Advanced SWRO desalination plants based on hybrid tidal range/solar PV systems: Preliminary design

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Authors	Lourdes García Rodríguez, USE Agustín Delgado Torres as an external cooperation with the University of La Laguna, Spain.
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Preliminary design of off-grid seawater reverse osmosis (SWRO) desalination plants driven by hybrid tidal range/solar PV systems

Lourdes García-Rodríguez[(1)], Agustín M. Delgado-Torres[(2)*]

[(1)]*Escuela Técnica Superior de Ingeniería. Universidad de Sevilla. ETSI, Camino de Los Descubrimientos, s/n. 41092- Sevilla, Spain. Tel. +34 95 4487231. e-mail: mgarcia17@us.es*

[(2)]*Dpto. Ingeniería Industrial, Escuela Superior de Ingeniería y Tecnología. Universidad de La Laguna. ESIT, Avda. Astrofísico Francisco Sánchez s/n, 38206 La Laguna, Tenerife, Spain. Tel. +34 922846045, e-mail: amdelga@ull.edu.es*

Abstract

This paper deals with innovative desalination systems based on tidal range/PhotoVoltaic (PV)-driven reverse osmosis, proposed by the authors as a technology with interesting prospects to promote Renewable-Energy RE-powered desalination at medium to large capacity ranges. Key features to complement PV systems are that a tidal range power plant allows a predictable water production pattern along with ensuring water production at night. In this paper main design parameters are selected namely, basin area, sluicing area, starting head, minimum head, nominal power of the tidal and PV generators, specific energy consumption and nominal plan capacity. A thorough analysis in a favourable location, Bromme (Australia), concludes that per each 100,000 m^3/d of nominal desalination capacity the recommended hybrid energy generator corresponds to 29.2 MW of nominal tidal power and 29.2-36.5 MW of peak PV power if the desalination plant is able to operate only with nominal power consumption, being the expected annual water production about one half of the nominal production. In addition, 19.4 MW of nominal tidal power and 19.4-24.33 MW of peak PV power would be enough if the desalination plant is able to operate at variable power consumption thus obtaining similar annual water production. Accurate estimations of water costs are out of the aim of this paper.

Keywords: *tidal power; desalination; reverse osmosis; hybrid tidal/PV systems; solar desalination*

Highlights:

- Modelling of seawater desalination powered by hybrid systems based on tidal range and PV energies at Brome, Australia.
- Sizing of solar PV and seawater desalination systems per MW of tidal turbine installed at a favourable location.
- Recommendations on preliminary design of seawater reverse osmosis desalination powered by tidal/PV systems.
- Dependence of operating strategy of the desalination plant on sizing of a tidal/PV-driven desalination plant.

1 Introduction

This paper deals with innovative desalination systems based on tidal range/PhotoVoltaic (PV)-driven reverse osmosis proposed by the authors in a previous paper [1] that justified their interesting prospects to promote Renewable-Energy RE-powered desalination at medium to large capacity ranges by means of a preliminary assessment of the temporal complementarity of both energy resources. As described, literature survey shows that desalination powered by tidal range energy has been scarcely analysed [2-4].

Main advantages of hybrid tidal/PV energy systems for driving off-grid desalination plants in comparison to PV-powered desalination are the following:

- Unforeseen days with nil water production are impossible since tidal range resources are fully predictable. This allows to prevent periods with lack of fresh water production by inexpensive water storage instead of energy storage in batteries, which result in both, increased capital costs and energy losses.
- The tidal plant allows a predictable water production pattern over nights and daylight whereas solar PV plant powers the water production mostly on daily and seasonal peak water demands. Therefore, the temporal water production profile throughout the year exhibited by such hybrid energy systems is excellent to water production. This results in a significantly expanded time of operation of the desalination plant.

Those issues solve key problems which likely are, along with high capital costs, the essential barriers for developing medium to large scale desalination based on off-grid RE systems. Therefore, hybrid PV/tidal-desalination should be explored in spite of the high costs of tidal energy in comparison to competitive costs of PV energy currently achieved. Li et al (2018) [5] report on estimations of electricity cost of 0.28-0.55 $/kWh corresponding to nominal power of the tidal range plant lower than 10 MW, suitable to power nominal desalination capacities up to $68.5 \cdot 10^3$ m^3/d in Australian coasts. Costs drop to 0.24-0.29 if the power achieves more than 1000 MW, which is extremely high to power a desalination plant. Therefore, 0.28 $/kWh could be a reasonable estimation adopted in this paper for medium to large capacity desalination in a favorable location as Broome, Australia. Such a high cost is similar than that of PV technology in the recent past since IRENA [6] reports 0.36 $/kWh in 2010, which goes down to 0.10 $/kWh in 2017. The latter is the value assumed in this paper.

Within this framework, main objectives of this paper are to select the preliminary design of an off-grid desalination system based on SeaWater Reverse Osmosis (SWRO) powered by a hybrid tidal/solar PV generator. To this end Broome, Australia, was selected as a favourable location to conduct this analysis.

2 System description and methodology

This paper analyses a stand-alone desalination system based on the SWRO technology powered by a hybrid tidal range/PV generator. A 0D model described in Delgado-Torres et al [1] with input parameters given in table 1 is developed. Next figure depicts the behavior of several exemplary days at Broome, Australia. The corresponding operation of the tidal range plant is explained as follows. First chart of figure 1 shows the sea level (H_{sea}) and the basin level (H_{basin}) according to filling and generating modes. Basin level goes up (filling mode) whenever the sea level is higher than the basin level, decreases if basin level is high enough than sea level to allow generating mode and remain unchanged over intermediate periods. Therefore the second chart depicts energy resources, thus corresponding positive available head (H) to higher basin level than sea level. In addition, solar irradiance available on the titled surface (G_{PV}) exhibits temporal profile with low overlapping to tidal range resources. Finally, the third chart shows production of the hybrid tidal/PV generator (P_e) with short periods of time of nil power production at night.

