3: Summary of a state-based EMS [10]

Battery SOC	State	Load Power	Fuel cell reference power
SOC > 80%	1	$P_{\text{load}} \leq P_{\text{FCmin}}$	$P_{\text{FCmin}}$
	2	$P_{\text{load}} \leq P_{\text{FCmin}} + P_{\text{optdis}}$	$P_{\text{FCmin}}$
	3	$P_{\text{load}} \leq P_{\text{FCmax}} + P_{\text{optdis}}$	$P_{\text{FC}} = P_{\text{load}} - P_{\text{optdis}}$
	4	$P_{\text{FCmax}} + P_{\text{optdis}} < P_{\text{load}}$	$P_{\text{FCmax}}$
$50\% \leq \text{SOC} \leq 80\%$	5	$P_{\text{load}} \leq P_{\text{FCmin}}$	$P_{\text{FCmin}}$
	6	$P_{\text{load}} \leq P_{\text{FCopt}} - P_{\text{BATopt}}$	$P_{\text{load}}$
	7	$P_{\text{load}} \leq P_{\text{FCopt}} + P_{\text{BATopt}}$	$P_{\text{FCopt}}$
	8	$P_{\text{load}} \leq P_{\text{FCmax}}$	$P_{\text{load}}$
	9	$P_{\text{load}} > P_{\text{FCmax}}$	$P_{\text{FCmax}}$
SOC < 50%	10	$P_{\text{load}} \leq P_{\text{FCmax}} - P_{\text{optchar}}$	$P_{\text{load}} + P_{\text{optchar}}$
	11	$P_{\text{load}} > P_{\text{FCmax}} - P_{\text{optchar}}$	$P_{\text{FCmax}}$

184 rent limits of these systems in an attempt to maximize the  
 185 efficiency of the hybrid system. According to  $P_{\text{load}}$  and  
 186 the battery SOC, the fuel cell power is determined. Then,  
 187 the battery is charged or discharged based on the differ-  
 188 ence between the fuel cell power and  $P_{\text{load}}$ . As illustrated  
 189 in Table 3, the fuel cell system operates at its minimum  
 190 power limit during low required power with normal and  
 191 high battery SOC as in states 1, 2, and 5. Fuel cell system  
 192 works at its maximum limit when the battery SOC is low  
 193 or during high required power as in states 4, 9, and 11.  
 194 Meanwhile the fuel cell system follows the required load  
 195 power as in states 3, 6, 8, and 10 and it operates at its  
 196 optimum power in state 7.

### 197 3.2. Equivalent fuel consumption minimization strategy 198 (ECMS)

199 ECMS is one of the real-time optimization approach  
 200 control methods which is based on cost functions. The  
 201 objective of ECMS is to minimize the instantaneous fuel  
 202 consumption of the hybrid system and its concept was pro-  
 203 posed by [24]. The hybrid system fuel consumption ( $C$ ) in  
 204 this strategy consists of the actual fuel cell hydrogen  
 205 consumption ( $C_{\text{FC}}$ ) in addition to the equivalent consumption  
 206 of the battery ( $C_{\text{Batt}}$ ). The optimization problem in order  
 207 to minimize the equivalent hydrogen consumption can be  
 208 formulated as follows:

$$P_{\text{FCopt}} = \underset{P_{\text{FCopt}}}{\text{argmin}^C} = \underset{P_{\text{FCopt}}}{\text{argmin}(C_{\text{FC}} + \alpha \cdot C_{\text{Batt}})} \quad (1)$$

209 where ( $\alpha$ ) is a penalty coefficient used to modify the equiv-  
 210 alent fuel consumption of the battery according to the bat-  
 211 tery SOC deviation from its target and it is calculated as  
 212 a function of battery SOC limits as follows:

$$\alpha = 1 - 2\mu \frac{(\text{SOC} - 0.5(\text{SOC}_H + \text{SOC}_L))}{\text{SOC}_H - \text{SOC}_L} \quad (2)$$

213 where ( $\mu$ ) is the SOC constant used to balance the bat-  
 214 tery SOC during operation [25], ( $\text{SOC}_H$ ) and ( $\text{SOC}_L$ ) are  
 215 the upper and lower limit of the battery SOC respectively  
 216 [26, 27]. According to 1, an optimum fuel cell power is cal-  
 217 culated as a function of the load power and battery SOC.

218 This optimum fuel cell power is limited between a mini-  
 219 mum and maximum fuel cell power to avoid the operation  
 220 in a poor efficiency region. The calculated fuel cell power is  
 221 subtracted from the required load power to determine the  
 222 battery power. Then, fuel cell power and battery power  
 223 are divided by the voltage to calculate the required current  
 224 from each system as shown in Figure 5.

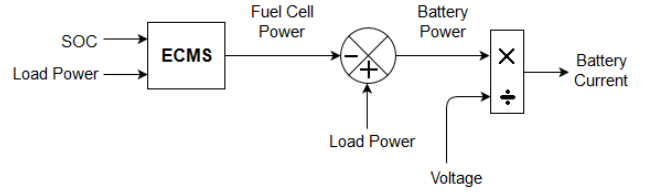


Figure 5: Equivalent fuel consumption minimization strategy scheme

### 225 3.3. Classical PI EMS

226 Due to its simplicity and ease of online tuning, EMS  
 227 that based on PI controllers have been proposed for hy-  
 228 brid propulsion systems. The objectives of PI EMS is to  
 229 maintain the battery SOC at a reference value and allow  
 230 the fuel cell to provide a steady state power [11, 12].  
 231 By maintaining the battery SOC at a nominal value, its  
 232 performance and lifetime can be improved. This strategy  
 233 uses a PI controller to decide the battery power as a func-  
 234 tion of the battery SOC deviation from its reference value  
 235 (SOC\_Ref). The battery power is then removed from the  
 236 required load power to obtain the fuel cell power as shown  
 237 in Figure 6.

