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Systemic Design and Energy Management of a Standalone Battery-less PV/Wind driven Brackish Water Reverse Osmosis Desalination System

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Abstract

This work investigates a small-scale reverse osmosis desalination system dedicated for off-grid communities lacking freshwater. This system, constituted of motor-pumps, desalination process and hydraulic network (pipes and valves), is powered by hybrid photovoltaic-wind turbine source. It exploits hydraulic storage in water tanks filled when renewable energy is available instead of electrochemical storage. Such specificity makes the power/freshwater supply a challenging issue for these communities. To maximize freshwater production of this autonomous system, a “systemic design approach” integrating couplings between architecture, sizing, and energy management is proposed. According to the specific system architecture and its component sizing, a specific quasi-static model-based energy management strategy (EMS) is developed. In this regard, the influence of the main component sizing on the system energy efficiency and the EMS performance is analyzed. This study proved the strongly coupling between power/water management and pump sizing. According to the iterative process of the systemic design approach, simulation results showed that the EMS objective is reached by increasing the brackish water storage tank capacity and improving the system energy efficiency. The latter is achieved by choosing the pumps-combination composed of three pumps having the lowest rated powers (0.37kW/0.37kW/1.5kW), but offering higher energy efficiency over other analyzed pumps-combinations.

Keywords: systemic design; electrochemical and water storage; quasi-static modeling; water/power management; renewable energy.

1. Introduction

Reverse osmosis (RO) desalination applications have been becoming the primary choice to produce freshwater from brackish or sea water for many water-stressed regions [1-2] not only for drinking, but also for agriculture [3]. Typically, these applications, especially small-scale units for off-grid communities, are powered by renewable energies [4-6]. The most commonly used renewable energies to power such desalination units are the solar energy [7-8] and the wind energy [9-10]. For example, according to the comprehensive review and the techno-economic feasibility carried out, respectively, in [11] and [8], photovoltaic PV-RO desalination systems are considered better than other desalination combinations due to their availability in the market and economic feasibility; this has encouraged poor farmers in rural regions to use these systems to produce freshwater. Another techno-economic analysis of several wind-driven variable flow RO systems in United Arab Emirates was conducted [9].

41 This analysis concluded that Wind-RO combination is an economic alternative to produce freshwater. However,
 42 although wind and solar energies are the most widespread and environmentally friendly Renewable Energy
 43 Sources (RESs) worldwide, both are of variable and intermittent nature due to unpredictable and rough changes in
 44 weather conditions (*e.g.* simultaneous cloudy sky or wind speed slowing down). For that, using single RES cannot
 45 always meet the electrical demand of the RO plant during the day [12].

46 Hybrid power generation systems, such as solar PV panels combined with wind turbine [10], are becoming more
 47 suitable with the advantage that one RES could be available when the other is not [6]. Such a temporal
 48 complementarity will increase the reliability and improve the environmental aspect of the desalination system
 49 [12]. On the other hand, standalone RO systems can be powered by different combinations of renewable energy
 50 sources (*e.g.* PV-RO, Wind-RO and PV/Wind-RO) with one or more energy storage device, such as batteries [10],
 51 super capacitors [13], fuel cell [14-15], and diesel generator backup [16]. A summary of different studied
 52 standalone small-scale RES-brackish water RO units in different sites around the world is reported in Table1.

53 Table 1 Summary of the reported standalone small-scale RES-BWRO units ($\leq 10\text{m}^3/\text{d}$) in the last decade

Ref.	Year	Country	PV (kW)	Wind (kW)	Battery	Diesel (kW)	Hydrogen	Freshwater (m ³ /d)	Energy Recovery (%)
[17]	2010	Spain	0.36	no	yes	no	no	0.2 (12h)	no
[18]	2010	Uzbekistan	0.03	no	yes	no	no	0.075 (9.5h)	no
[19]	2010	Babylon, Iraq	4.1	no	yes	1.8	no	5 (24h)	no
[19]	2010	Babylon, Iraq	1.6	no	yes	1	no	5 (6h)	no
[20]	2011	Australia	not mentioned	no	no	no	no	4.8 (12h)	no
[21]	2011	Jordan	0.433	no	yes	no	no	0.5	54
[13]	2012	Marseille, France	0.5	no	no	no	no	1	not mentioned
[22]	2012	Jordan	0.432	no	yes	no	no	5.7 (24h)	no
[23]	2012	Egypt	5	not mentioned	yes	no	no	5 (24h)	no
[24]	2013	Dhahran, Saudi Arabia	2.4	2	yes	no	no	5 (12h)	not mentioned
[25]	2013	Amarika, Namibia	19.8	no	yes	no	no	3.3	23
[26]	2014	Nairobi, Kenya	5	1	yes	1.5	no	3.5	no
[26]	2014	Nyala, Sudan	5	1	yes	1.5	no	3.5	no
[27]	2015	Egypt	2.5	no	no	no	no	4-5	not mentioned
[28]	2015	India	0.075-3	no	yes	no	no	1.04 (4h)	no
[29]	2015	La Mancalona, Mexican	0.4	no	yes	no	no	1	33
[30]	2015	India	not mentioned (with & without freshwater storage)	no	no	no	no	2.4-6	no
[31]	2016	Bangi, Malaysia	2	no	yes	no	no	5.1 (10h)	not mentioned
[32]	2016	Pakistan	0.75	no	yes	no	no	0.0295 (5h)	not mentioned
[32]	2016	Pakistan	0.12	no	no	no	no	0.0266 (7h)	not mentioned
[33]	2016	St. Dorcas borehole, Tanzania	0.3	no	no	no	no	1.3-1.6	23.1-27.8
[34]	2017	Saudi Arabia	0.25	no	no	no	no	0.126	not mentioned
[35]	2018	South Khorasan, Iran	not mentioned	not mentioned	yes	no	yes	10	no
[36]	2019	Tanzania	2.25	no	yes	no	no	2.36	6-18
[8]	2020	Pakistan	2	no	no	no	no	4 (8h)	no

54 Combining RESs with energy storage device has the advantage of providing constant energy flow during
 55 insufficient power generation time and offering the ability to buffer the energy production variations. Nonetheless,
 56 besides to the environmental issues, the capital and maintenance cost of batteries (and/or burned fuel cost) is often

57 a major concern [37], especially for remote and poverty areas. Therefore, minimizing or even suppressing the
58 energy storage device such as electrochemical storage means is a challenging issue facing such standalone
59 desalination systems, especially in the light of continuous freshwater supply.

60 In case of RES-RO desalination system without batteries, freshwater will be produced by a variable and
61 discontinuously operated desalination system. That is, RO membrane will operate under variable feed pressure. It
62 has been demonstrated that the operation of the RO membrane under variable power supply remains unaffected
63 [38-39]. Moreover, several studies at the laboratory scale have demonstrated the possibility of operating RES-RO
64 desalination units without battery storage device [40-42]. Another study concluded that it is possible to completely
65 eliminate batteries in PV-RO systems; it needs to automatically adjust the operating point of the RO-pump with
66 fluctuating solar energy [43]. An economic analysis was also conducted in [32] for PV-RO system with and
67 without battery, where results demonstrated that battery-less PV-RO system is more economically suitable than
68 that using battery storage. A comprehensive review of desalination technologies powered by solar energy
69 including solar PV-RO desalination systems without batteries was conducted in [44]. It is concluded that coupling
70 RO and PV systems is relatively straightforward, especially for small-scale units.

71 Another option to reduce the capital cost is to store water in a storage tank such as the example of using buffer
72 tank for freshwater storage [30] [45]. Such an alternative enables to minimize the needed number of batteries and
73 overcome the challenge of longer-term renewable energy variation. In ref. [30], authors showed that the system
74 productivity increased up to 36% by storing produced freshwater. It was demonstrated that a buffer tank can be
75 considered as a surrogate energy storage device. The concept is that the generated renewable energy during sunny
76 and/or windy days is a stored energy in the form of water. This can be considered very cost-effective and
77 environmentally friendly alternative compared with RES-RO units using battery banks or diesel generator backup.

78 In this context, a focus on a standalone small-scale Brackish Water Reverse Osmosis (BWRO) desalination
79 system in rural area is put forward in this paper. This system is powered by hybrid PV/Wind turbine source
80 without electrochemical storage device, but exploiting hydraulic storage (brackish water and freshwater) in
81 storage tanks. The idea is: *i*) to take advantage of storing the well brackish water and the produced freshwater in
82 tanks when renewable energy is available, and *ii*) to exploit motor-pumps modularity (*i.e.* several pumping
83 subsystems that can be switched on/off and tuned) versus the given generated power. For this sake, an
84 experimental BWRO desalination unit at the laboratory scale (freshwater production of 300 liters/h) using an
85 elevated brackish water storage tank was designed and mounted to investigate the feasibility and reliability of
86 PV/Wind-BWRO desalination system in rural areas. A second storage tank is also used in this unit to store the
87 produced freshwater, for later use when renewable energy is unavailable.

88 To overcome the variable and discontinuously operated PV/Wind-BWRO unit, a specific energy (power and
89 water flows) management is then required in order to manage simultaneously power and water flows into the
90 desalination system while fulfilling technological (power and pressure ranges) and functional (tank filling state)
91 constraints of the system. The energy management strategy to be developed must take into consideration the
92 strongly coupled system design: “water/power management and device sizing”. In particular, the generated power
93 from RESs is strongly coupled with the water process system efficiency. In addition to that, the coupling between
94 sizing and management performance is of a paramount importance in this study. Therefore, it is mandatory to
95 study the sizing of pumps and the different pump-combinations in the desalination system to get an optimal
96 system design enabling to maximize as much as possible the freshwater production according to the available

97 generated power. All of these aspects put forward the necessity of a “systemic design approach” integrating the
 98 strong coupling between architecture (modularity), sizing and flow (power, water) management. In this regard,
 99 authors in ref. [46] have investigated a global optimization approach taking account of the couplings between the
 100 system architecture, sizing and energy management. They proposed an optimization dispatching algorithm for
 101 sharing the variable input power between the three installed motor-pumps: the choice of the objective function for
 102 the optimization algorithm to evaluate the operating efficiency has been justified. The influence of the pump
 103 sizing on the system efficiency has been also analyzed.

104 This paper proposes a first design approach based on specific modeling and management strategy. It primarily
 105 aims to maximize as much as possible the water production of the system according to the renewable energy
 106 generation. First, a quasi-static modeling stemming from dynamic modeling of the experimental BWRO
 107 desalination test bench is developed for simulations. In order to validate the developed model, the latter is
 108 compared with the experimental model obtained from experimental characterizations of the BWRO test bench.
 109 Then, an energy management strategy is developed using Deterministic Rule-based power sharing algorithm.
 110 Such algorithm should conveniently dispatch the instantaneous generated power between the different water
 111 process subsystems into the studied system while taking into consideration: *i*) the aforementioned system
 112 constraints, and *ii*) the objective of maximizing freshwater production. For the sake of optimality, the sizing
 113 influence of both pump combinations and brackish water storage tank capacity on the energy management
 114 performance is then analyzed. As regards the capacity sizing of the freshwater storage tank, it is not studied during
 115 simulations and analysis, since it is viewed as an infinite storage tank (in simulations) aiming to store a maximum
 116 amount of produced freshwater.