Table 1. Main input parameters of the system analysed in figure 1.

Design parameters	
Nominal power of the tidal range plant [MW]	20
Peak power of the PV solar field [MW_p]	30
Basin area, A_{basin} [km^2]	3
Sluice area, A_{sluice} [m]	200.0
Turbine nominal capacity [MW_e]	20
Starting head, H_{st} [m]	2
Minimum head, H_{min} [m]	1
Sea level, H_{sea} [m]	Broome coast thorough year 2018(*)
Solar resources, G_{PV} [W/m^2]	North-oriented tilted surface according to latitude (18º)(**)

(*) From raw data of Australian Government Bureau of Meteorology [7] interpolated to 0.1 h time step and with minor corrections as explained in reference [1].
(**)System Advisor Model software NREL – data from Broome airport - [8].

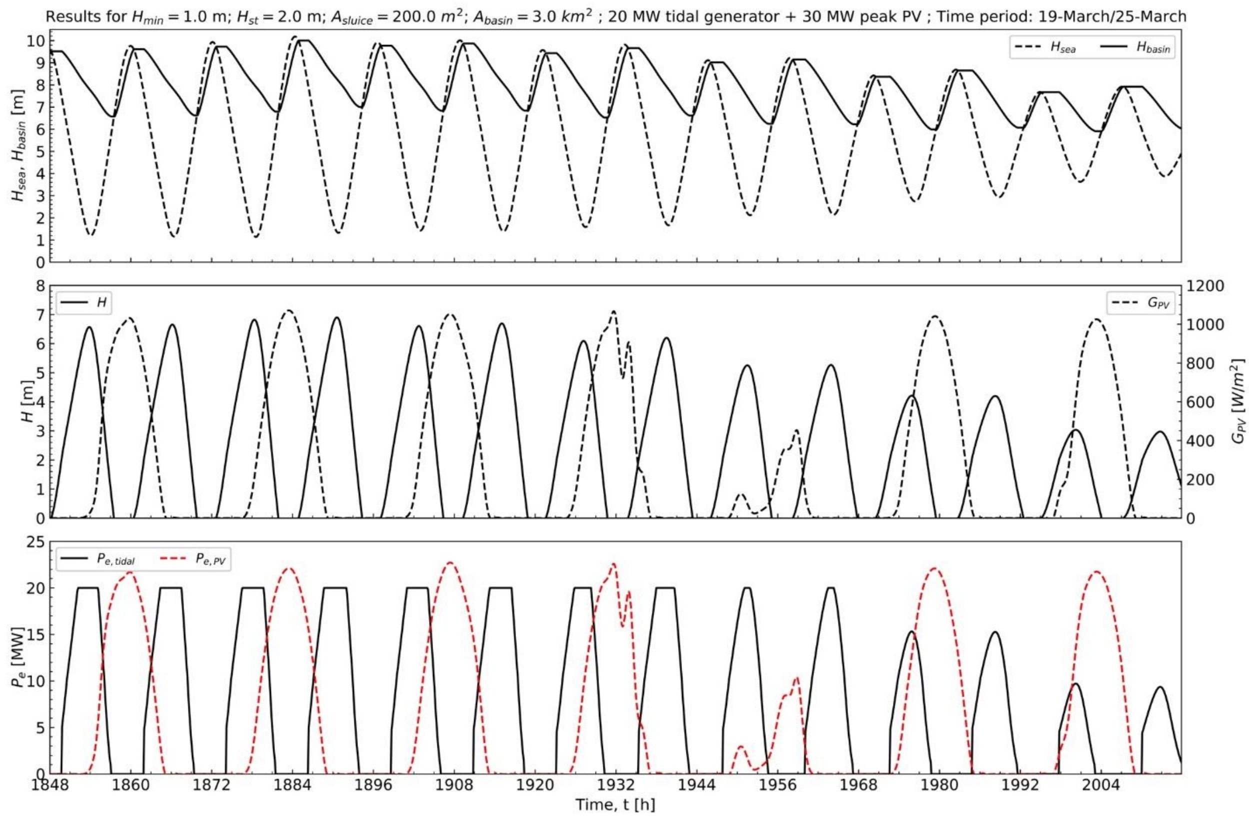

Figure 1. Description of the hybrid tidal range/PV system operation in Broome, Australia, with a 20 MW tidal turbine and a 30 MWp PV generator. Sea level, H_{sea}; Basin level, H_{basin}; Available head, $H = H_{basin} - H_{sea}$; Electricity production, P_e.

In this paper, main parameters of the basin namely, basin and sluicing areas are analyzed considering a tidal range generator of 20 MW.

Concerning the hydraulic turbine, figure 2 and table 2 describe the selected tidal turbine [4] used in this work. The starting head is analysed to identify the best value along with the convenience of operating the plant with fixed or variable value.