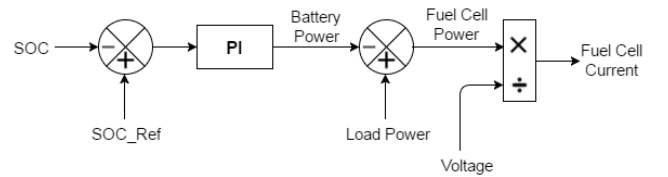


Figure 6: Classical PI control energy management strategy [11]

238 The main inputs to this strategy are the required load  
 239 power and battery SOC. This strategy tends to use more

240 power from the battery system when the battery SOC is  
 241 above its reference value meanwhile the fuel cell provides  
 242 low power. When the battery SOC below its reference  
 243 value, the fuel cell system is used to provide the load power  
 244 and charge the battery to its reference value. In order  
 245 to have balance between the PI controller response time  
 246 and stability, the controller parameters are tuned for the  
 247 examined driving cycle using the MATLAB control system  
 248 toolbox [28].

### 249 3.4. Charge-depleting charge-sustaining EMS

250 One of the most popular strategies for hybrid systems  
 251 is the CDCS strategy in which the hybrid system required  
 252 power is supplied from the battery system in a charge-  
 253 depleting (CD) mode until the battery SOC decreases to  
 254 a certain limit while the fuel cell system is turned off or  
 255 works at its minimum power [29, 30]. By reaching the bat-  
 256 tery SOC limited threshold, the hybrid system is switched  
 257 to a charge-sustaining (CS) mode for the rest of the jour-  
 258 ney where the fuel cell system provides the required power  
 259 for the load and keeps the battery SOC constant as shown  
 260 in Figure 7.

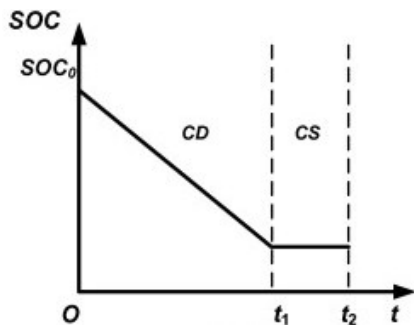


Figure 7: Charge depleting charge sustaining strategy scheme [7]

261 CDCS strategy is often used if the trip length is not  
 262 known a priori. Moreover, beside its simplicity, prioritiz-  
 263 ing battery power consumption by the CDCS EMS results  
 264 in minimizing the hydrogen fuel consumption and its op-  
 265 erational cost [30, 31].

### 266 3.5. Multi-scheme EMS

267 Because each EMS has its main objective and has dif-  
 268 ferent impacts on the overall efficiency, hydrogen and to-  
 269 tal energy consumption and operational cost of the hy-  
 270 brid system, a multi-scheme EMS should be used [11]. A  
 271 multi-scheme EMS that contains different strategies, then  
 272 it switches between different strategies during the voyage  
 273 and chooses the suitable strategy at each instant to further  
 274 improve the performance of the fuel cell hybrid system. In  
 275 order to increase the ship's energy efficiency, the objec-  
 276 tive of the developed multi-scheme EMS is to minimize  
 277 the total consumed energy by the hybrid system. The  
 278 total energy not only includes the hydrogen consumption  
 279 used by the fuel cell system, but also includes the depleted

280 energy from the battery system during the voyage and  
 281 the required energy to charge the battery system back to  
 282 its initial SOC. The developed multi-scheme EMS consists  
 283 of the four considered strategies in this study which are:  
 284 state-based EMS, ECMS, classical PI EMS, and CDCS  
 285 strategy. These strategies are combined in addition to a  
 286 code that switches between these strategies during the voy-  
 287 age to minimize the total consumed energy based on the  
 288 required load power and the current battery SOC.

289 In order to design the multi-scheme EMS, the typi-  
 290 cal power requirements of the examined ship is divided  
 291 into three modes; low power mode, cruising mode, and  
 292 high power mode as shown in Figure 8. Low power mode  
 293 includes the stopping phase of the ship voyage and low  
 294 power requirements during the docking phase. The cruis-  
 295 ing mode contains the ship power consumption around its  
 296 cruise speed while the high power mode includes the peak  
 297 requirements of the ship during acceleration and docking.

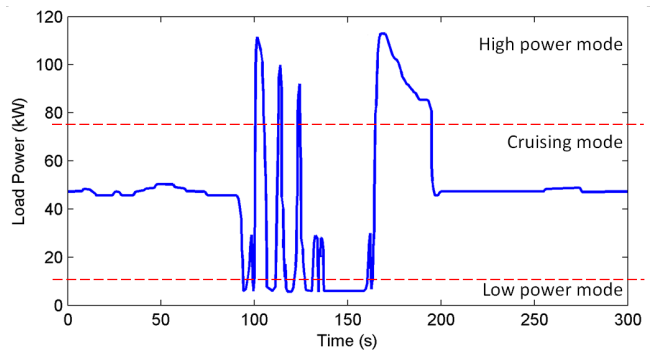


Figure 8: Different modes of the ship typical power requirements for the multi-scheme EMS

298 Regarding the battery SOC which affects the power  
 299 split between the fuel cell and battery systems, it has been  
 300 divided into low, medium, and high SOC regions. Then,  
 301 the four considered strategies has been compared in terms  
 302 of the total consumed energy for the three different power  
 303 modes shown in Figure 8 starting with different initial bat-  
 304 tery SOC. By doing this comparison, the suitable strategy  
 305 that minimizes the total consumed energy is selected at  
 306 different battery SOC and different power modes for the  
 307 examined voyage. Finally, a code has been developed to  
 308 implement this comparison to select the the suitable strat-  
 309 egy during the voyage based on the required load power  
 310 and battery SOC as illustrated in Figure 9.

311 In the case of starting with high initial battery SOC  
 312 as for example, the multi-scheme EMS uses the classical  
 313 PI EMS until the battery SOC decreases to the medium  
 314 SOC region. Then, the ECMS and CDCS strategies are  
 315 used instead of the classical PI as shown in Figure 9. This  
 316 is because the classical PI EMS consumes more energy  
 317 than the ECMS and CDCS strategies at the medium SOC  
 318 region since the classical PI EMS maintains the battery  
 319 SOC around a reference value of 60%. Consequently, the  
 320 developed code allows the hybrid system to use different  
 321 strategies during the voyage according to the required load