117 This paper is organized as follows: the architecture and specifications of the BWRO desalination system are
 118 described in Section 2. The adopted systemic design approach is defined in Section 3. The analytical modeling of
 119 the studied system is detailed in Section 4. The EMS is described in Section 5. Section 6 is dedicated to analyze
 120 the simulation results. In this Section the influence of pumps and tank capacity sizing on the energy management
 121 performance are investigated and analyzed. Finally, main conclusions and prospects are summarized in Section 7.

Nomenclature

Acronyms

BWRO	Brackish Water Reverse Osmosis	g	gravity acceleration, N/Kg
CV	Control Valve of the RO membrane	H_{geo}	geodetic head that the pump must overcome, m
DC	Direct Current	H_{tank}	height of the stored brackish water amount in tank T_1 , m
EMS	Energy Management Strategy	H_{asp}	brackish water aspiration height of the HPP, m
HPP	High Pressure Pump	HMT	total dynamic head of the pump, m
IM	Induction Motor	P_{feed}	feed pressure of the RO membrane, bar
PV	Photovoltaic	P_{asp}	brackish water aspiration pressure of the HPP, bar
RES	Renewable Energy Source	P_{tank}	resulting pressure from stored amount of brackish water in the tank T_1 , bar
RO	Reverse Osmosis	P_{hyd_load}	required pressure of a hydraulic load, bar
WP	Well Pump	P_{HPP}	proper pressure given by the HPP, bar

Greek symbols

α	power sharing factor, –	\mathcal{P}_{dc}	renewable generated power transferred via a DC bus, W
ρ	water density, Kg/m ³	\mathcal{P}_{HPP}	assigned electric power to the HPP, W
φ_r	rotor flux of the induction motor, Wb	\mathcal{P}_{WP}	assigned electric power to the WP, W
φ_{rd}	d-axis rotor flux in the (d,q) reference frame, Wb	\mathcal{P}_{min}	minimum electric power, W

φ_{rq}	q-axis rotor flux in the (d,q) reference frame, Wb	\mathcal{P}_{\max}	maximum electric power, W
Ω	angular speed of the induction motor, rad/s	Q_p	pump flowrate, liters/min
<i>Variables/parameters</i>			
FS	filling state of the storage tank T_1 , %	Q_{fresh}	freshwater flowrate, liters/min
FS_0	initial filling state of the tank T_1 , %	Q_{feed}	feed water flow of the RO membrane, liters/min
FS_{\max}	maximum limit of the tank filling state, %	Q_{reject}	rejected water flow rate of the RO membrane, liters/min
FS_{\min}	minimum limit of the tank filling state, %	Q_{WP}	well pump flowrate, liters/min
I_p	consumed current by the pump, A	Q_{HPP}	high pressure pump flowrate, liters/min
I_{sd}	d-axis stator current in the (d,q) reference frame, A	q_{fresh}	produced freshwater quantity, m ³
I_{sq}	q-axis stator current in the (d,q) reference frame, A	R_s	stator resistance of the induction motor, Ohms
I_c	current of the DC-link capacitor, A	R_r	rotor resistance of the induction motor, Ohms
I_{dc}	DC-link current, A	S_1	surface area of the storage tank T_1 , m ²
L_m	mutual inductance in the induction motor, H	T_1	storage tank of brackish water, –
L_r	rotor inductance in the induction motor, H	T_p	pump torque, N.m
L	water level in the storage tank T_1 , m	T_m	motor torque, N.m
L_{\min}^{Inf}	inferior minimum limit level in the storage tank, m	V_{dc}	DC-link voltage, V
L_{\min}^{Sup}	superior minimum limit level in the storage tank, m	V_{sd}	d-axis of the stator voltage in the (d,q) reference frame, V
L_{\max}^{Inf}	inferior maximum limit level in the storage tank, m	V_{sq}	q-axis of the stator voltage in the (d,q) reference frame, V
L_{\max}^{Sup}	superior maximum limit level in the storage tank, m	ΔP_{pipe}	pressure drop in pipelines, bar
		$\Delta \mathcal{P}_M$	electrical power losses through the induction motor associated with its inverter, W
		$\Delta \mathcal{P}_p$	hydraulic power losses through the centrifugal pump

122 2. Description of the BWRO desalination system

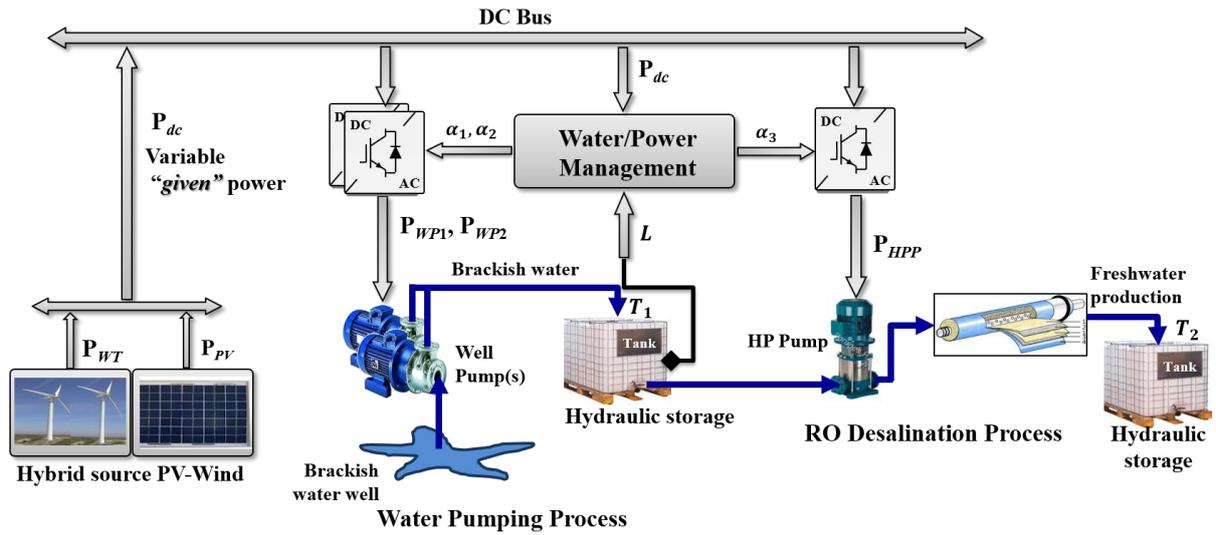
123 2.1. System architecture overview

124 The studied system, depicted in Fig.1, consists of small-scale standalone brackish water pumping and desalination
125 unit. It is mainly composed of two hydro-mechanical subsystems:

- 126 1) “*Water Pumping Process*” that uses well Pump(s) (WP) to pump brackish water from the well to an
127 elevated storage tank T_1 . This process is dedicated for gravitational brackish water storage.
- 128 2) “*Reverse Osmosis (RO) Desalination Process*” enabling to produce freshwater using a RO membrane(s)
129 fed by a High Pressure Pump (HPP). The HPP exploits the stored amount of brackish water in the tank T_1
130 to feed the RO membranes under high pressure. The produced freshwater is stored in the tank T_2 .

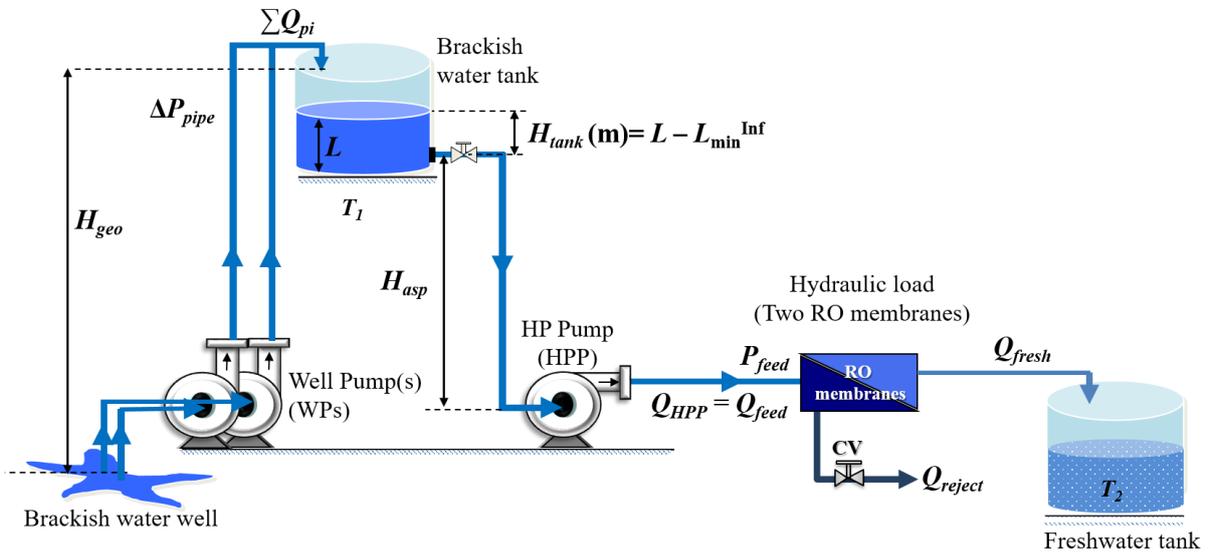
131 This unit would be powered via a Direct Current (DC) bus with a variable generated power \mathcal{P}_{dc} offered along
132 wind speed and solar irradiation conditions (PV/Wind turbine) without battery storage.

133 The hydraulic architecture of the desalination system depicted in Fig. 2 is defined so that the desalination system
134 includes two independent hydraulic subsystems decoupled through the elevated water storage tank T_1 . The latter
135 presents the first key element of the chosen architecture. In other words, pumped brackish water from the well can
136 be stored into the elevated tank T_1 , when renewable energy is available, for later or simultaneous use by the RO
137 desalination process to produce freshwater. The latter in turn is stored in high capacity tank T_2 , for later use when
138 the renewable energy is unavailable. This constitutes the second key element of the system architecture.
139 Therefore, the electrochemical storage device can be replaced by hydraulic storage (brackish water and
140 freshwater) in water tanks.



141
142

Fig. 1. Synoptic of the autonomous BWRO desalination system



143
144

Fig. 2. Hydraulic configuration of the BWRO desalination system

145 2.2. Experimental test bench

146 An experimental test bench, shown in Fig.3, was designed and mounted in our research laboratory (L.S.E in
147 ENIT-UTM, Tunis, Tunisia). The synoptic scheme of the experimental test bench is depicted in Fig.4. The
148 specifications of the presented test bench are reported in Table 2. This experimental unit is used for the
149 experimental characterizations of the hydro-mechanical processes in order to validate the system model. Indeed,
150 the two hydro-mechanical processes have been experimentally characterized and dynamically modeled in
151 previous studies [47-50].

152 Based on the dynamic modeling of hydro-mechanical processes of the presented RO unit, a quasi-static modeling
153 is developed for energy management which is described in Section 4.