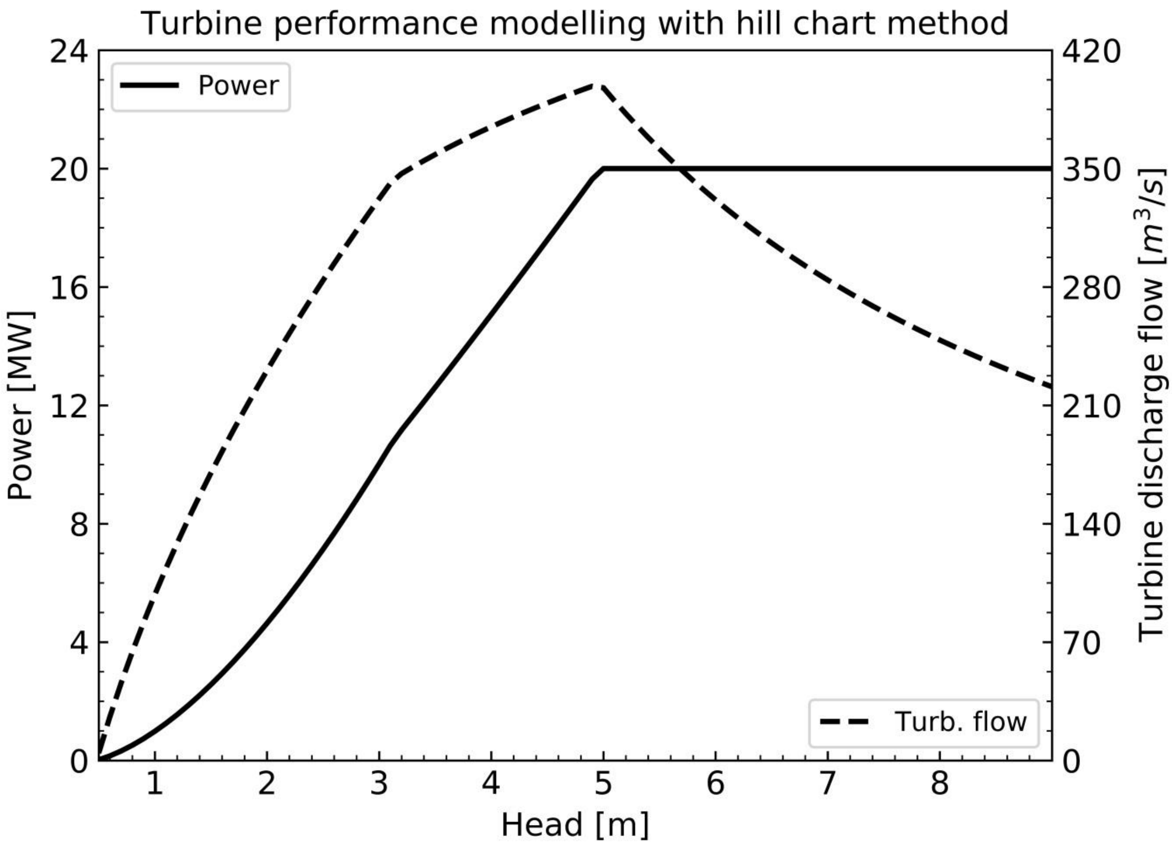

Figure 2. Model of selected turbine for the Swansea Bay Lagoon project [9] (20 MW) and used in this work.

Table 2. Tidal turbine specifications.

	Case base
Turbine capacity [MW]	20[9]
Generator poles	97[9]
Turbine diameter [m]	7.35[9]
Electricity grid frequency [Hz]	50[9]
Turbine speed [rpm]	61.9[9]
Starting head [m]	2
Minimum head [m]	1
[9]Angeloudis and Falconer (2017).	

The Specific Energy Consumption (SEC) of the SWRO desalination plant varies within a range of 3.5-4.8 kWh/m^3 considering values of several desalination plants of Australia reported by Heihsel et al [10] namely, Gold Coast Desalination plant (3.6 kWh/m^3; award year, 2006) and Victoria Desalination plant (4.8 kWh/m^3; award year, 2009). Daily fresh water production from a given power generation profile depends on SEC and nominal capacity set. This paper analyses both parameters in order to achieve minimum contribution of investment costs per unit of water production.

In addition, not only conventional operation of the desalination plant (full load) is considered, but also independent operation of either, the productive core and additional auxiliaries. The SEC attributable to an efficient productive core of the SWRO desalination was estimated by the authors as 1.96 kWh/m^3 [1]. Besides that, the auxiliary consumption of the SWRO desalination plan are analysed from Wilf [11] in order to determine if the surplus energy generated could be used to drive independent items as the pumping due to seawater intake, pretreatment or product distribution. According to Wilf [11], a reasonable SEC attributable to pretreatment losses and other auxiliaries amounts to 0.33 kWh/m^3, thus excluding raw seawater and permeate pumping. Besides, said reference reports on pretreatment losses of 0.28 kWh/m^3. Therefore, methodology adopted to break down the total SEC consists in assuming main running consumption of 2.34 kWh/m^3, plus 0.58 kWh/m^3 due to permeate pumping plus 0.58 kWh/m^3 for raw seawater pumping. The plant model uses those conservative values in order to set quite different operation modes in the desalination plant subsystem as follows. Depending on the power available, the desalination plant consumes:

- 0.58 kWh/m^3, thus operating either, raw seawater pumping or permeate pumping.
- 1.16 kWh/m^3 corresponding to simultaneous operation of aforementioned pumping.
- 2.34 kWh/m^3 with fresh water production by means of operating only the core of the process.
- 2.92 kWh/m^3 with fresh water production and only one of the auxiliary pumping.
- 3.50 kWh/m^3 considering full plant operation.

This plant model makes suitable the assumption that fresh water production takes place whenever the available power achieves 2.34 kWh/m^3. Then, the corresponding power of the core is 10 MW if the total nominal power of the desalination plant is 15 MW. Besides that, the auxiliary energy consumed associated to the annual fresh water production amounts to 1.16 kWh per m^3 of fresh water effectively produced, being 5 MW the corresponding power in aforementioned case. This total auxiliary energy can be consumed within time periods with insufficient power production to generate fresh water along with some of the periods with power production high enough to full plant operation. Therefore, the concept of surplus energy means energy that could not be consumed. The only use of surplus energy in the analysed off-grid system would be to install batteries for energy storage.

Considering this methodology, a desalination plant with 15 MW of nominal power could be partially operated as follows: 2.5 MW (a single auxiliary pumping); 5 MW (raw water and pretreatment pumping); 10 MW (only the core of the process), and 15 MW (full plant at nominal conditions).

3 Results and discussion

3.1 Preliminary design of the tidal range plant

This subsection studies the preliminary design of the tidal range plant. First stage consists in selecting main parameters of the basin defined by the basin and sluicing areas, A_{basin} and $A_{sluicing}$, under the assumption of negligible effect of the basin level on the basin area. For a tidal turbine of 20 MW, figure 3 justifies the selection of 3.0 km^2 and 200 m^2 for A_{basin} and $A_{sluicing}$, respectively as reasonable values to perform the general analysis of the following subsections. However, recommendations in a specific project will require the corresponding cost study in order to perform the best selection.