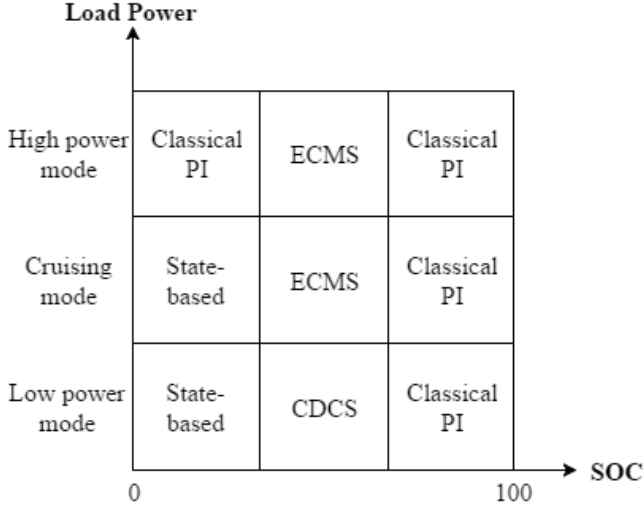


Figure 9: Developed code of the multi-scheme EMS for the examined case study

322 power and current battery SOC in a way that reduces the  
 323 total consumed energy by the end of the voyage. In the  
 324 next section, the developed multi-scheme EMS as well as  
 325 the state-based EMS, ECMS, classical PI EMS, and CDCS  
 326 strategy are implemented in MATLAB/Simulink environ-  
 327 ment to be compared. Moreover, the examined ship's hy-  
 328 brid system is also implemented in Simulink environment  
 329 using Simscape Power Systems (SPS) toolbox.

#### 330 4. Simulation implementation

331 The hybrid fuel cell/battery system of the examined  
 332 ship as well as the studied strategies are modelled math-  
 333 ematically and implemented in MATLAB/Simulink envi-  
 334 ronment in order to study each strategy and its effect on  
 335 the total consumed hydrogen, energy, operational cost,  
 336 and stresses. The hybrid system simulation model con-  
 337 sists of a Fuel cell&DC-DC converter subsystem, Battery  
 338 subsystem, Load power requirement subsystem, and an  
 339 EMS subsystem as shown in Figure 10. In this section,  
 340 the modelling approach of each subsystem is described.

##### 341 4.1. Fuel cell & DC-DC converter subsystem

###### 342 4.1.1. Fuel cell

343 A considerable number of PEMFC performance mathe-  
 344 matical models have been developed due to its advantages  
 345 and potential applications which includes portable, sta-  
 346 tionary, and transportation applications. A generic model  
 347 of PEMFC has been developed and implemented in Simulink  
 348 as shown in Figure 11.

349 This model has been validated against experimental  
 350 data and real datasheet performance in [32] with an error  
 351 within  $\pm 1\%$ . This model combines the features of  
 352 PEMFC electrical and chemical models and it can repre-  
 353 sent the PEMFC steady-state performance as well as its  
 354 dynamic performance taking into consideration fuel cell

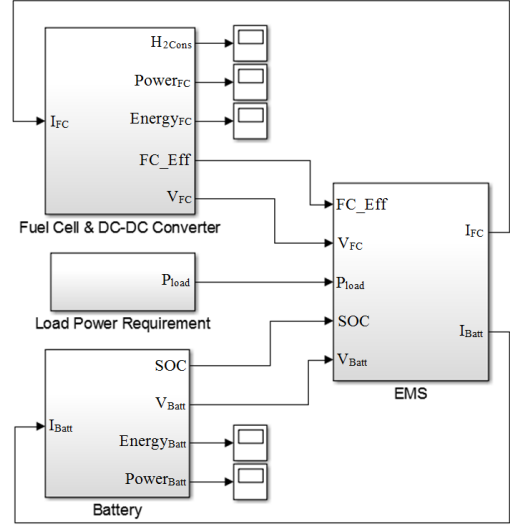


Figure 10: Hybrid fuel cell/battery power system in Simulink/MATLAB environment

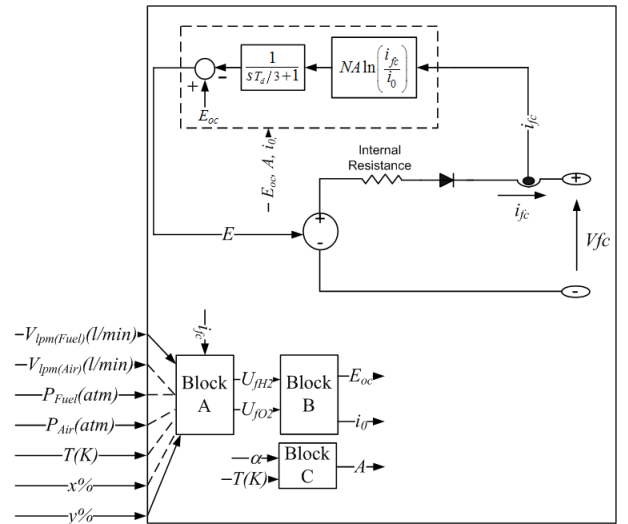


Figure 11: Fuel cell model in Simulink/MATLAB environment adapted from [32]

355 response time. This model is integrated in the SPS tool-  
 356 box in the Simulink library of electric drives. The required  
 357 information to define this model can be obtained from the  
 358 fuel cell polarization curve or from the its datasheet which  
 359 makes this model easy to use.

360 For this study, a preset validated Simulink PEMFC  
 361 model of 50 kW nominal power and 120 kW maximum  
 362 power is used assuming that it is fed with hydrogen and  
 363 a constant resistance of 0.664 Ω. Figure 12 shows the fuel  
 364 cell model characteristics. The nominal efficiency of the  
 365 used PEMFC model is 55% as shown in Figure 13. The  
 366 consumed energy by the fuel cell subsystem is calculated  
 367 as follows

$$\text{Energy}_{\text{FC}} = \text{H}_{2\text{Cons}} \times \text{HHV}_{\text{H}_2} \quad (3)$$

368 where ( $\text{HHV}_{\text{H}_2}$ ) is the hydrogen higher heating value and  
 369 ( $\text{H}_{2\text{Cons}}$ ) is the PEMFC hydrogen consumption which is  
 370 calculated as follows

$$\text{H}_{2\text{Cons}} = \frac{N}{F} \int I_{\text{FCnet}}.dt \quad (4)$$

371 where (N) is the number of cells, (F) is the Faraday con-  
 372 stant and ( $I_{\text{FCnet}}$ ) is the net current drained from the  
 373 PEMFC.