154
155

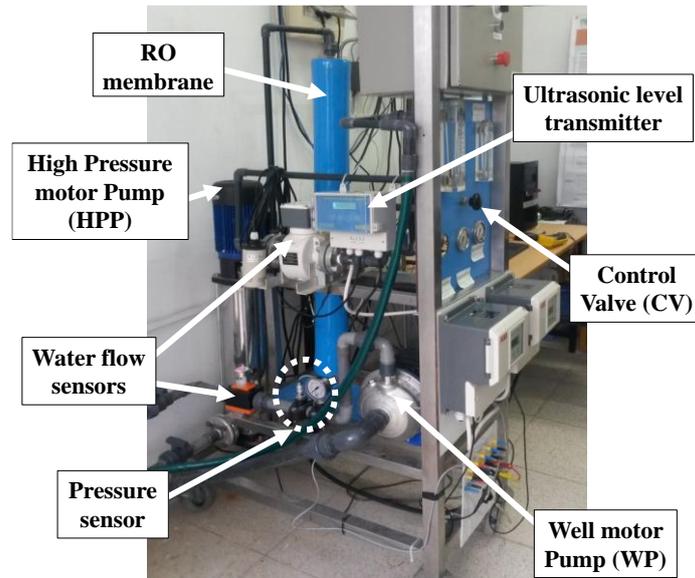
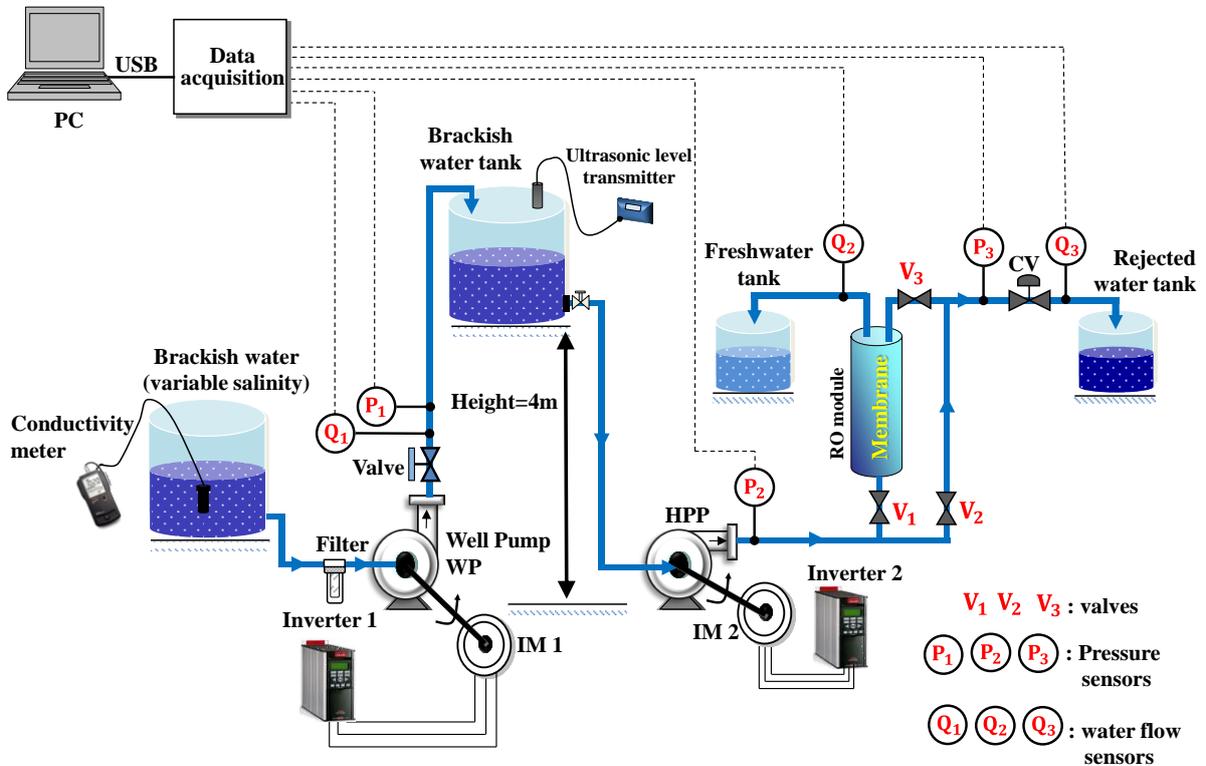


Fig.3. Experimental BWRO desalination test bench



156
157

Fig.4. Synoptic scheme of the experimental BWRO desalination test bench

158

Table 2 Specifications of the experimental desalination test bench

Components	Characteristics	Component constraints
High Pressure Pump (HPP)	Model: EBARA EVM2 22F/2.2 Type: centrifugal 3-ph motor pump Power output: 2.2 kW Rated Pressure: 8.17-18.6 bar Rated flow rate: 20- 60 l/min	Minimum absorbed electric power: 620 W Maximum absorbed electric power: 1800 W
Well Pump 1 (WP ₁)	Model: PEDROLLO CP158 Type: centrifugal 3-ph motor pump Power output: 0.75 kW Rated Pressure: 2.5-3.4 bar Rated flow rate: 10-90 l/min	Minimum absorbed electric power: 120 W Maximum absorbed electric power: 1020 W
Well Pump 2 (WP ₂)	Model: LOWARA CEA70/3 Type: centrifugal 3-ph motor pump Power output: 0.37 kW	Minimum absorbed electric power: 120 W Maximum absorbed electric power: 370 W

	Rated Pressure: 1.3-2 bar Rated flow rate: 30-80 l/min	
RO membrane	Model: TORAY TM710 Feed water salinity: 4 g/l Maximum freshwater production: 300 l/h	Minimum feed pressure: 8.4 bar Maximum feed pressure: 16.2 bar
Storage tank (T_1)	Capacity: 2.18 m ³ Height: 2.1 m Elevation height: 4 m	Inferior minimum limit level L_{\min}^{Inf} : 0.2 m Superior minimum limit level L_{\min}^{Sup} : 0.25 m Inferior maximum limit level L_{\max}^{Inf} : 1.9 m Superior maximum limit level L_{\max}^{Sup} : 2 m

159 *2.3. Characteristic specificity of the chosen architecture*

160 Due to the hydraulic processes decoupling, the system has more degrees of freedom than conventional used
161 architecture where motor-pumps are usually coupled in series (without brackish water storage tank). In fact, the
162 system can independently operate as: *i*) “pumping system” by operating solely the water pumping process in case
163 of low level of generated power, or *ii*) “RO desalination system” by operating solely the RO desalination process
164 in case of high level of generated power, or also *iii*) “pumping and RO desalination system” in case of very high
165 level of generated power. In the latter operating mode, the two hydraulic processes operate simultaneously to
166 pump brackish water from the well to fill the storage tank and, in the same time, produce freshwater using the
167 pumped brackish water from T_1 . Indeed, this configuration offers a great flexibility for the experimental
168 characterization of each hydro-mechanical process.

169 Within this hydraulic configuration, the “gravitational water storage” involves an advantage of great importance in
170 terms of energy efficiency improvement; this fact enables to take benefit of an additional free hydraulic energy
171 boosting the RO desalination energy efficiency. As a result, freshwater productivity can be improved. This point
172 has been highlighted in previous work [51]. Moreover, besides the advantage of being environmentally friendly,
173 another advantage of using hydraulic storage over electrochemical storage device is the simplicity of such a
174 configuration (no need to control laws), as well as it offers lower cost alternative (no need to additional power
175 converters for control and no maintenance requirements).

176 On the other hand, the studied system is classified among complex energy systems. Its complexity is
177 characterized by the combination of components of different natures and functionalities, all interacted within the
178 system under study. Such heterogeneity leads to several physical phenomena coexistence, and several system
179 constraints of different domains. These constraints can be listed as: *i*) functioning under variable energy supply
180 (*i.e.* variable feeding power and pressures), *ii*) technological constraints of pumping devices (power ranges) and
181 RO membrane (flow-pressure range), and *iii*) functioning constraints (*i.e.* filling state of the storage tank). This
182 makes the modeling and the flow (power, water) management of the system a difficult task.

183 Given the diversification of the system constraints, it becomes necessary to move towards a new approach
184 permitting to connect all system components by integrating “intra”- and “inter-disciplinary” coupling. This
185 methodology is based on the “systemic design approach” [52] described in the following section.

186 **3. Definition of the systemic design approach**

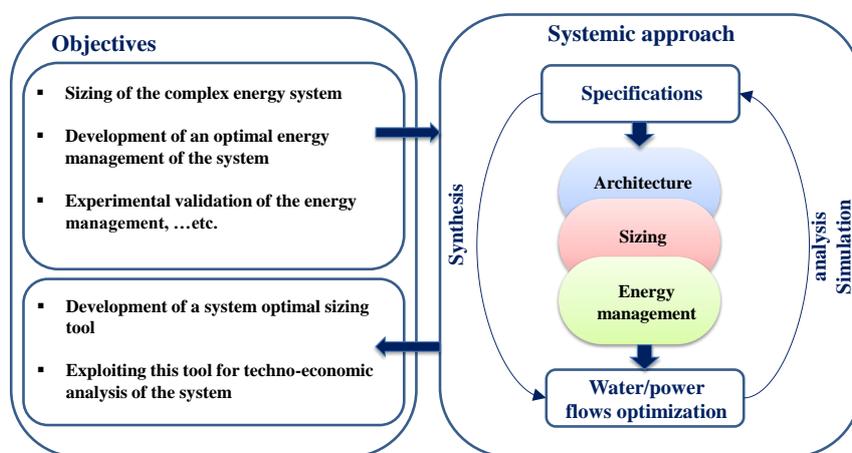
187 The adopted systemic design approach is described in Fig. 5. It relies on the choice of: *i*) architecture and
188 components, *ii*) sizing, and *iii*) development of control/management process. The design has to meet
189 requirements defined by the bill of specifications. This constitutes a fundamental and preliminary step for the
190 designer. Therefore, satisfying the bill of specifications needs a “synthesis” (*i.e.* structure determination) and

191 “sizing” (*i.e.* parameters determination) that meet: *i)* these requirements while anticipating by “simulation” and
 192 “analysis” (Fig.5) of the system being designed, *ii)* system performance, and *iii)* system constraints.

193 The systemic design approach is an iterative process based on three main phases:

- 194 - *Phase 1:* the choice of the system architecture (as defined in the previous section). This allows
 195 performing the modeling and simulation of these components.
- 196 - *Phase 2:* the optimal pre-sizing of the system components. Such a phase allows characterizing of these
 197 elements and specifying the instantaneous energy transfers during an idealized operating cycle. This
 198 leads to understand the energy behavior of the system.
- 199 - *Phase 3:* the optimization of the energy flows into the system with the objective of determining the
 200 optimal energy management of the system.

201 Therefore, following the energy optimization and the simulation of the system behavior it may happen that the
 202 components previously chosen are oversized or undersized. For that reason, the “system sizing – energy
 203 optimization” cycle is repeated several times off-line in order to refine the system specifications. The objective
 204 here is to design a system that should be well adapted to the energy management strategy which, in turn, will be
 205 implemented on-line. For this sake, several iterations are performed in this work as part of the systemic design by
 206 testing several combinations of different sized pumps and even different storage tank capacities. At each iteration,
 207 the architecture is defined, then, the system components are characterized and modeled based on the experimental
 208 set-up. This provides deep understanding of the system energy behavior. At the end of the cycle, the proposed
 209 energy management strategy is applied to the chosen architecture, and obtained results are analyzed.