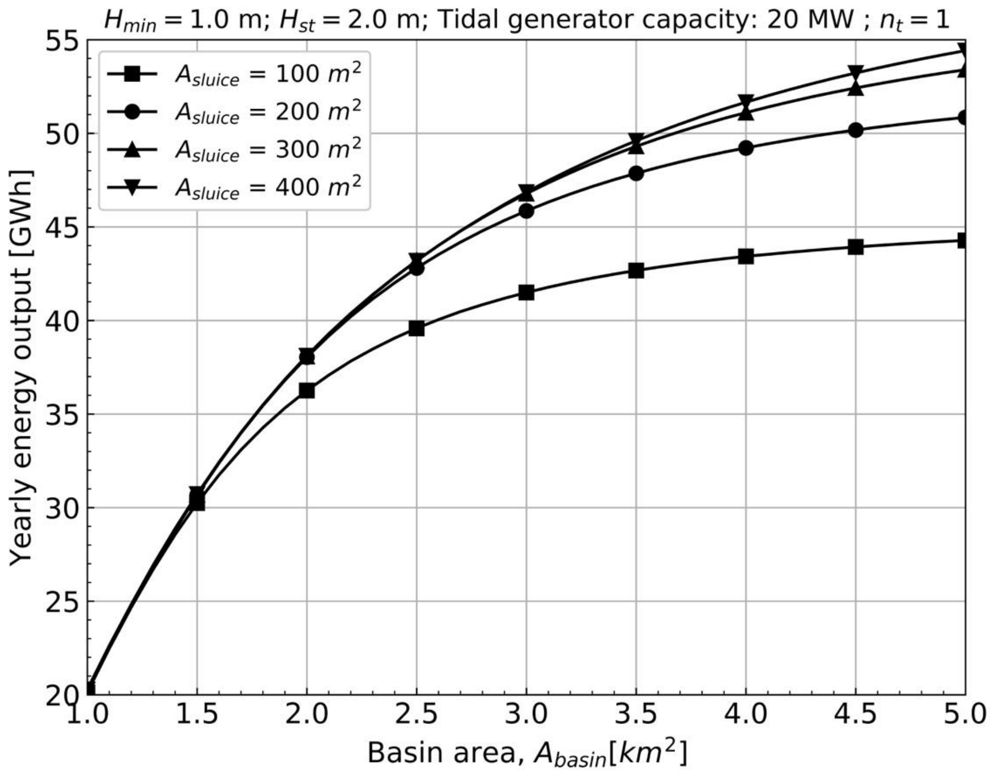

Figure 3. Effect of sluicing area and basin area on annual energy production.

In a second stage, the starting head of the tidal turbine should be individually analyzed in order to ensure its efficient operation. As can be seen in table 3 the value of the starting head fixed throughout the study (H_{st}, 2.0 m) optimizes the annual energy output of the tidal range power plant for the given values of basin and sluicing areas. However, table 3 shows slight influence on annual power production, so this parameter could be varied in specific periods to improve, if possible, the desalination plant operation. Therefore, the thorough analysis of this parameter corresponds to the assessment of control strategy, which is out of the aim of this paper.

Table 3. Annual energy output of the tidal range power plant. A_{basin} = 3.0 km^2, A_{sluice} = 200 m^2, generator capacity 20 MW, consisting in a single tidal turbine.

H_{st} [m]	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
Only tidal [MWh]	44,989	45,187	45,379	45,576	45,738	45,853	45,849	45,789

Finally concerning the selection of tidal turbine nominal electricity output, 20 MW is set in order to analyze large capacity desalination plants. Results of power and water productions can be used considering several turbines similar to that selected.

3.2 *PV generator sizing*

This subsection considers the number of tidal turbines installed (n_t) of 1 with 20 MW of nominal electricity power, being the associated basin area 3.0 km^2. Considering parameter selection of subsection 3.1, figure 4 depicts the effect of the size of the PV generator on the total energy produced by the hybrid tidal/PV system calculated at Broome in 2018. It shows that the energy annual production of 25 MWp is similar to the selected tidal range generator, thus this hybrid system duplicate the energy production of the tidal system. However in off-grid desalination systems, an essential issue is the temporal profile of each power production. According to figure 1, there are days in which PV and tidal systems complements each other, thus improving the water desalination process. Otherwise, figure 1 also shows days with energy production overlapping, which could generate waste energy in off-grid systems. Therefore, additional information to figure 4 is needed to analyse the PV plant sizing.