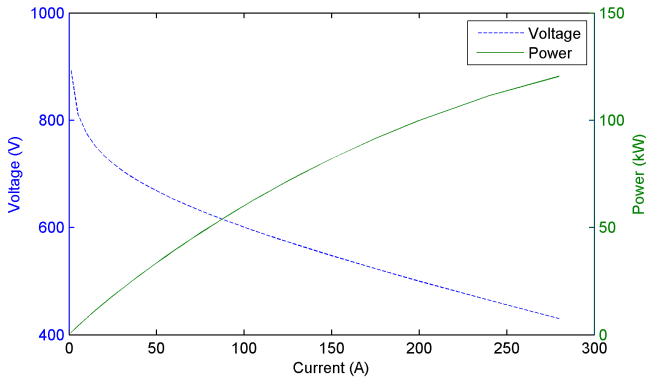


Figure 12: Fuel cell voltage and power versus current

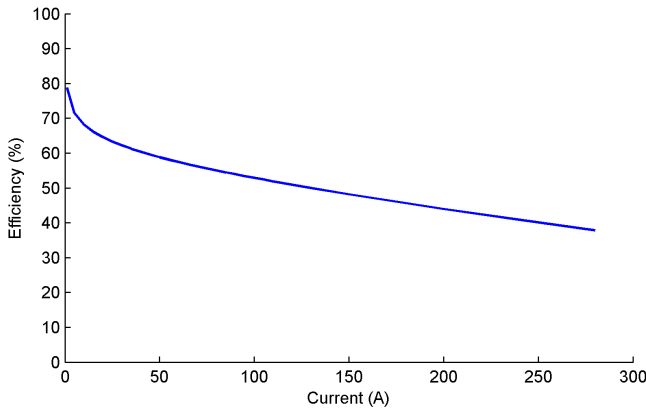


Figure 13: Fuel cell efficiency versus current

#### 4.1.2. DC-DC converter

374 A boost type unidirectional DC-DC converter is used  
 375 to connect the PEMFC to the DC bus as shown in Figure  
 376 1 in order to regulate its output power and voltage. The  
 377 operating voltage ratio (k) of the DC-DC converter is used  
 378 to readjust the net current supplied by the PEMFC into  
 379 the DC bus as follows [33]  
 380

$$\begin{aligned} k &= V_{\text{Batt}}/V_{\text{FC}} \\ I_{\text{FCnet}} &= I_{\text{FC}} \times k \times \eta_{\text{Conv}} \end{aligned} \quad (5)$$

381 where ( $V_{\text{Batt}}$ ) is the battery voltage, ( $V_{\text{FC}}$ ) is the fuel cell  
 382 voltage and ( $I_{\text{FC}}$ ) is the required current from the fuel  
 383 cell/DC-DC converter subsystem assuming a constant effi-  
 384 ciency of the converter ( $\eta_{\text{Conv}}$ ) to be 95% [34]. As shown  
 385 in Figure 14, the used converter is composed of a switch  
 386 S, an inductor L, and a diode D.

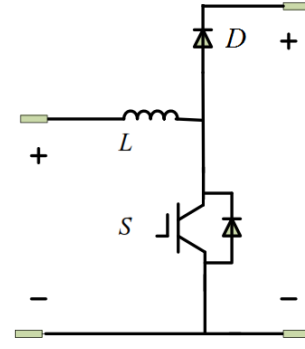


Figure 14: Boost DC-DC converter electrical scheme [10]

#### 4.2. Battery subsystem

387 For transportation applications, batteries are usually  
 388 used as an energy storage device. The examined ship is  
 389 equipped with a lead-gel battery with a capacity of 360 Ah  
 390 and a voltage of 560 V. For this study, an improved easy-  
 391 to-use battery model has been developed and validated in  
 392 [35] is used. This model can represent the steady state  
 393 battery behaviour as well as its dynamic behaviour taking  
 394 into consideration the battery response time assuming a  
 395 constant internal resistance of 0.0156 Ω. Figure 15 plots  
 396 the battery voltage versus its SOC. Moreover, this model  
 397 is integrated in the SPS toolbox and Figure 16 shows its  
 398 implementation in Simulink.  
 399

400 The consumed energy from the battery subsystem  
 401 ( $\text{Energy}_{\text{Batt}}$ ) is calculated as a function of its power  
 402 ( $\text{power}_{\text{Batt}}$ ) as follows

$$\text{Energy}_{\text{Batt}} = \int \text{power}_{\text{Batt}}.dt \quad (6)$$

403 The battery power is calculated as a function of its  
 404 voltage and current ( $I_{\text{Batt}}$ ) as follows

$$\text{power}_{\text{Batt}} = V_{\text{Batt}} \times I_{\text{Batt}} \quad (7)$$

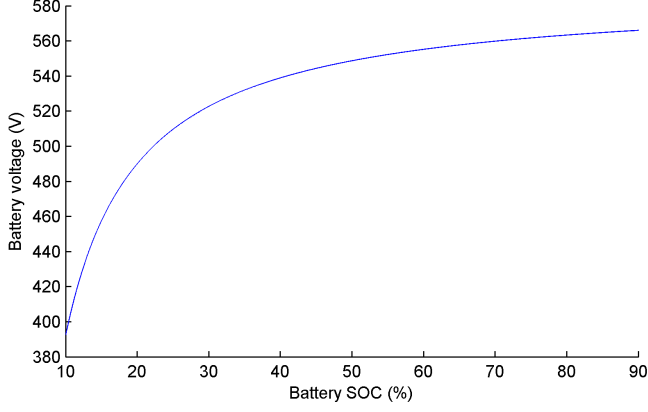


Figure 15: Battery voltage versus SOC

The energy required to recharge the battery back to its initial SOC ( $SOC_{ini}$ ) is calculated as a function of the final battery SOC ( $SOC_{fin}$ ) and its capacity ( $Q$ ) as follows

$$Energy_{BattCh} = \frac{(SOC_{ini} - SOC_{fin}) \times Q \times V_{Batt}}{\text{Charging efficiency}} \quad (8)$$

#### 4.3. EMS subsystem

The four examined EMS as well as the developed multi-scheme EMS are modelled and implemented in Simulink environment in order to be compared in terms of hydrogen consumption, total consumed energy and operational cost and stresses on the power sources of the hybrid propulsion system considering a developed full driving cycle of 8 hours that based on the real typical load requirements of the examined ship shown in Figure 2. The total energy includes the fuel cell consumed energy from (3), battery depleted energy from (6), and the used energy to recharge the battery back to its initial battery SOC ( $Energy_{BattCh}$ ) assuming a charging efficiency of 88% [37] as follows

$$Energy_{Total} = Energy_{FC} + Energy_{Batt} + Energy_{BattCh} \quad (9)$$

The main inputs of the EMS subsystem are the required load power, fuel cell voltage and efficiency, and battery SOC and voltage. Based on these inputs, the used EMS converts the required load power into current and splits it between the fuel cell and battery subsystems as shown in Figure 10. The EMS subsystem using the state-based EMS is validated against the published results in [10] for the same examined ship considering the typical load requirements shown in Figure 2. By implementing the hybrid fuel cell/battery system in Simulink as described earlier and using the same initial battery SOC of 65% as suggested in [10], the state-based EMS is validated as shown in Figures 17 to 19.