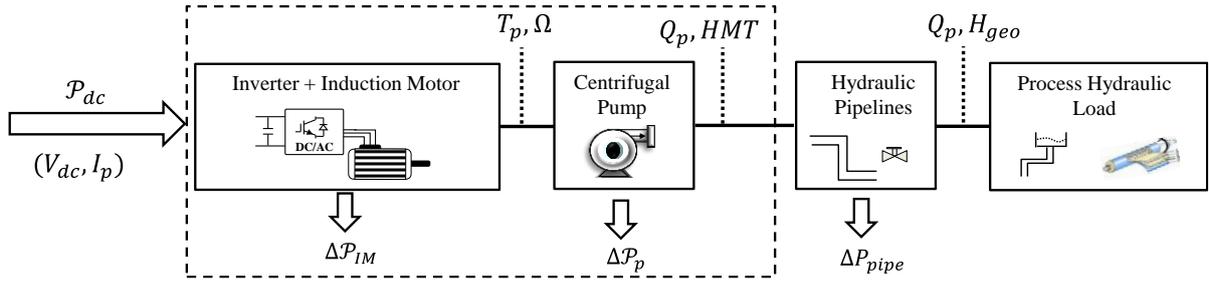


210
 211 Fig.5. Optimization process of a complex energy system by the systemic approach

212 4. System modeling

213 This study focuses on the steady-state functioning of the system in order to simplify the energy management task.
 214 The quasi-static model constitutes a “power flow model” derived from dynamic energy behavior throughout the
 215 desalination chain. Therefore, in order to develop the quasi-static model of the hydro-mechanical system, several
 216 physical fields have to be considered. As depicted in Fig.6, it consists of the following subsystems from right to
 217 left: hydraulic load, centrifugal pump, and three phase induction motor fed and controlled by a voltage source
 218 inverter. The subsystems are linked each other by power flow variables: electrical voltage and current (V_{dc} , I_p),
 219 motor-pump torque and speed (T_p , Ω), and pump flow rate and pressure (Q_p , $P_p = \rho g HMT$). The *HMT* describes the

220 total dynamic head (in meter) which depends on hydraulic load and pressure losses in pipelines ΔP_{pipe} , ρ is the
 221 water density and g is the gravity acceleration.



222
 223 Fig. 6. Synoptic of the quasi-static modeling of a single-pump hydro-mechanical process: a power flow model

224 This section is divided into five parts: the first one is devoted for the modeling of the hydraulic subsystems (*i.e.*
 225 hydraulic loads). The second part presents the storage tank analytical model. The third part describes the hydro-
 226 mechanical subsystems modeling. Then, the analytical quasi-static model of a hydro mechanical process is
 227 presented in the fourth part. The last one is dedicated to the practical validation of the quasi-static model for each
 228 hydro-mechanical process.

229 4.1. Hydraulic subsystems modeling

230 As depicted in Fig.1 and Fig.2, we have two different hydro-mechanical subsystems decoupled through a storage
 231 tank T_1 . The modeling task here depends on the hydraulic load type of each subsystem:

232 1) In case of typical load as for the “**first water subsystem**”, where the water is moved from one level (the
 233 well) to another (*i.e.* an elevated tank) as shown in Fig.2, a pressure drop in pipelines ΔP_{pipe} occurs. The latter is
 234 caused by the height difference H_{geo} (geodetic head that the pump must overcome), and the hydraulic losses
 235 depending on the pump water flow $Q_p=Q_{WP}$ [53-54]. Thus, the hydraulic load model of the first process (*e.g.* case
 236 of one well pump) is expressed by:

$$\Delta P_{pipe} = \rho g H_{geo} + k Q_{WP}^2 \quad (1)$$

237 where, k is a constant.

238 2) The “**second subsystem**” is related to the water RO desalination process; it involves a complex and
 239 nonlinear hydraulic load (RO membrane + Control Valve (CV)) coupled to the HPP. The latter offers high water
 240 pressure to feed the RO membrane to produce freshwater. Based on the dynamic model of the RO membrane
 241 previously developed and detailed [48] and [55], the static model of the RO membrane expressed by (3), (4) and
 242 (5) is deduced by neglecting the dynamic elements effect, with some approximations:

$$P_{feed} = (R_{module} + R_{valve}) Q_{reject}^2 \quad (2)$$

$$Q_{fresh} = \frac{P_{feed}}{R_{membrane}} \quad (3)$$

$$Q_{feed} = Q_{fresh} + Q_{reject} \quad (4)$$

243 Where, Q_{feed} and P_{feed} denote respectively the feed flow rate and pressure of the RO membrane, Q_{fresh} the produced
 244 freshwater flow rate, Q_{reject} the rejected water flow rate (very salted water), and $(R_{module}, R_{valves}, R_{membrane})$ are the
 245 RO membrane parameters whose experimental values are reported in Table 3. Indeed, hydraulic losses into the
 246 RO process via the control valve CV (Fig.2), the RO module and the RO membrane are modeled as resistances

247 such as R_{module} , R_{valve} , $R_{membrane}$. It should be noted that a RO module can include one or several RO membranes
 248 coupled in series. In the studied case, each module contains one RO membrane.

249 Based on (2), (3) and (4), the static model of the hydraulic load (*i.e.* RO module) of the second process is deduced
 250 and expressed by (5) with respect to Q_{feed} .

$$P_{feed} = \left(\sqrt{\frac{R_{membrane}^2}{4(R_{module} + R_{valve})} + R_{membrane} Q_{feed}} - \frac{R_{membrane}}{2\sqrt{R_{module} + R_{valve}}} \right)^2 \quad (5)$$

251 According to the hydraulic structure of the desalination process depicted in Fig.2, the feed pressure P_{feed} of the RO
 252 module results from the sum of different pressures as follows:

$$\begin{aligned} P_{feed} &= P_{HPP} + P_{tank} + P_{asp} \\ &= P_{HPP} + \rho g(L - L_{min}^{inf}) + \rho g H_{asp} \end{aligned} \quad (6)$$

253 Where, P_{HPP} denotes the proper pressure given by the HPP which is expressed in the next subsection by (8), P_{tank}
 254 is the resulting pressure from the stored amount of brackish water in the tank T_1 , H_{asp} and P_{asp} denote respectively
 255 the brackish water aspiration height and pressure of the HPP.

256 4.2. Storage tank modeling

257 A storage tank is characterized by the stored water level L . The first tank T_1 is modeled by (7) describing a time-
 258 varying model.

$$L(t + \Delta t) = L(t) + \frac{1}{S_1} \int_t^{t+\Delta t} (Q_{WP}(t) - Q_{HPP}(t)) dt \quad (7)$$

259 where, S_1 being the surface area of T_1 , and (Q_{WP} and Q_{HPP}) denote respectively the well pump and the HP pump
 260 flow rates (*i.e.* input and output flow rates of the tank).

261 4.3. Hydro-Mechanical subsystem modeling

262 The static model of a centrifugal pump is obtained by neglecting the dynamic elements effect from its dynamic
 263 model performed in previous work [48]. Thus, the static part of a centrifugal pump is modeled as follows:

$$P_p(\Omega, Q_p) = (a\Omega + bQ_p)\Omega + cQ_p^2 \quad (8)$$

$$T_p(\Omega, Q_p) = (a\Omega + bQ_p)Q_p + f_p\Omega \quad (9)$$

264 Where, P_p being the water pump pressure, Q_p the pump flow rate, T_p the pump torque, Ω the motor-pump angular
 265 speed, and f_p is the coefficient of the hydraulic friction in the pump. The pump parameters (a , b , c , f_p) have been
 266 experimentally identified and are reported in Table 3.

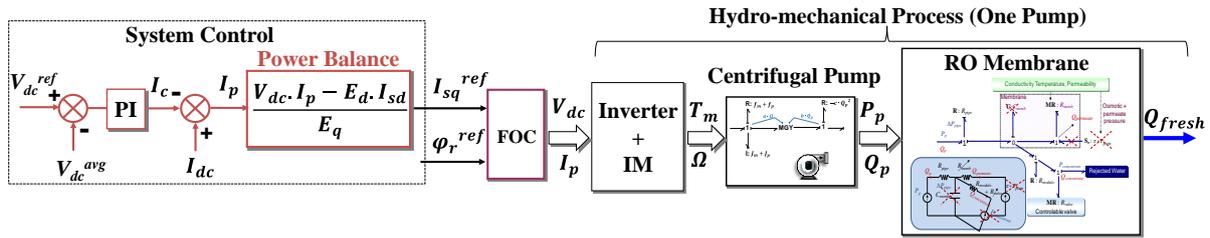
267 Table 3 Hydraulic parameters of different components of the experimental desalination test bench

Component	Parameter	Value	Unit
HPP	a	0.0002317	Ns ² /m ²
	b	-0.0005198	Ns ² /m ²
	c	-0.002427	Ns ² /m ²
	f_p	0.0038	Nms
WP ₁	a	4e-5	Ns ² /m ²
	b	-1.767e-5	Ns ² /m ²
	c	0.0002	Ns ² /m ²
	f_p	0.0019	Nms
WP ₂	a	2.446e-5	Ns ² /m ²
	b	-6.507e-5	Ns ² /m ²

	c	21.205e-5	Ns ² /m ²
	f_p	0.002	Nms
RO Membrane	R_{module}	1.038e12	Ns ² /m ⁸
	R_{valve}	7.785e12	Ns ² /m ⁸
	$R_{membrane}$	1.695e10	Ns/m ⁵

268 4.4. Quasi-static model of a hydro mechanical process

269 With regard to the three-phase Induction Motor (IM) driving the centrifugal pump, the Power Field Oriented
 270 Control (PFOC) method has been applied through the associated inverter as depicted in Fig.7. In such a case, the
 271 inverter is used to regulate the magnetic flux and control the torque being cascaded with the DC-link voltage
 272 control loop [56-57]. In the Park's d-q reference frame linked to rotating field, the rotor flux is controlled through
 273 the d-axis ($\phi_{rd} = \phi_r$, $\phi_{rq} = 0$).



274 Fig.7. Block diagram of the control strategy of a single-pump hydro-mechanical process

275 By neglecting power losses via the inverter (denoted $\Delta \mathcal{P}_{IM}$ in Fig. 6), the power balance is given by:

$$V_{dc} I_p = V_{sq} I_{sq} + V_{sd} I_{sd} \quad (10)$$

277 As a result, based on the above equation and the original equations of the stator and rotor voltages in the d-q
 278 reference frame, while neglecting the dynamic elements (*i.e.* fast transients), the electrical power \mathcal{P}_{IM} feeding the
 279 motor-pump can be expressed versus the angular speed and the electromagnetic torque (Ω , T_m). The latter
 280 variables are in turn expressed versus pump flow rate Q_p and are given by (11) and (12).

$$T_m(\Omega, Q_p) = T_p(\Omega, Q_p) + f_m \Omega \quad (11)$$

$$\Omega(Q_p) = \frac{-bQ_p + \sqrt{(bQ_p)^2 - 4a(cQ_p^2 - P_{hyd-load}(Q_p))}}{2a} \quad (12)$$

281 Where, $P_{hyd-load}$ denotes the hydraulic load pressure describing the analytical model of the hydraulic load of each
 282 hydro-mechanical process. It should be pointed out that the full expression of the motor-pump angular speed
 283 $\Omega(Q_p)$ can be derived from (1) and (8) in case of “pumping process”, and from (5), (6) and (8) in case of
 284 “desalination process”, by choosing the positive root of the 2nd order equation.