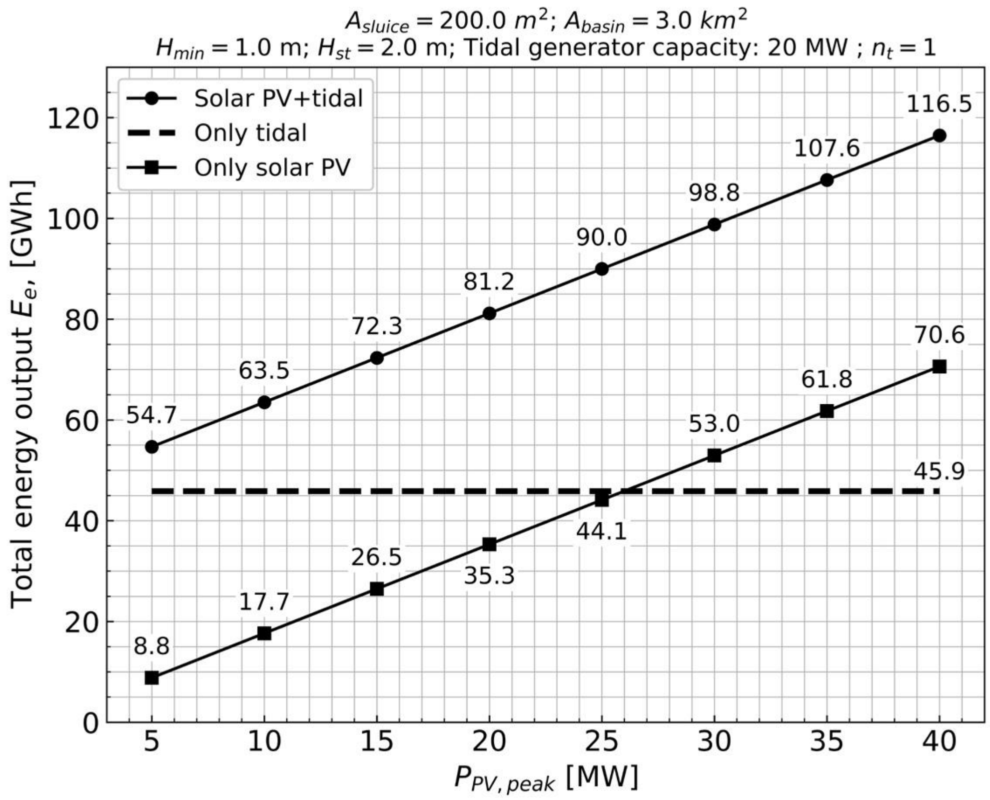

Figure 4. Effect of PV peak power on the total energy output in the year 2018 at Broome, Australia, corresponding to a 20MW of tidal generator.

Figures 5-7 depict the effect of PV plant size concerning the behaviour of hybrid power plant production when the total power production is greater than 25%, 50% and 75% of the tidal nominal power (20 MW) – i.e. 5MW, 10 MW, 15 MW -. Ranges of PV peak power in X-axis remains unchanged in order to make easy the overall comparison. The percentage of the year with power output above a given value is depicted in order to study the behaviour of the hybrid energy system if the power consumption of the desalination plant is 5.0 MW (Fig.5), 10.0 MW (Fig.6) or 15.0 MW (Fig.7). They all show that above 30 MWp, the effect of increasing the PV field power is not significant. On the contrary, the behaviour strongly depends on the PV sizing between 20 and 30 MWp. Therefore, preliminary decisions on PV selection could lay within this range as follows:

- *Decision with emphasis in water costs*. By means of installing a PV field of 20 MWp, one half of the tidal nominal power – i.e. 10 MW - is available throughout nearly one half of the year (48%) –

see Fig.6 -. This results in a total water production of $12.01 \cdot 10^6$ m^3/y, being directly attributable only to the tidal power generation more than one half of the production according to fig.4.

- *Decision with emphasis in water production.* A PV field of 30 MWp allows one half of the tidal nominal power – i.e. 10 MW – to be available throughout more than one half of the year (53%). This case corresponds to $13.26 \cdot 10^6$ m^3/y of water production. Note that the increasing of annual water production, $1.25 \cdot 10^6$ m^3/y, is directly attributable to the increase of PV capital costs, corresponding to $1.4 \cdot 10^6$ \$ based on IRENA data of 1400 \$/kW [6]. The corresponding influence on the actual water cost strongly depends on the financial scenario.

A more accurate analysis of the actual water production requires further analysis of the surplus energy, reported in the next subsection. In addition it is worthy of notice that hybrid tidal/PV systems based on nominal tidal power of 20 MW strongly increases the working period operated at full load (capacity factor) if the PV generator achieves 20 MWp. Figures 5-7 show that said PV peak power increases about a 43% the working period for power loads from 5 MW to 15 MW in comparison to tidal-only generation. Besides, for PV peak power of 30 MW the increase of working time ranged from 41% to 65%, being greater as the power of the load increases. Higher PV systems are not recommended considering nominal consumption of the desalination capacity installed up to 75% of the tidal generator (15 MW).

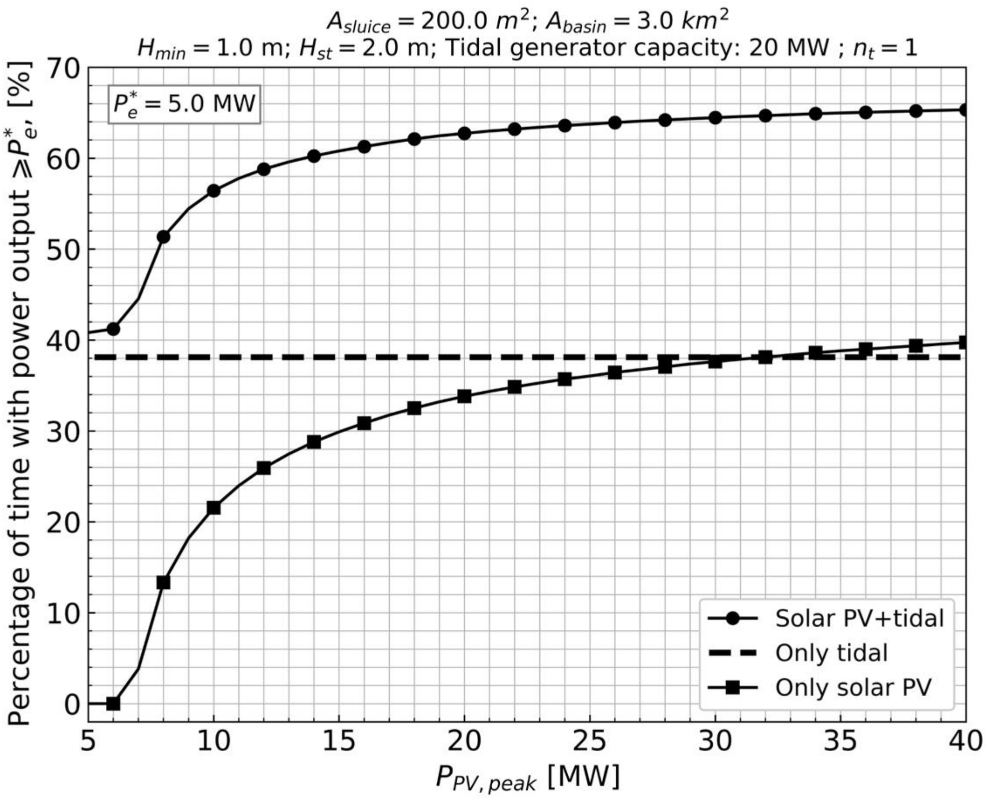

Figure 5. Effect of PV generator size on percentage of the year of power production over the 25% of the nominal power of the tidal range generator.