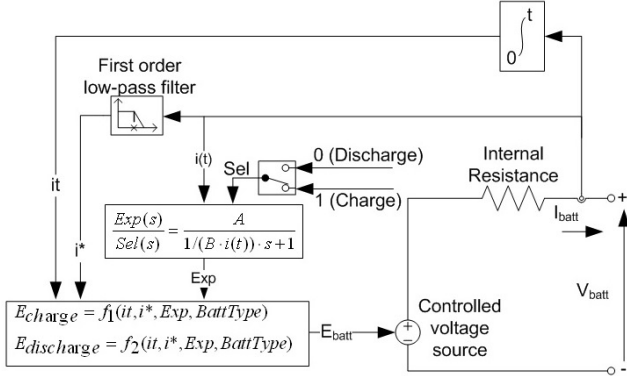


Figure 16: Battery model in Simulink/MATLAB environment adapted from [36]

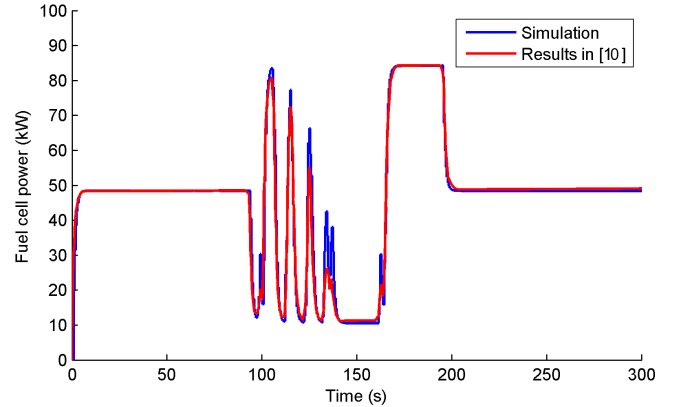


Figure 17: Validation of fuel cell power

As shown in Figures 17 to 19, there is a good agreement between the simulation results and the published results in [10] for the state-based EMS. In the following section, the



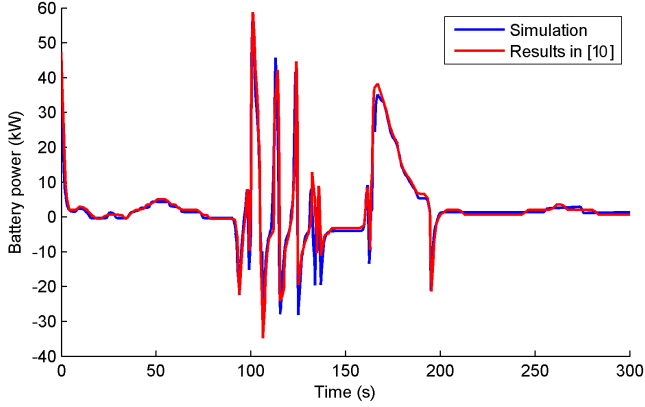


Figure 18: Validation of battery power

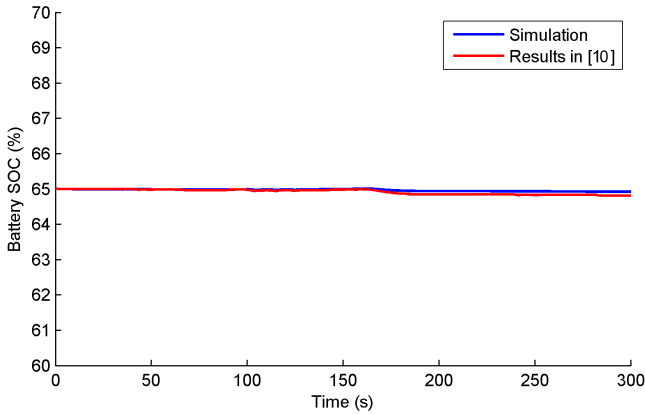


Figure 19: Validation of battery SOC

437 simulation results of the four studied EMS as well as the  
 438 developed multi-scheme EMS are compared in terms of  
 439 hydrogen consumption and total consumed energy, total  
 440 cost, and stresses considering a daily driving cycle of 8  
 441 hours of the examined ship.

#### 442 4.4. Simulation parameters

443 In order to compare different EMS appropriately, the  
 444 same fuel cell and battery models are used with the same  
 445 initial conditions and operating limits. To avoid operating  
 446 at poor efficiency region, fuel cell minimum power is 5 kW  
 447 and its maximum power is 80 kW as suggested in [10] while  
 448 its optimum power value is 50 kW the same as the nominal  
 449 power of the used PEMFC model. Regarding the battery,  
 450 a SOC of 65% is chosen as an initial condition for different  
 451 strategies. For the classical PI EMS, a reference value  
 452 of the battery SOC of 60% is selected as recommended  
 453 by automotive industry designers [12]. For the ECMS,  
 454  $SOC_H$  and  $SOC_L$  are set to 80% and 30% [38] and the  
 455 SOC constant  $\mu$  is set to be 0.6 as reported in [11, 27, 25].  
 456 Meanwhile, the battery threshold value for the CDCS EMS  
 457 is 30% [30]. The battery C-rate limits are 0.3C and 2C as  
 458 recommended by the battery manufacturer [10].