285 As a result, \mathcal{P}_{IM} can be expressed with respect to the pump flow rate Q_p by (13).

$$\mathcal{P}_{IM}(Q_p) = R_{sr} \frac{\phi_r}{L_m} - R_r \left(\frac{\phi_r}{L_r} \right)^2 + \left(\frac{R_{sr} L_r}{L_m \phi_r} T_m(Q_p) \right)^2 + \Omega(Q_p) T_m(Q_p) \quad (13)$$

286 where,

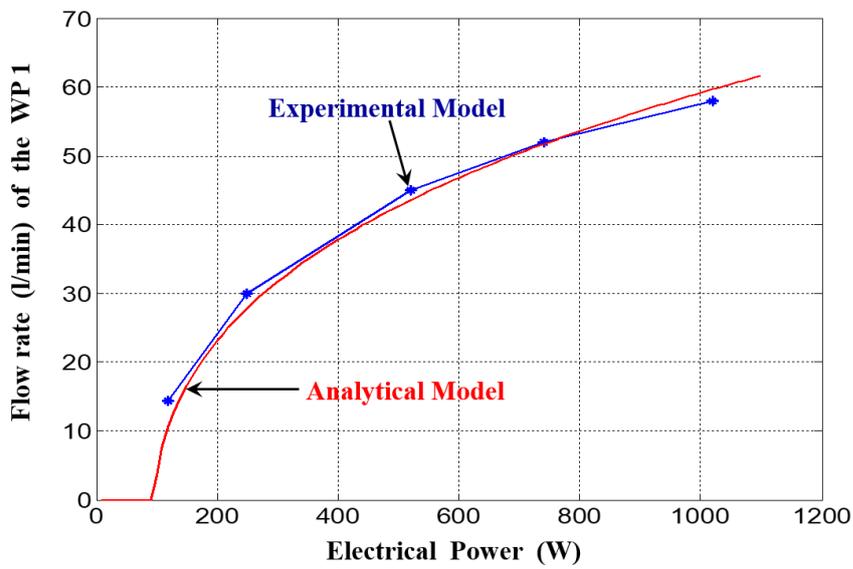
$$R_{sr} = R_s + R_r \left(\frac{L_m}{L_r} \right)^2 \quad (14)$$

287 The obtained equation (13) presents a nonlinear and multivariable expression of the feeding electrical power of the
 288 motor-pump with its corresponding hydraulic load. In order to determine the pump flow rate with respect to its

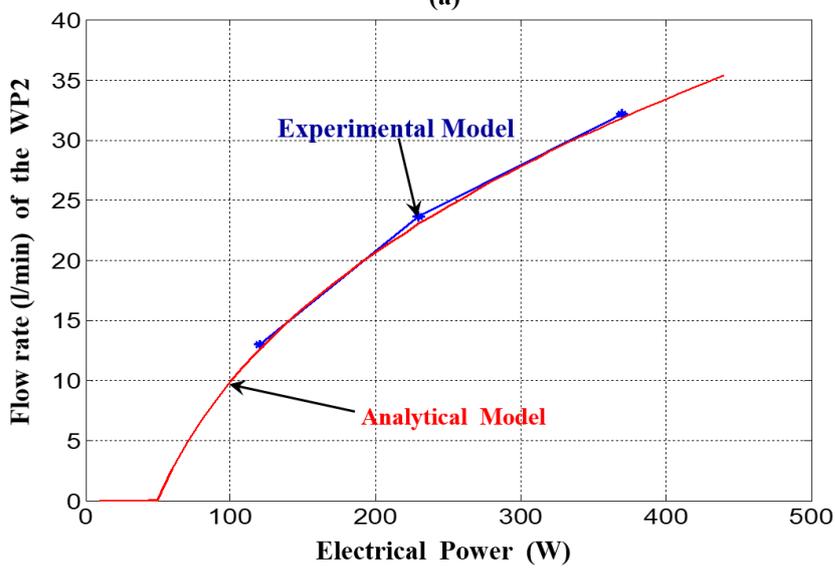
289 feeding electrical power, (13) can be reversed by using the “fsolve” function under Matlab® software. The inverse
290 expression (*i.e.* $Q_p=f(\mathcal{P}_{IM})$) describes the quasi-static model of a whole hydro-mechanical process in the
291 desalination system.

292 *4.5. Practical validation of the quasi-static model*

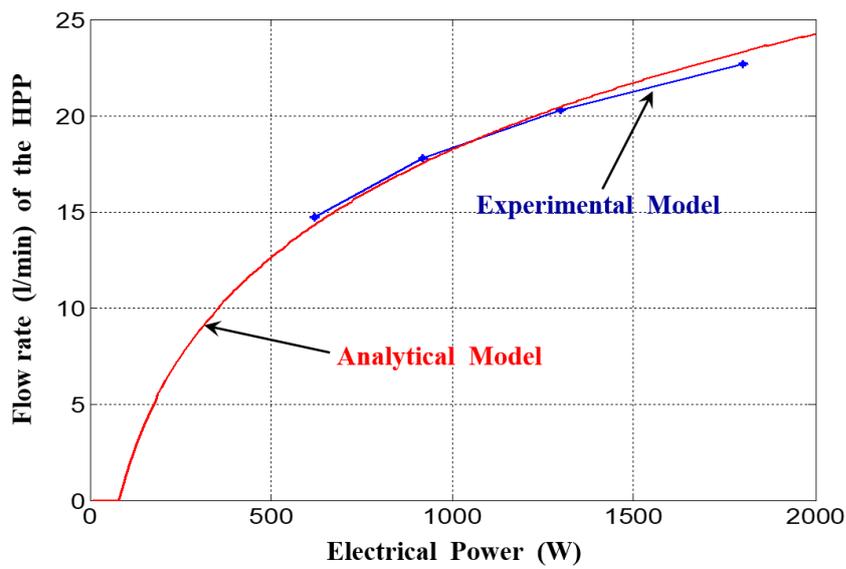
293 In order to validate the developed models of the two hydro-mechanical processes, model-based simulation results
294 are compared to the models extracted from experimental characterizations (in steady-state) of each hydro-
295 mechanical process of the desalination experimental set-up (for more details on the experimental characterizations
296 see sub-section 3.2) in ref. [51]). This comparison is illustrated by Fig.8 that presents the water flow rate variation
297 curves $Q_p=f(\mathcal{P}_{IM})$ for the three used motor-pumps (WP1, WP2 and HPP) with respect to the drawn electrical
298 power by each motor-pump. According to this, an energetic coherence between the dynamic and quasi-static
299 models of each hydro-mechanical process has been proved. These results put forward the great worth of the quasi-
300 static modeling to be used in order to set and optimize the energy management strategy which is defined and
301 discussed in the next section.



(a)



(b)



(c)

302
303
304

Fig.8. Comparison of the developed and experimental models for the different hydro-mechanical subsystems of (a) well pump WP1 (b) well pump WP2 and (c) high pressure pump HPP.

305 5. Energy management strategy

306 This section is divided into two parts. The first one is devoted for setting the energy management problem. The
 307 second part is dedicated to describe the energy management strategy (EMS) that is based on deterministic rules.

308 5.1. Setting the water/power management problem

309 As electrochemical storage is substituted by hydraulic storage in water tanks, the desalination system includes two
 310 decoupled and independent hydro-mechanical subsystems. The energy requirements of these subsystems are not
 311 the same depending on their operating points. The latter depend on both the hydraulic characteristic curve of the
 312 pump (imposed following the rotational angular speed of the motor-pump) and the hydraulic load characteristic
 313 curve of each pump. This needs to develop a specific EMS permitting to manage simultaneously the power and
 314 water flows into the system while fulfilling the technological (power and pressure ranges) and functional (tank
 315 filling state) constraints. The principle of the proposed EMS is defined such as the input variable generated power
 316 from RESs can be dispatched between the different pumping devices according to a power sharing factor (α_i)
 317 defined as:

$$318 \mathcal{P}_{p_i} = \alpha_i \mathcal{P}_{dc} \quad (15)$$

318 With:

$$\sum_{i=1}^n \alpha_i = 1 \quad (16)$$

$$\mathcal{P}_{p_i}^{\min} \leq \mathcal{P}_{p_i} \leq \mathcal{P}_{p_i}^{\max} \quad (17)$$

$$L_{\min}^{\text{Inf}} \leq L \leq L_{\max}^{\text{Sup}} \quad (18)$$

319 Where \mathcal{P}_{p_i} and α_i denote respectively the electrical power that should be addressed to the i^{th} motor-pump of the
 320 system, and its corresponding power sharing factor, \mathcal{P}_{dc} denotes the input DC-link power to be dispatched, and n
 321 is the total number of pumping devices.

322 The objective of the EMS described by equations (15), (16), (17) and (18) is to maximize the freshwater
 323 production of the system according to the available renewable energy generation while respecting the system
 324 constraints. Maximizing freshwater production following the available renewable energy is beneficial in terms of
 325 freshwater storage that presents a new form of energy storage. The idea is to maximize and store freshwater, for
 326 later use when renewable energy is unavailable.

327 The power value \mathcal{P}_{p_i} for the i^{th} switched-On pump is considered as reference value that should be given by the
 328 EMS based on (15). The choice of the \mathcal{P}_{p_i} value is constrained by both the power range of the i^{th} motor-pump and
 329 the tank filling state confines as defined in (17) and (18), respectively. This principle is applied for all pumping
 330 devices. Thus, according to both input generated power and the T_1 filling state, the α_i value is computed and
 331 subsequently the \mathcal{P}_{p_i} value of each pump is determined. Then, according to the power value \mathcal{P}_{p_i} and to the
 332 operation time of each pump the brackish water level in the tank T_1 (defined by (7)) will be varied (*i.e.* increased
 333 or decreased). For example, in case of low value of $\alpha_1 = (\mathcal{P}_{WP1} / \mathcal{P}_{dc})$, the well pump (WP₁) operates in the region
 334 of low efficiency due to the very low input power. For this reason, no remarkable increase in the water level can
 335 be noticed, but on the other side the high pressure pump (HPP) operates with high input power and good
 336 efficiency (*i.e.* $\mathcal{P}_{HPP} = \alpha_2 \mathcal{P}_{dc} = (1 - \alpha_1) \mathcal{P}_{dc}$, in case of $n = 2$). This, advantageously leads to increase the freshwater

337 production. On the opposite case with higher α_1 values, WP efficiency can be improved and the brackish water
338 level in the tank increases accordingly. This enables to increase the storage amount of brackish water in the tank
339 for later use by the RO process when the renewable energy is available. It is also possible to simultaneously store
340 brackish water in the tank and produce freshwater when the renewable energy is abundant (*i.e.* very high
341 generated power supply). Therefore, the generated power from renewable sources is strongly coupled with the
342 water process system efficiency: in particular, the importance of respecting pumping power limits as defined in
343 (17) is put forward to prevent problematic operations that degrade efficiency and could also reduce the lifetime of
344 pumps. The latter issue emphasizes the first coupling between “power and subsystems efficiency”.

345 On the other hand, EMS performance is affected when modifying the sizing of motor-pumps. It depends on the
346 choice of the motor-pump rated power: here respectively (0.75kW and 2.2kW) as initial combination in the
347 desalination system, then (0.37kW and 2.2kW) as a second combination. Indeed, by choosing another motor-
348 pump with lower rated power, but with relatively high flow rate, energy efficiency of the motor-pump can be
349 relatively improved with a lower power consumption \mathcal{P}_{pi} . Consequently, EMS performance will be influenced.
350 This issue emphasizes the second coupling between “sizing and management performance”.

351 A third coupling between “tank level and power management” has to be managed. Indeed, after a certain
352 operation time of the WP(s), the maximum filling level of the tank T_1 can be attained and subsequently WPs must
353 be shut down. On the other hand, operating the HPP is only possible if the tank T_1 is not empty.