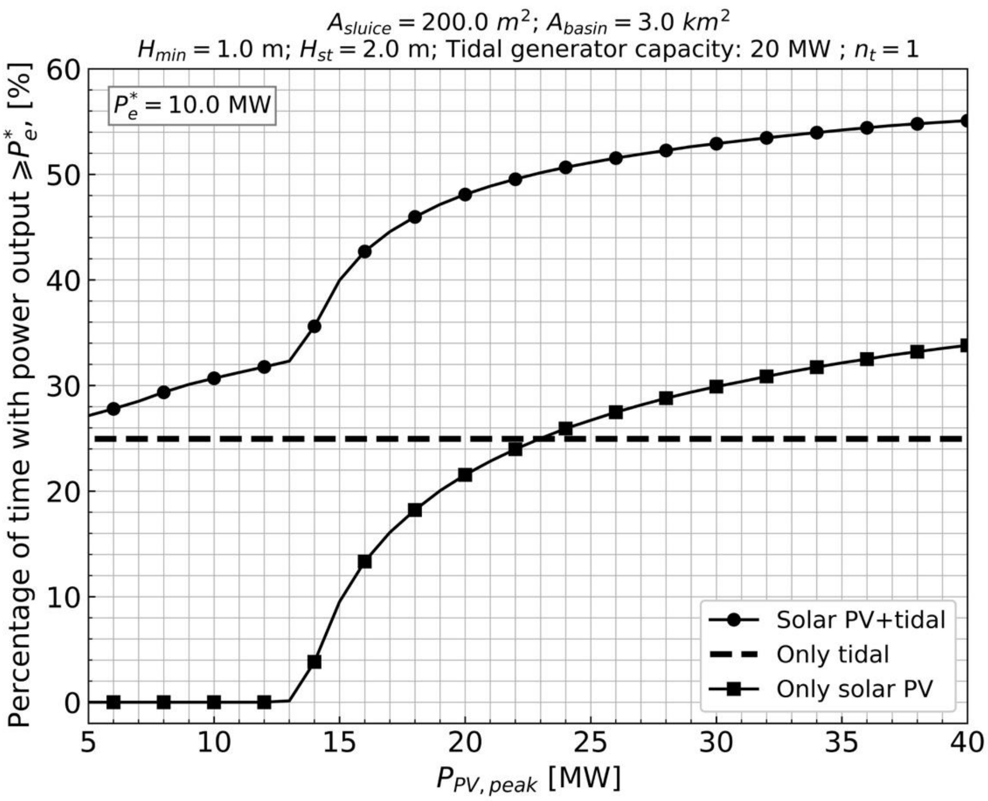

Figure 6. Effect of PV generator size on percentage of the year of power production over the 50% of the nominal power of the tidal range generator.

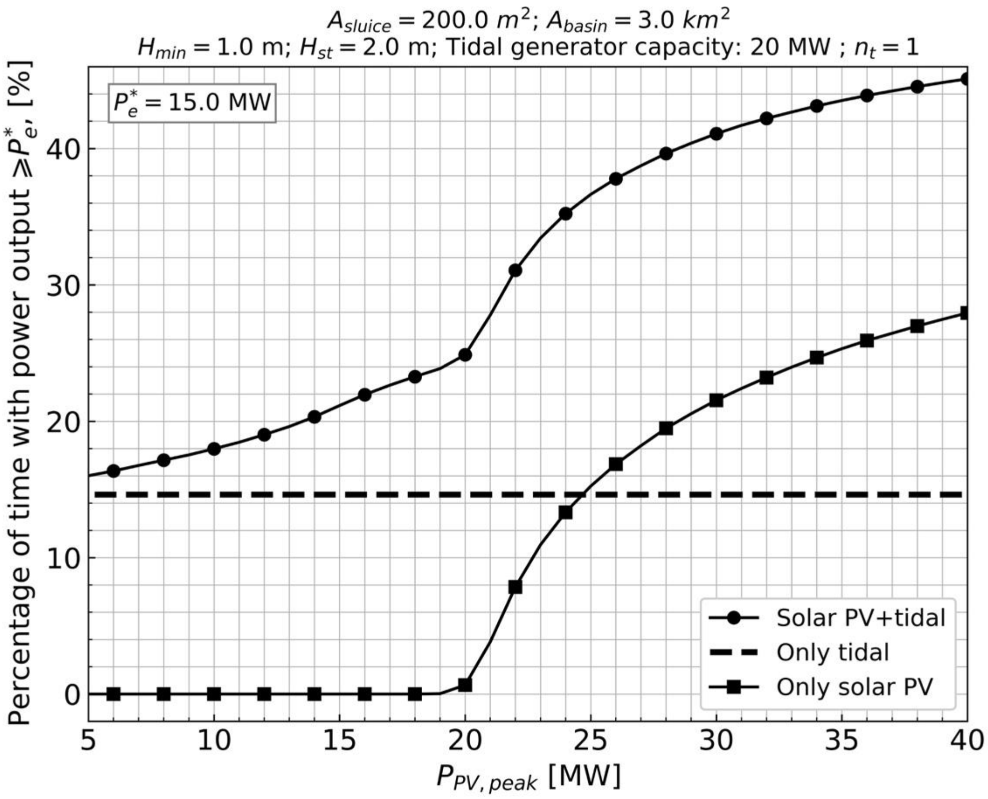

Figure 7. Effect of PV generator size on percentage of the year of power production over the 75% of the nominal power of the tidal range generator.