## 5. Results & discussion

459 Considering a daily driving cycle of the ship of 8 hours,  
 460 simulation results show that the developed multi-scheme  
 461 EMS has less energy consumption than the state-based,  
 462 ECMS, CDCS, and the classical PI strategies by 1.4%,  
 463 3.9%, 2.8%, and 0.8% respectively as shown in Figure 20.  
 464 This indicates that changing the used EMS during the  
 465 voyage can be better than using a single EMS and result  
 466 in an energy saving. The total consumed energy shown  
 467 in Figure 20 includes fuel cell and battery used energy  
 468 during the voyage as well as the required energy to charge  
 469 the battery back to its initial SOC.  
 470

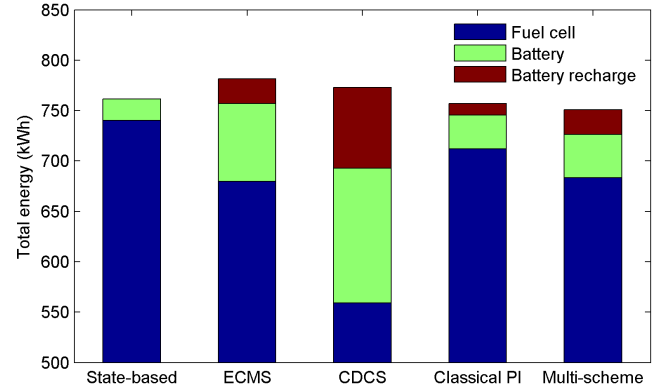


Figure 20: Total consumed energy comparison

471 Regarding the total cost, the multi-scheme EMS has  
 472 approximately the same operational cost as other strate-  
 473 gies as shown in Figure 21. The multi-scheme EMS results  
 474 in a cost saving of 0.7% and 0.02% compared to the CDCS  
 475 and state-based strategies respectively. However, the to-  
 476 tal cost of the multi-scheme EMS is slightly higher than  
 477 the ECMS and classical PI strategies by 0.5% and 0.2%  
 478 respectively. This cost includes the hydrogen cost and the  
 479 battery recharging cost assuming a wind generated hydro-  
 480 gen cost of 4.823 \$/kg [39] and an average electricity price  
 481 of 0.284 \$/kWh for the battery recharging using shore-  
 482 shared (or shore-side) energy [40].

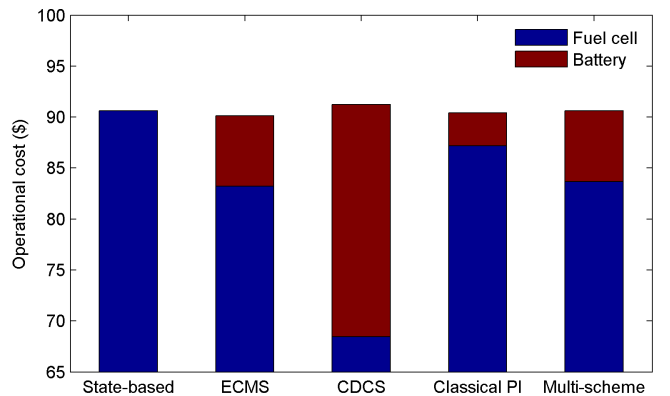


Figure 21: Total cost comparison

483 Figure 22 plots the ship hydrogen consumption using  
 484 different EMS for the examined 8 hours driving cycle. It  
 485 can be noted that the CDCS EMS has the lowest fuel con-  
 486 sumption as expected since it prioritizes the usage of bat-  
 487 tery energy as shown in Figure 23. The developed multi-  
 488 scheme EMS has lower hydrogen consumption than the  
 489 state-based and classical PI EMS by 7.7% and 4% respec-  
 490 tively. However, it has higher hydrogen consumption than  
 491 the ECMS and CDCS EMS by 0.6% and 22.2% respec-  
 492 tively.

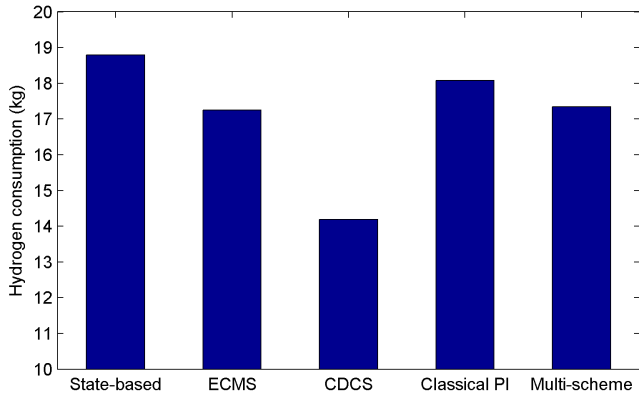


Figure 22: Hydrogen consumption comparison

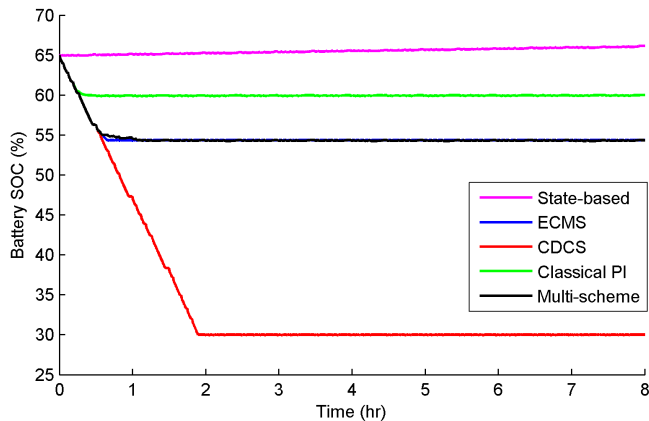


Figure 23: Battery SOC during the examined voyage for different strategies

493 As shown in Figure 23, at an initial battery SOC of  
 494 65%, the developed multi-scheme EMS discharges the bat-  
 495 tery energy in a similar way to the ECMS which makes  
 496 the hydrogen consumption of both of them very close as  
 497 reported by Figure 22. The classical PI and CDCS strat-  
 498 egies tend to discharge the battery energy until it reaches its  
 499 reference value at 60% and 30% respectively. Meanwhile,  
 500 the state-based strategy regulates the fuel cell to provide  
 501 most of the power since the battery SOC is not high to be  
 502 discharged therefore it has higher hydrogen consumption  
 503 as shown in 22.