354 Based on this strongly coupled system design (water management and pump sizing), a Deterministic Rule-based
355 EMS is developed. It consists of deterministic energy dispatch that evaluates the system states of the desalination
356 system based on set rules, then computes the respective energy dispatches.

357 It should be noted that the experimental desalination test bench installed in our research laboratory (L.S.E in
358 ENIT-UTM, Tunis, Tunisia) presents a prototype including two pumping devices: one WP and one HPP. Indeed,
359 the experimental test bench is exploited for two sizing steps: the first sizing is 0.75kW for well pumping and
360 2.2kW for the RO process, and the second sizing is respectively 0.37kW and 2.2kW whose characteristics are
361 reported in Table 2. It is a simplified case study, but the methodology may be extrapolated to any number of
362 subsystems. In this work, it can be extrapolated to three pumping devices: two parallel WPs functioning through
363 exploiting pumps modularity versus the input power, and one HPP. So, in the next subsection the influence of
364 both “pump sizing” and “modularity” on management performance are investigated and analyzed.

365 In this work, the suitable power range $[\mathcal{P}_{\min} - \mathcal{P}_{\max}]$ of each pumping device has been experimentally identified
366 (for more details see ref. [51]) while functioning with a given hydraulic load.

367 5.2. Rule-based EMS

368 According to the given power \mathcal{P}_{dc} , and given the hydraulic loads characteristics, a modular approach (*i.e.* several
369 motor-pumps that can be switched on/off and tuned) for energy management is applied to the studied system. This
370 management approach is based on different operating modes that can be switched during the system operation.
371 Indeed, from the power ranges of motor-pumps, three main operating modes are considered and explained in
372 Table 4. The operating mode preference essentially depends on: *i*) the given power supply \mathcal{P}_{dc} , *ii*) the stored water
373 level L in the tank T_1 that must vary on its specified confines ($L_{\min}^{\text{Inf}} \leq L \leq L_{\max}^{\text{Sup}}$), and *iii*) the operating power
374 range of each pumping device $[\mathcal{P}_{\min} - \mathcal{P}_{\max}]$.

Operating mode	Description
Mode P	Pumping mode: at least one WP is switched On, the HPP is shut down. During this mode, pumped brackish water (to be treated) is stored in the tank T_1 .
Mode D	Desalination mode: all WPs are shut down and the HPP is switched On. During this mode, the stored brackish water in the tank is exploited to produce freshwater.
Mode P&D	'Pumping and Desalination' mode: the HPP and at least one WP are switched On. This mode is recommended when the generated power is abundant.
Mode OFF	The system is shut down.

376

377 Regarding the storage tank T_1 , four limit levels (L_{\min}^{Inf} , L_{\min}^{Sup} , L_{\max}^{Inf} , L_{\max}^{Sup}) are defined in this study. The idea
378 of choosing such boundaries is to maintain the tank filling state within an acceptable range [$L_{\min}^{\text{Sup}} - L_{\max}^{\text{Inf}}$].
379 Moreover, each limit interval ($[L_{\min}^{\text{Inf}} - L_{\min}^{\text{Sup}}]$, $[L_{\max}^{\text{Inf}} - L_{\max}^{\text{Sup}}]$) permits to avoid respectively the tank
380 emptying and overflow. These intervals make a "safety margin" against the successive occurrence of motor-
381 pumps-switched On/Off. For example, within the $[L_{\min}^{\text{Inf}} - L_{\min}^{\text{Sup}}]$ margin the HPP must be shut down in order
382 to avoid emptying the tank and only the WP should operate to increase the water level if the renewable power is
383 available. This may avoid the successive HPP-switched On/Off. The opposite case is considered for the $[L_{\max}^{\text{Inf}} -$
384 $L_{\max}^{\text{Sup}}]$ margin.

385 In order to study the influence of pump sizing and modularity on management performance, four pump
386 combinations are proposed that are summarized in Table 5 and corresponding operating ranges are illustrated in
387 Fig.9. For example, for Comb.3 where the WP_1 , WP_2 and HPP are used, three different power ranges have to be
388 considered in the energy management that are respectively as follows: [120W–1020W], [120W–370W] and
389 [620W–1800W]. Three additional limits are also added which are as follows: (2170W = 370W+1800W),
390 (2820W = 1020W+1800W), and (3190W = 370W+1020W+1800W). As a result, nine power intervals are
391 obtained to be tested on the input generated power \mathcal{P}_{dc} in the rule-based power sharing algorithm. So, the decision
392 making for power sharing depends on the \mathcal{P}_{dc} value and the filling state of the storage tank as depicted in Fig.9.
393 For example, if ($\mathcal{P}_{dc} = 700\text{W} \in [620\text{W}–1020\text{W}]$) and ($L_{\min}^{\text{Sup}} < L < L_{\text{intermed}}$) then ($\alpha_1 = 1$, $\alpha_2 = 0$ and $\alpha_3 = 0$). That
394 means that the WP_1 is set On (*i.e.* $\mathcal{P}_{WP1} = \mathcal{P}_{dc}$), and the $\{WP_2$ and HPP $\}$ are shut down (*i.e.* $\mathcal{P}_{WP2} = \mathcal{P}_{HPP} = 0$). In
395 this case, the system takes benefit of the total generated power to operate only in pumping mode in order to
396 increase the brackish water storage amount in the tank. When the generated power increases (*e.g.* $\mathcal{P}_{dc} = 1000\text{W}$)
397 and the brackish water level exceeds the intermediate level (*i.e.* $L > L_{\text{intermed}}$), then ($\alpha_1 = 0$, $\alpha_2 = 0$ and $\alpha_3 = 1$). In
398 this case, the system operates only in desalination mode (*i.e.* $\mathcal{P}_{HPP} = \mathcal{P}_{dc}$) to produce freshwater and the well
399 pumps are both shut down (*i.e.* $\mathcal{P}_{WP1} = \mathcal{P}_{WP2} = 0$).

400 According to the different pump-combinations four different Deterministic Rule-based algorithms are developed
401 and tested for energy management. One example of the developed rule-based algorithms is described through the
402 flowchart depicted in Fig.10 giving an idea on the mode preference according to the input power and the current
403 water level in the tank. Indeed, the presented algorithm offers several degrees of freedom permitting to optimize
404 the different pumps operation, namely: for the input electrical power by defining thresholds (\mathcal{P}_{WP}^{\min} , \mathcal{P}_{WP}^{\max} ,

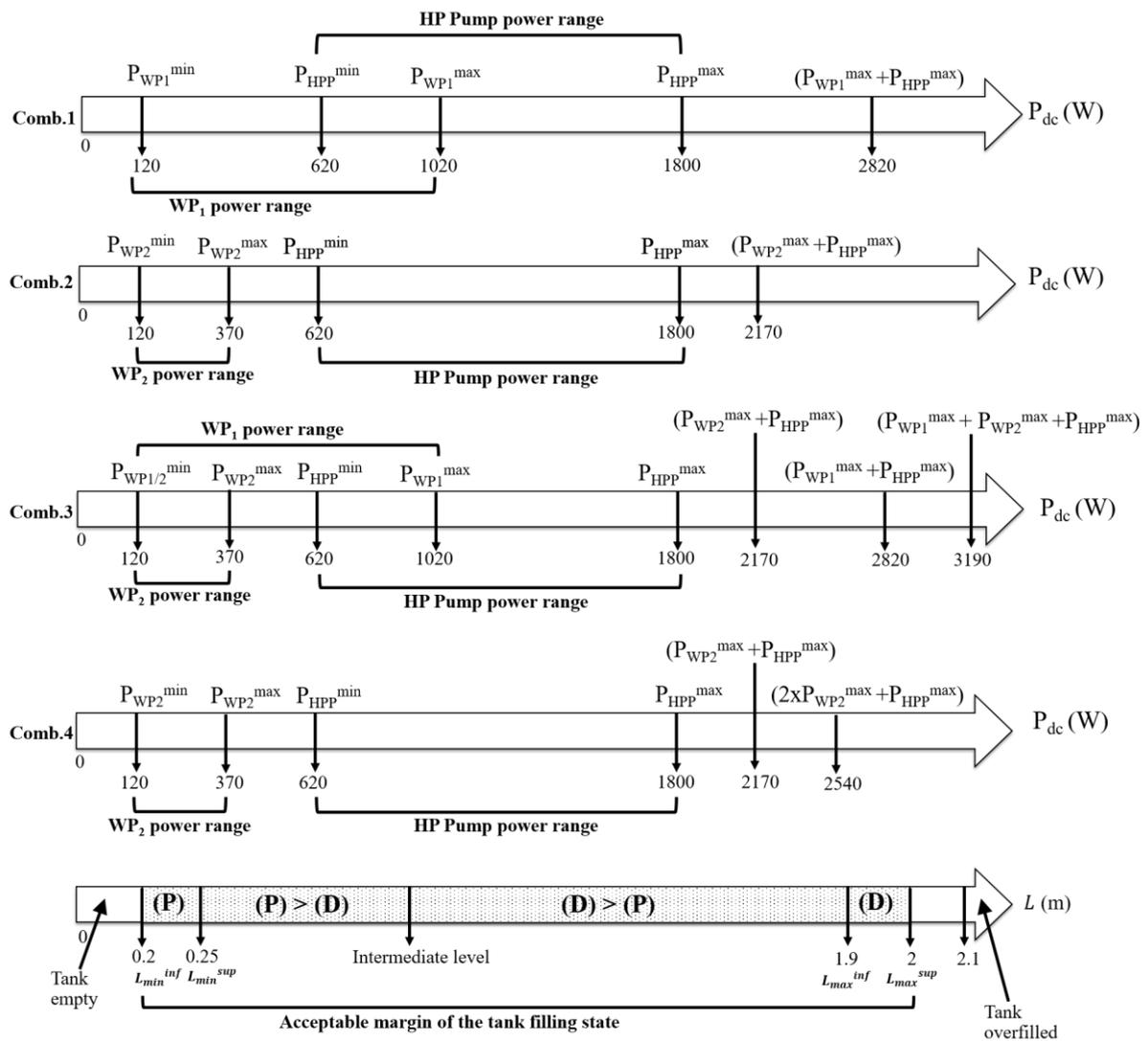
405 \mathcal{P}_{HPP}^{\min} , \mathcal{P}_{HPP}^{\max} , $\mathcal{P}_{\max}=\mathcal{P}_{WP}^{\max}+\mathcal{P}_{HPP}^{\max}$), and for the storage tank by defining thresholds (L_{\min}^{Inf} , L_{\min}^{Sup} , L_{intermed} ,
406 L_{\max}^{Inf} , L_{\max}^{Sup}). The intermediate level defined by (19) is a supplementary threshold limit defining the power
407 dispatching strategy. So, as illustrated in Fig.9 under this level ($L \leq L_{\text{intermed}}$), the priority is addressed to the well
408 pumping (brackish water storage) over the desalination process so that WP(s) can function as much as possible to
409 fill the storage tank. In addition, when the renewable energy is abundant, it is possible to operate simultaneously
410 the two processes while ensuring that: $Q_{WP} \geq Q_{HPP}$ in order to prevent emptying the tank. In this case, the system
411 operates in pumping mode with “desalination mode in a moderate way”. On the opposite, when $L > L_{\text{intermed}}$ there
412 is enough stored brackish water. This enables to switch the priority to the desalination process over well pumping
413 leading to maximize the freshwater production. In addition to that, when the renewable energy is abundant both
414 processes can operate simultaneously while ensuring that: $Q_{WP} \leq Q_{HPP}$ in order to prevent tank overflow. In this
415 case, the system operates in desalination mode with “pumping mode in a moderate way”. This strategy is
416 implemented and described through the flowchart of one developed EMS that is illustrated in Fig.10.

$$L_{\text{intermed}} = \frac{L_{\min}^{\text{Inf}} + L_{\max}^{\text{Sup}}}{2} \left(\frac{Q_{HPP}}{Q_{WP}} \right) \quad (19)$$

417 Table 5 Different pump combinations

	Comb.1	Comb.2	Comb.3	Comb.4
Pump combination	WP ₁ /HPP	WP ₂ /HPP	WP ₁ /WP ₂ /HPP	WP ₂ /WP ₂ /HPP
	(0.75/2.2 kW)	(0.37/2.2 kW)	(0.75/0.37/2.2 kW)	(0.37/0.37/2.2 kW)

418 Note that the flow rate Q_{pi} of the i^{th} pump is computed by inverting the expression (13) and using the reference
419 feed power value of the i^{th} pump calculated by (15). The task here is to compute the instantaneous values of the α_i
420 factor enabling to reach the sought objective of EMS. Simulation results are analyzed in the next section.