Besides that, figure 8 describes the behaviour of the system if the nominal consumption of the desalination plant fits the nominal tidal power. In this case a 40 MW PV generator is needed to achieve operation at full load over one third of the year. In addition, the operation at full load due to the tidal plant amounts only to 6%, thus making no sense to use hybrid energy systems.

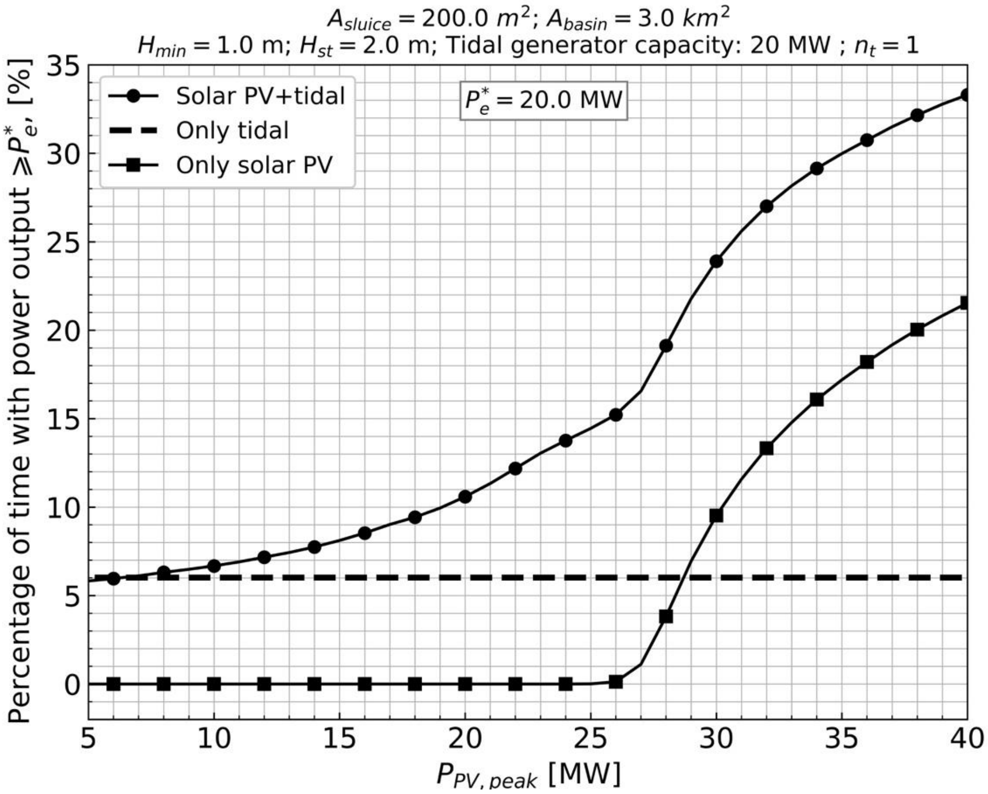

Figure 8. Effect of PV generator size on percentage of the year of power production over the nominal power of the tidal range generator.

Moreover, figure 9 shows a case even more unfavourable corresponding to consumption of 125% of the tidal generator – ratio of 25 MW to 20 MW -. Therefore, to sum up reasonable ratios of nominal consumption to nominal tidal power ranged from 25% to 75%. The corresponding surplus energy analysis will add relevant information on this regard.

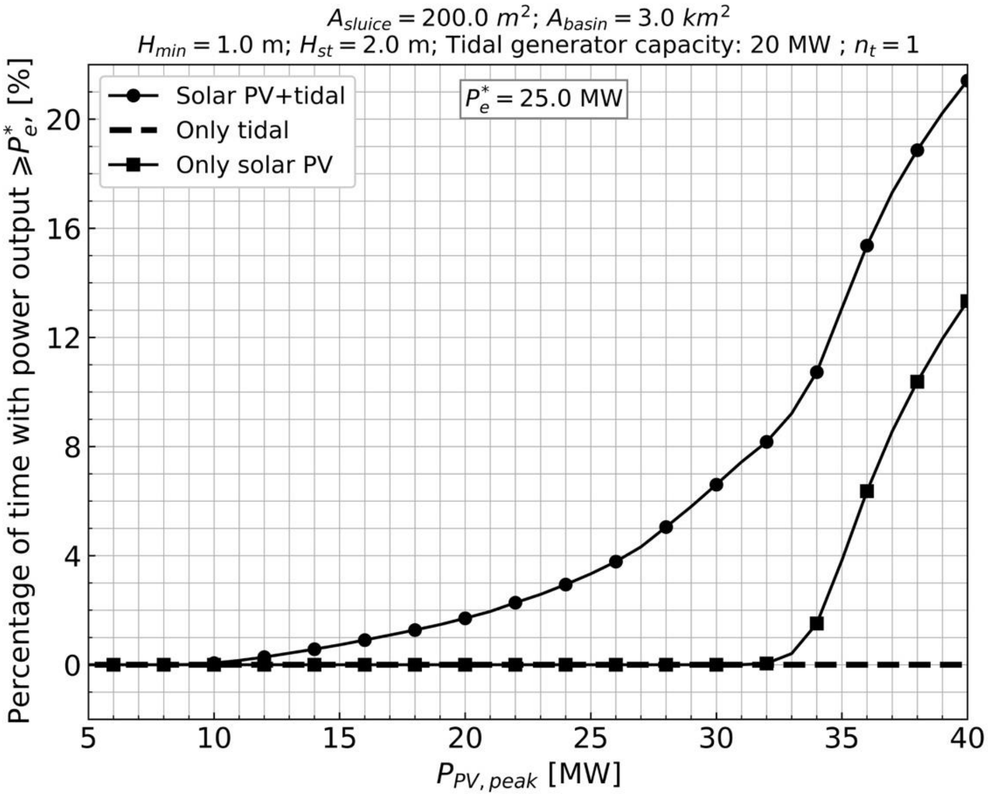

Figure 9. Effect of PV generator size on percentage of the year of power production over a 125% of the tidal nominal power plant.