## 5.1. Stress analysis

504 An analysis of the stresses seen by each power source  
 505 is performed to investigate the effect of changing the used  
 506 energy management strategy during the voyage by the  
 507 multi-scheme strategy on the fuel cell and battery systems.  
 508 These stresses affect the propulsion system's durability,  
 509 maintenance, and lifetime. The instantaneous power from  
 510 the fuel cell and battery systems during the voyage are  
 511 decomposed into low frequency and high frequency compo-  
 512 nents using Haar wavelet transform as suggested in [11].  
 513 Then, the standard deviation of the high frequency compo-  
 514 nent is calculated to have a good indication of the stresses  
 515 on the fuel cell and battery for the examined voyage. As  
 516 can be found in Table 4, changing the used EMS during  
 517 the voyage by the proposed multi-scheme EMS doesn't in-  
 518 crease the stresses on the hybrid fuel cell/battery system.  
 519 Moreover, the fuel cell and battery stresses are lower using  
 520 the multi-scheme EMS than the ECMS and CDCS strat-  
 521 egies but at the cost of more hydrogen consumption.  
 522

## 5.2. Sensitivity analysis

### 5.2.1. Impact of different initial battery SOC

523 The reported saving percentages of the developed  
 524 multi-scheme EMS in terms of total consumed energy,  
 525 cost and hydrogen consumption can be affected by the  
 526 initial conditions of the battery SOC. Therefore, different  
 527 battery initial SOC have been used for the same exam-  
 528 ined voyage to study the impact of this parameter on  
 529 the resulted saving percentages of the developed multi-  
 530 scheme EMS. As detailed in Figure 24, the developed  
 531 multi-scheme EMS has lower energy consumption than  
 532 the four examined EMS at different initial battery SOC.  
 533 The maximum energy saving percentage is 8% compared  
 534 to the classical PI EMS at an initial battery SOC of 50%  
 535 while the minimum energy saving percentage is 0.3% com-  
 536 pared to the state-based EMS at an initial battery SOC  
 537 of 50%.  
 538  
 539

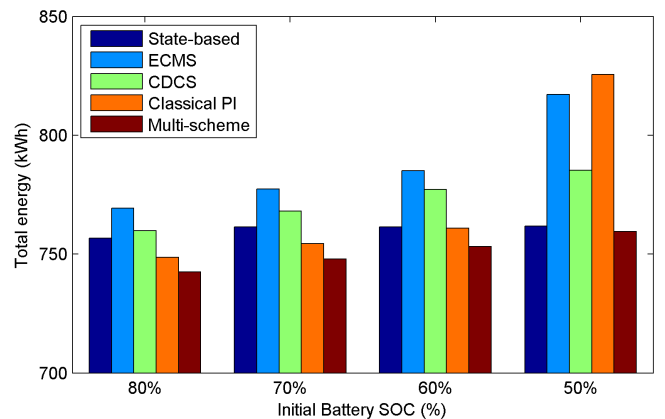


Figure 24: Impact of different initial battery SOC on total energy saving percentage of the developed multi-scheme EMS compared to other EMS

Regarding the operational cost saving percentage, the developed multi-scheme EMS can result in a saving of 7.9%

Table 4: Overall performance comparison of different energy management strategies for the examined voyage at an initial battery SOC of 65%

	State-based	ECMS	CDCS	Classical PI	Multi-scheme
Fuel cell stress	29.26	37.92	42.37	31.69	32.03
Battery stress	15.85	29.92	40.61	19.18	22.49
Hydrogen consumption (kg)	18.79	17.25	14.19	18.07	17.35
Battery SOC (%)	65 – 66.11	65 – 54.35	65 – 30	65 – 59.99	65 – 54.33

542 compared to the classical PI EMS starting with an initial  
 543 battery SOC of 50%. However, the developed multi-  
 544 scheme EMS can have higher operational cost than the  
 545 state-based EMS by 1.9% starting with an initial battery  
 546 SOC of 80%. In case of starting with normal initial battery  
 547 SOC between 60% and 70%, the difference between the de-  
 548 veloped multi-scheme EMS and other strategies in terms  
 549 of operational cost is less than 1% as shown in Figure 25.

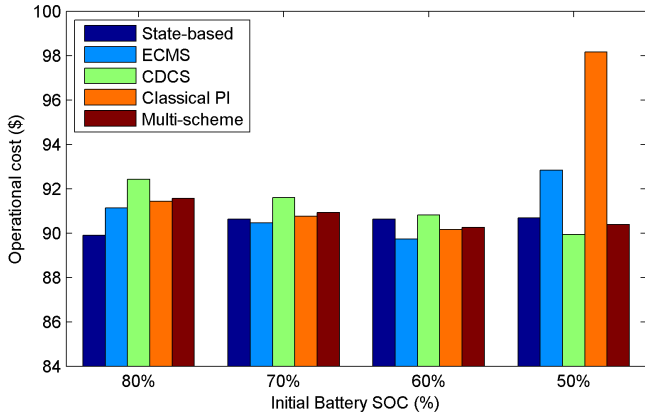


Figure 25: Impact of different initial battery SOC on total cost saving percentage of the developed multi-scheme EMS compared to other EMS

550 As can be seen from Figure 26, CDCS EMS has the  
 551 lowest hydrogen consumption at different initial battery  
 552 SOC due to the fact that CDCS supplies the required  
 553 load power from the battery system whenever possible.  
 554 Therefore, the maximum difference between the CDCS  
 555 EMS and the developed multi-scheme EMS in terms of hy-  
 556 drogen consumption occurs at a high initial battery SOC  
 557 of 80%. Comparing with other strategies, the developed  
 558 multi-scheme EMS has lower hydrogen consumption than  
 559 the state-based and classical PI strategies at different ini-  
 560 tial battery SOC with a maximum hydrogen consumption  
 561 saving percentages of 16.7% compared to the state-based  
 562 EMS at an initial battery SOC of 80% and 7.9% compared  
 563 to the classical PI EMS at an initial battery SOC of 50%.  
 564 Moreover, the developed multi-scheme EMS has lower hy-  
 565 drogen consumption by 2.6% compared to the ECMS at  
 566 an initial battery SOC of 50% meanwhile it has approxi-  
 567 mately the same hydrogen consumption of the ECMS at  
 568 other initial battery SOC.