(P) > (D) : favoring Pumping (P) over Desalination (D) mode

(D) > (P) : favoring Desalination (D) over Pumping (P) mode

421

422

Fig.9. Power ranges for different pump combinations with operating mode preference according to the stored water level

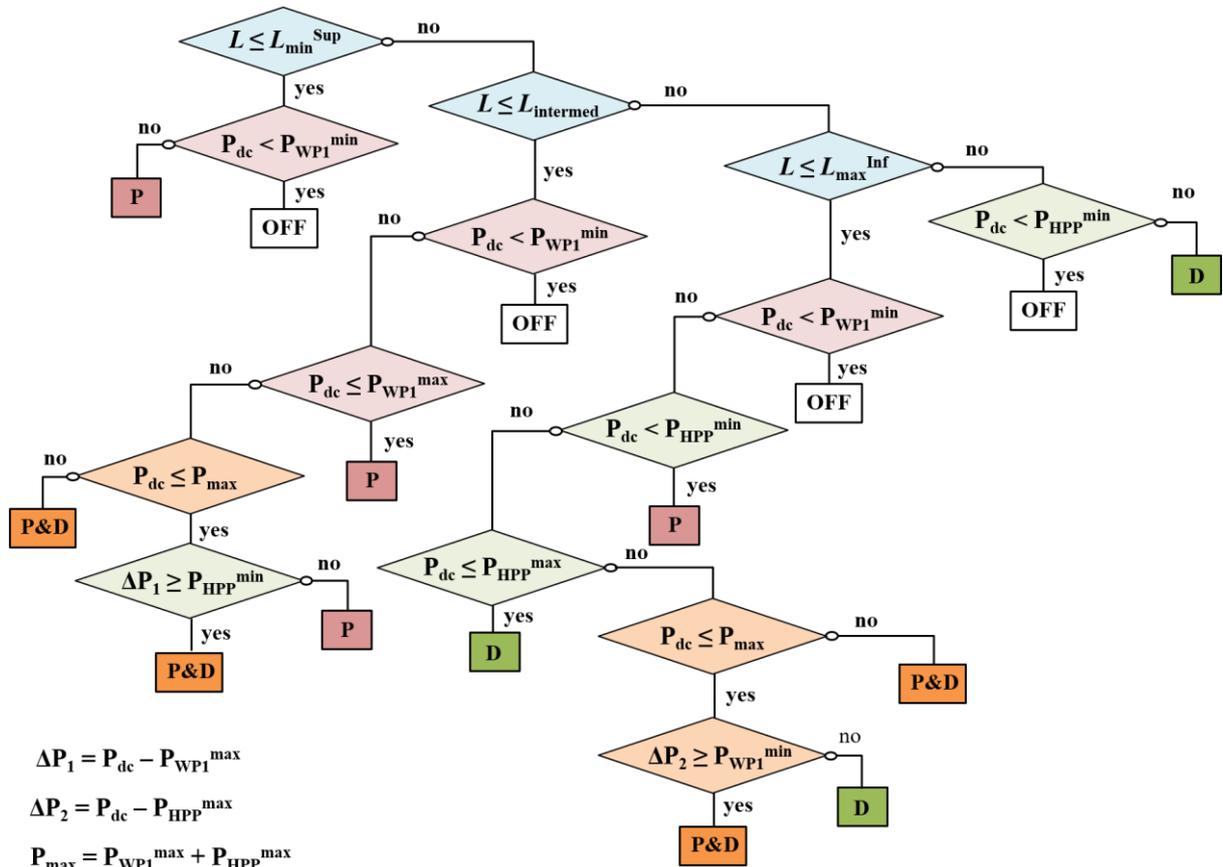


Fig.10. Flowchart of the Deterministic Rule-based energy management strategy for Comb.1

6. Simulation results analysis

This section is dedicated to analyze the EMS performance through simulations where different components sizing and different pump-combinations are considered.

The simulations have been accomplished using real data of hybrid PV/Wind power generation recorded every hour from January to December, 2007 of a region in Southeast Tunisia: Djerba-Midoun. The PV source is composed of 8 monocrystalline modules (from elysun) of 250Wp each, where the total generated power is of 2kWp. As for the wind turbine source, the Aeolos-H 2kW wind turbine is used with rated power of 2kW.

The different dispatch algorithms have been coded under Matlab[®] software using the simulation parameters reported in Table 6 where the considered sampling period is 2.5 minutes (*i.e.* the sampling period is $T_s = 2.5 \times 60 = 150$ s). Indeed, an interpolation has been performed on the recorded hourly power profile in order to modify the sampling period ($T_s = 1$ h) which represents a long time interval for the proposed EMS. A daily and weekly power profiles, depicted in Fig.11, were considered for tests and analysis. It should be noted that during simulations two RO membranes have been considered.

Table 6 Simulation parameters

Symbol	Description	Value	Unit
k_1	Number of samples in a day	553	samples
k_2	Number of samples in a week	4009	samples
k_3	Number of samples in a year	210217	samples
T_s	Sampling period	150	s
T_t	Total time for one day	82950	s
FS_{max}	Maximum Filling State of the tank	100	%
FS_{min}	Minimum Filling State of the tank	10	%
FS_0	Initial Filling State of the tank	60	%

\mathcal{P}_{HPP}^{\min}	Minimum power of HPP	620	W
\mathcal{P}_{HPP}^{\max}	Maximum power of HPP	1800	W
\mathcal{P}_{WP1}^{\min}	Minimum power of WP ₁	120	W
\mathcal{P}_{WP1}^{\max}	Maximum power of WP ₁	1020	W
\mathcal{P}_{WP2}^{\min}	Minimum power of WP ₂	120	W
\mathcal{P}_{WP2}^{\max}	Maximum power of WP ₂	370	W
\mathcal{P}_{dc}^{\max}	Maximum generated DC power	4000	W

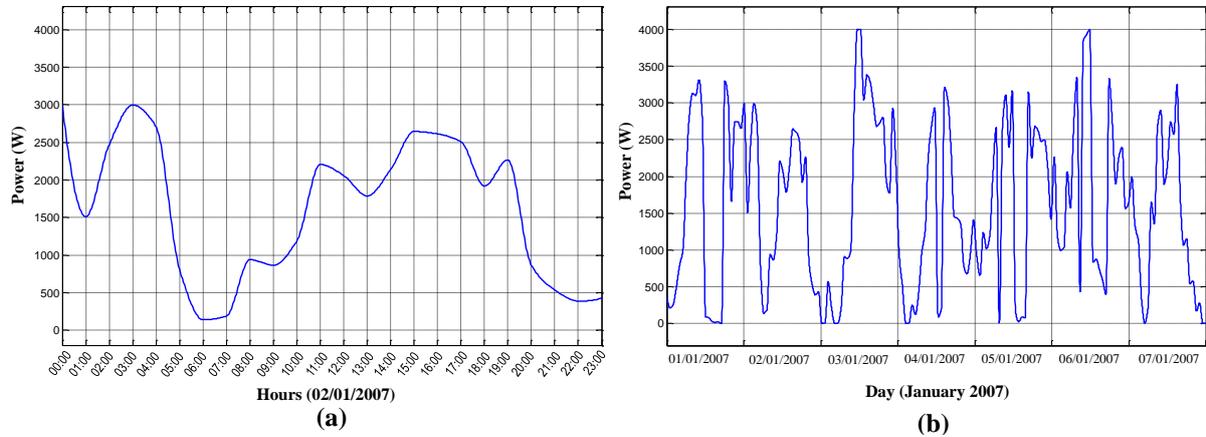


Fig.11. Daily (a) and weekly (b) PV-Wind generated electrical power profiles

439
440

441 Results of the developed EMS for each pump combination are reported in Table 7. These results are assessed in
 442 terms of freshwater production q_{fresh} (in m^3) for the two presented power profiles. As it is previously explained, the
 443 main objective of the EMS is to maximize as much as possible the freshwater production while taking benefit of
 444 the available renewable energy. This permits to increase as much as possible the freshwater amount storage that
 445 will be used later when renewable energy is unavailable. In such a way, electrochemical storage device can be
 446 avoided. According to this criterion, best results (*i.e.* the higher produced freshwater amount) are indicated in bold
 447 type in Table 7. It can be deduced from this table that the most appropriate combination in terms of freshwater
 448 production is Comb.4 where two parallel identical well pumps with a rated power of 0.37kW each are used for the
 449 welling process. The pump modularity approach is applied here; according to the generated input power level the
 450 well pumping process can operate either a single pump (0.37kW), or simultaneously the two parallel pumps where
 451 the input power is shared between them. This approach has the advantage of operating only one pump WP₂ with
 452 lower rated power (0.37kW), but with higher energy efficiency when the given input power is very low compared
 453 with the single pump WP₁ (0.75kW). Then, when the input power level rises, the modularity approach offers the
 454 possibility to operate simultaneously more than one pump operating each with good energy efficiency.

455 Moreover, the influence of HPP sizing on the system efficiency is also analyzed: so the previously used HPP
 456 (EBARA EVM2 22F/2.2) is substituted now by a new HPP (rated power of 1.5kW instead of 2.2kW) and used for
 457 all previous pump combinations. The new HPP, where characteristics are reported in Table 8, was selected from
 458 the Grundfos manufacturer's catalog. Its electrical and hydraulic characteristic curves were taken from the
 459 Grundfos Product Center, an online tool proposed by Grundfos for the research and design of pumps. Simulation
 460 results for the different pump combinations with the new HPP are reported in Table 9. For the sake of visibility,
 461 the obtained results are illustrated in Fig.12 and Fig.13 where changes on the freshwater amounts are more
 462 visualized. It is noticed that the freshwater production is improved when using the new HPP whose rated power is
 463 lower than the first one, but with higher energy yield.