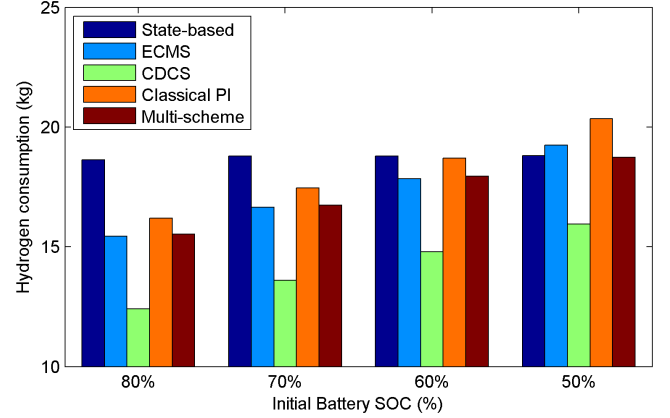


Figure 26: Impact of different initial battery SOC on hydrogen consumption saving percentage of the developed multi-scheme EMS compared to other EMS

### 5.2.2. Impact of varying energy prices

569 The prices of hydrogen and electricity vary spatially  
 570 and temporally depending on the used production method.  
 571 In order to study the impact of varying energy prices on  
 572 the total cost saving percentages of the developed multi-  
 573 scheme EMS compared to other EMS, an energy price ratio  
 574 ( $\beta$ ) is used and it can be calculated as follows  
 575

$$\beta = \frac{\text{Price of Hydrogen per kWh}}{\text{Price of Electricity per kWh}} \quad (10)$$

576 The total cost saving percentages reported to this point  
 577 corresponds to an energy price ratio of  $\beta = 0.43$  assuming  
 578 hydrogen cost of 4.823 \$/kg with an energy content of  
 579 39.4 kWh/kg and electricity price of 0.284 \$/kWh. At an  
 580 initial battery SOC of 65%, different values of  $\beta$  are used  
 581 to show how this parameter affects the total cost saving  
 582 percentage as can be found in figure 27.

583 The results shown in Figure 27 are associated with two  
 584 factors; the hydrogen consumption saving of the multi-  
 585 scheme EMS compared to other strategies and the percent-  
 586 ages of the hydrogen and battery recharging costs from the  
 587 total operational cost. Since the developed multi-scheme  
 588 and ECMS strategies have approximately the same hy-  
 589 drogen consumption, the cost saving percentage of the  
 590 developed multi-scheme EMS compared to the ECMS is  
 591 levelled off at different  $\beta$  values. Also, the cost saving per-  
 592 centage of the developed multi-scheme EMS is more sig-  
 593 nificant over the CDCS EMS at lower  $\beta$  values because  
 594 of the high battery recharging cost of the CDCS com-

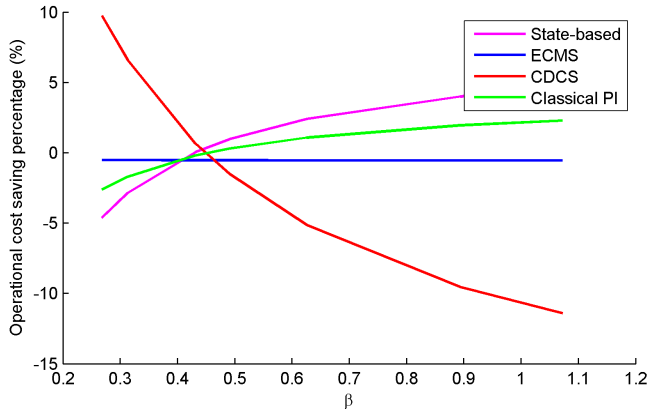


Figure 27: Impact of energy price ratio on total cost saving percentage of the developed multi-scheme EMS compared to other EMS at initial battery SOC of 65%

pared to other strategies. However, at higher  $\beta$  values which means higher hydrogen prices, the total cost becomes dominated by the hydrogen cost. Consequently, the total cost saving percentage over CDCS strategy gradually drops at higher  $\beta$  values since CDCS has the lowest hydrogen consumption. Compared to the state-based and classical PI strategies, the developed multi-scheme EMS has higher operational cost at low  $\beta$  values. At higher  $\beta$  values, the operational cost saving percentage of the developed multi-scheme EMS over the state-based and classical PI strategies becomes higher due to the hydrogen consumption saving achieved by the developed multi-scheme EMS over the state-based and classical PI strategies.

## 6. Conclusions

The recent growth in popularity of hybrid fuel cell propulsion systems for transportation applications is due to its advantages of quiet operation, low emissions and high efficiency. The dynamic behaviour of these systems depends remarkably on the strategy used to split the required power between different components of the hybrid system. Different energy management strategies have been reported in the literature for hybrid fuel cell propulsion systems with different objectives and advantages. Therefore, the development of a multi-scheme energy management strategy that contains different strategies and chooses the suitable EMS during the voyage based on a specific criterion is necessary.

A performance comparison of four different energy management strategies in terms of total consumed energy, hydrogen consumption, total cost, and the stresses seen by the fuel cell and battery systems has been presented for the world's first fuel cell passenger ship *FCS Alsterwasser* in this paper. Then, a novel multi-scheme EMS has been developed using the examined four strategies with an objective of minimizing the energy consumption that takes the required energy to recharge the battery back to its initial SOC into consideration in addition to the fuel cell

and battery depleted energy during the examined voyage. The developed multi-scheme EMS has been well compared with other strategies considering a full driving cycle of 8 hours. Simulation results show that the developed multi-scheme EMS is more efficient at different initial battery SOC with a maximum energy saving percentage of 8%. Regarding the hydrogen consumption, CDCS strategy has the lowest consumption at all initial battery SOC since it prioritizes the usage of the battery energy. However, the developed multi-scheme EMS can result in a hydrogen consumption saving over the state-based and the classical PI strategies at different initial battery SOC with a maximum saving percentage of 16.7%. Furthermore, using the developed multi-scheme EMS results in approximately the same operational costs as other strategies. A sensitivity analysis shows that at higher hydrogen prices, cost saving percentages of the developed multi-scheme EMS becomes higher compared to the state-based and the classical PI strategies. Moreover, the stress analysis reveals that switching between different strategies during the voyage using the proposed multi-scheme EMS doesn't increase the operational stresses on the fuel cell and battery systems.

## Acknowledgement

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