464 Table 7 Produced freshwater quantity (in m^3) according to component sizing

	Comb.1	Comb. 2	Comb.3	Comb.4
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Storage tank T_1 capacity C1: 2.18 m ³				
Daily power profile	11.96	11.86	11.95	12.03
Weekly power profile	78.47	78.93	78.86	79.35
Storage tank T_1 capacity C2: 4.36 m ³				
Daily power profile	12.12	12.06	12.12	12.2
Weekly power profile	80.46	80.45	80.68	80.88

465 Table 8 Characteristics of the new HPP Grundfos 1.5kW – CRE 1-21

Components	Characteristics	Component constraints
Grundfos HPP	Model: CRE 1-21 Type: centrifugal pump Power output: 1.5 kW Rated Pressure: 7.7-18 bar Rated flow rate: 13.3- 46.6 l/min	Minimum absorbed electric power: 596 W Maximum absorbed electric power: 1563 W

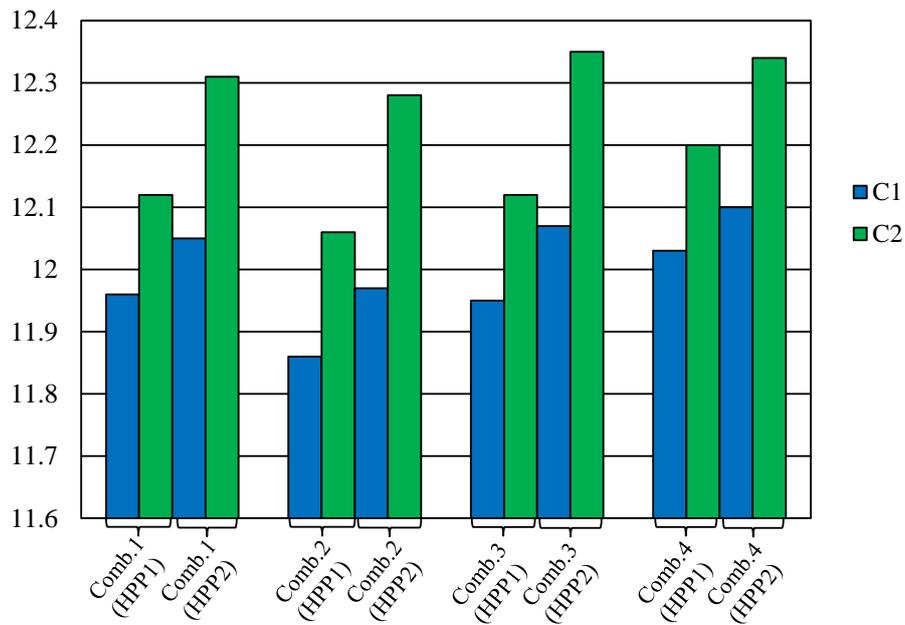
466 On the other hand, besides to the influence of pump sizing, the influence of the brackish water storage tank sizing
467 (capacities C1 and C2) on the management performance is also investigated by doubling the tank capacity
468 (C2=4.36m³). As it can be seen in Table 7, Table 9, Fig.12 and Fig.13 when doubling the hydraulic storage
469 capacity, the freshwater production is improved for all combinations. This means that increasing the hydraulic
470 storage capacity enables to improve the system productivity and the renewable energy use. The later in turn could
471 play an important role in the energy optimization. In addition to that, Comb.4 is always still the most appropriate
472 combination in terms of freshwater production, especially when using the new HPP (1.5kW – CRE 1-21).

473 All of the above mentioned findings highlight the great importance of:

- 474 - The strongly coupling between “the power and subsystems efficiency”, and coupling between “the pump
475 sizing and the energy management performance”.
- 476 - The strongly coupling between “water management and pump sizing”.

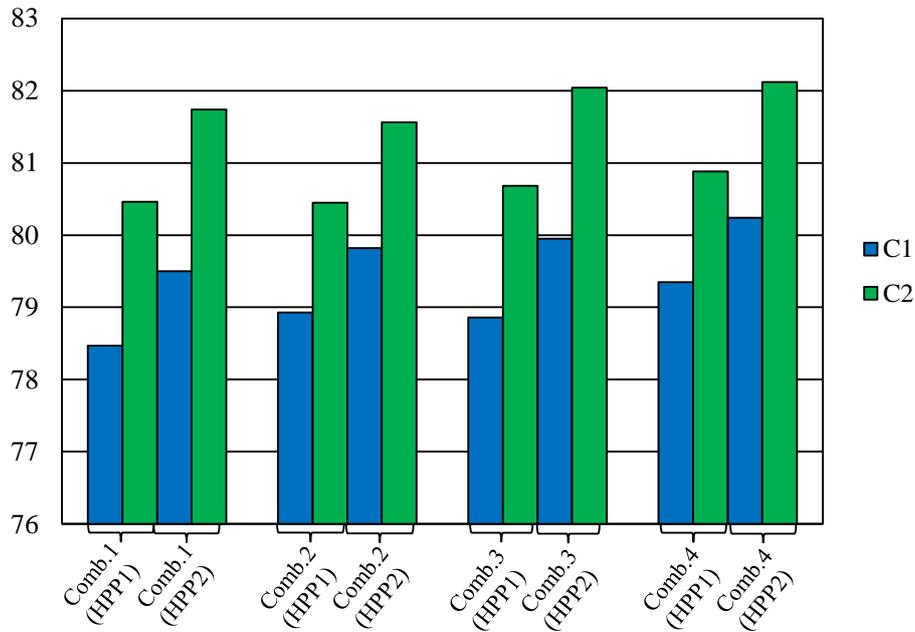
477 Table 9 Produced freshwater quantity (in m³) according to component sizing using the new HPP 1.5kW – CRE 1-21

	Comb.1	Comb.2	Comb.3	Comb.4
Storage tank T_1 capacity C1: 2.18 m ³				
Daily power profile	12.05	11.97	12.07	12.1
Weekly power profile	79.5	79.82	79.95	80.24
Storage tank T_1 capacity C2: 4.36 m ³				
Daily power profile	12.31	12.28	12.35	12.34
Weekly power profile	81.74	81.56	82.04	82.12



478
479

Fig.12. Produced freshwater quantity (in m³) for the different pump-combinations for a daily power profile.



480
481

Fig.13. Produced freshwater quantity (in m³) for the different pump-combinations for a weekly power profile.

482 It should be pointed out that designing the desalination system based on the modularity approach is advantageous
 483 for non-expert small communities enabling them to easily configure such a desalination unit. In such a case the
 484 system becomes flexible and is assembled from modular components such as motor-pumps, RO membranes and
 485 even the solar PV modules. So, non-experts have the possibility to reduce or extend in a second step the number
 486 of these modular components according to the community demand. This can reduce the capital cost, and makes its
 487 maintenance and repair tasks simpler and easier than conventional design approaches.

488 The adopted concept of storing the generated renewable energy during sunny and/or windy days in the form of
 489 water offers a simple, very cost-effective and environmentally friendly alternative, especially for small-scale
 490 desalination units. Nonetheless, this solution does not deal with the impact of frequent system shutdown or
 491 successive On/Off cycling of motor-pumps that may occur. Generally, this may increase the potential wear on

492 motor-pumps and reduce their lifetime. For this purpose, the systemic design approach is applied in this work to
493 investigate the suitable pump combination and sizing according to both the chosen architecture and the available
494 renewable energy, in one-side. Indeed, this approach puts forward the strong coupling between the renewable
495 generated power and the water process system efficiency, and coupling between device sizing (especially motor-
496 pumps) and energy management performance. Such a design approach can help to reduce the non-recommended
497 successive On/Off cycling of motor-pumps and the frequent system shutdown. In the other-side, the proposed
498 power sharing algorithm is developed so that successive On/Off of motor-pumps is minimized following the
499 available PV/Wind generated power. This is achieved by including supplementary level limits ($L_{intermed}$, L_{min}^{Inf} ,
500 L_{min}^{Sup} , L_{max}^{Inf} , L_{max}^{Sup}) on the brackish water storage tank T_1 . The idea is to operate the pump in a moderate way
501 rather than setting it Off in some level intervals, and favoring single-pump operation rather than multi-pump
502 operation in other level intervals making a safety margin against the successive occurrence of pumps-switched
503 On/Off. Besides to the deterministic rules, fuzzy logic is also a useful tool that can be used in the energy
504 management for this sake. For example, a genetic algorithm optimized fuzzy logic-based energy management
505 strategy was previously developed by authors (ref. [51]) and applied to the first pump combination Comb.1 of the
506 desalination unit with a storage tank capacity of 2.18 m³. This helps to reduce the number of successive On/Off of
507 motor-pumps.

508 7. Conclusion

509 This work is within the context of complex energy system design. The principle of the adopted systemic design
510 approach is to start from component system characterization, going through the modeling phase, to achieve an
511 efficient energy management in real-time. In this regard, the system architecture was defined so that continuously
512 freshwater productivity and supply are insured while taking into account the environmental and capital cost issues.
513 This is achieved by means of integrating hydraulic storage (brackish water and freshwater) in water tanks when
514 renewable energy is available instead of electrochemical storage device; the available renewable energy can be
515 stored in the form of water. This is very advantageous and cost-effective in terms of energy storage. An
516 experimental BWRO desalination test bench at the laboratory scale has been installed by authors according to the
517 defined system architecture. It is considered as a prototype in order to investigate the feasibility and reliability of
518 such autonomous desalination system in rural and poverty region for drinking and/or agriculture. The different
519 hydraulic processes were previously experimentally characterized. Based on both previous experimental study and
520 dynamic modelling, a quasi-static model of the whole desalination system was carried out and presented in this
521 work for simulations and performance analysis. Then, a deterministic rule-based energy management strategy
522 (EMS) was defined enabling to manage simultaneously the water and power flows into the system. The EMS was
523 developed so that freshwater production is maximized according to the available generated power while fulfilling
524 the technical and functional constraints of the system. Maximizing the system productivity and storing freshwater
525 is beneficial from a continuous water supply perspective, especially when renewable energy is not available. For
526 the sake of system design optimality, the influence of the component sizing (pumps and tank capacity) on the
527 system efficiency and the energy management performance were investigated and analyzed in this work. Several
528 pumps sizing and combinations for two different capacities of the brackish water storage tank are proposed. It was
529 demonstrated that there is a strong coupling between “power and system efficiency”, a coupling between “sizing
530 and management performance”, and also a third coupling between “tank level and power management”. All of
531 these couplings and their interrelationships are defined within the so-called systemic design approach.

532 Simulation results showed that by applying the modularity approach, the most convenient components sizing
533 corresponds to the motor-pumps of lower rated powers, but offering higher energy efficiencies compared to those
534 of higher rated powers. The same observation was noticed when increasing the capacity of the brackish water
535 storage tank. These findings demonstrated that the available renewable energy use can be optimized and the
536 freshwater production can be maximized by choosing the convenient system architecture and the optimized
537 components sizing, highly correlated with the energy management strategy.

538 Another issue was highlighted in this work related to the influence of the successive switching On/Off of motor-
539 pumps on their lifetime. The adopted systemic design approach with the defined system architecture and the
540 developed EMS enabled to initially reduce the number of pumps-switching On/Off events. However, this issue
541 has to be addressed with the greatest accuracy. For instance, renewable energy forecast can be a viable solution to
542 predict renewable power generation for the next time intervals. This enables to significantly improve the energy
543 management performance while taking into consideration the constraint of motor-pumps lifetime by reducing the
544 number of pumps-switching On/Off events.

545 All of these findings justify a deep and more sophisticated study to investigate global optimization approaches
546 taking account of the couplings between the system architecture, sizing and energy management, while respecting
547 the different system constraints.

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