3.3 *Surplus energy analysis with conventional operation of the SWRO plant*

To minimise the surplus energy by means of adequate design and operation strategy of the desalination plant is a key issue in minimising water costs. Given the current high cost of tidal power production in comparison to that of PV plant, low values of nominal desalination consumptions lead to tidal surplus energy that should be avoided. Besides that, the tidal range plant is not able to produce higher power than that of nominal value, so if the power consumption of the desalination plant equals this nominal power, surplus energy is fully attributable to the PV generator. Figure 10 depicts surplus energy generated by the hybrid system as a function of PV peak power, within a wide range of possible power consumption (P_e^*). Having regard of recommendations from subsection 3.2 and figure 10, further analysis only focuses on cases with electricity consumption of 10-15 MW, thus corresponding to a range of 0.50-0.75% of the nominal tidal power.

Table 4 gives a summary of the analysis considering cases with of nominal consumption of the desalination plant of 10 and 15 MW for peak power PV generators ranged from 20 to 30 MWp and setting a SEC value of 3.5 kWh/m^3 – see cases of nominal power consumption P_e^* = 10, 15 MW (Figs. 6-7) along with Figs. 4 and 10 -. Besides that, table 5 corresponds to SEC value of 4.8 kWh/m^3, being the highest reported concerning Australian desalination plants.

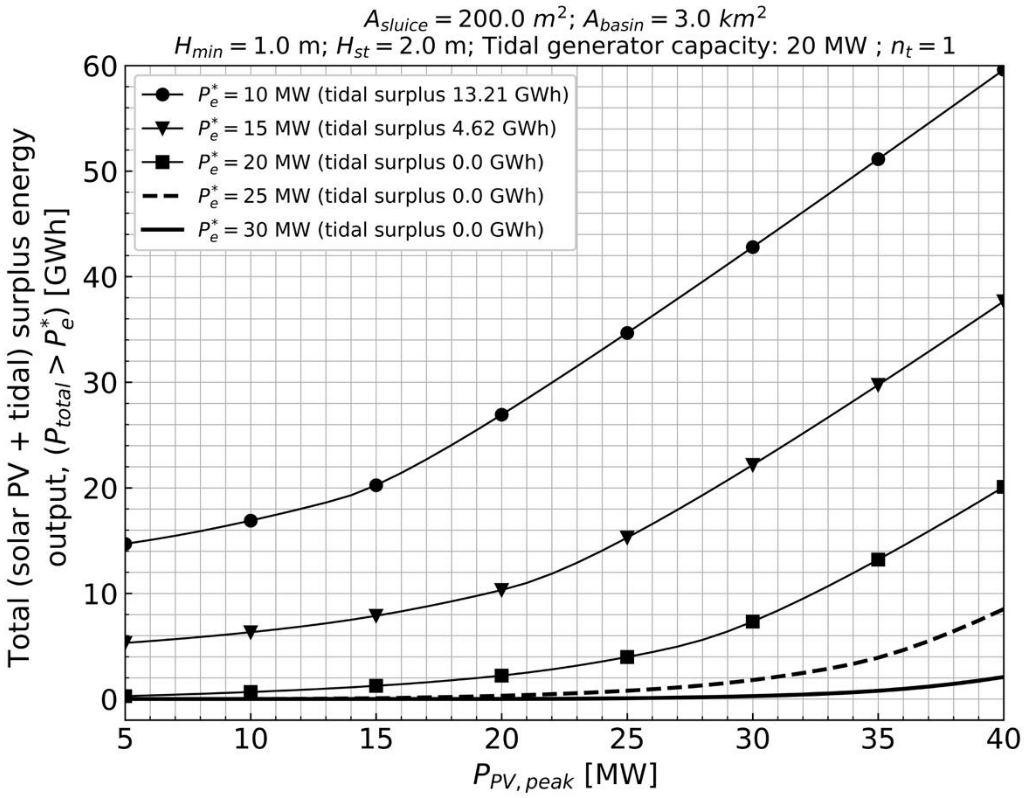

Figure 10. Effect of PV generator size on the total surplus energy if the power consumption corresponds to 50%, 75%, 100%, 125% and 150% of the tidal nominal power plant (20 MW).

Table 4. Annual energy balance of the hybrid tidal range/PV power plant and desalination capacity only operated at full load (SEC= 3.5 kWh/m³) - A_{basin} = 3.0 km², A_{sluice} = 200 m², generator capacity 20 MW (a single turbine) -.

PV generator	30 MWp		25 MWp		20 MWp	
Nominal desalination consumption [MW]	**10**	**15**	**10**	**15**	**10**	**15**
Corresponding nominal capacity [m³/h] – SEC= 3.5 kWh/m³ -	2,857	4,286	2,857	4,286	2,857	4,286
Capacity factor - Figs.6-7 - [% y] (full load)	53	41	51	35	48	25
Water production [10^6 m³/y]	13.26	15.39	12.76	13.14	12.01	9.39
Cost associated to investment - 1,100 $/(m³/d), 15 y - [$/m³]	**0.38**	**0.49**	**0.39**	**0.57**	**0.42**	**0.80**
Total production - Fig. 4 - [GWh/y]	98.8	98.8	90.0	90.0	81.2	81.2
Solar PV production - Fig.4 - [GWh/y]	53.0	53.0	44.1	44.1	35.3	35.3
Tidal energy production - Fig. 4 - [GWh/y]	45.9	45.9	45.9	45.9	45.9	45.9
Energy consumed – associated to water production - [GWh/y]	46.4	53.9	44.7	46.0	42.0	32.9
Surplus energy – production minus actual consumption - [GWh/y]	52.4	44.9	45.3	44.0	39.2	48.4
Surplus to generated energy ratio	0.53	0.45	0.50	0.49	0.48	0.60
Cost associated to total energy production [$/m³]	**1.37**	**1.18**	**1.35**	**1.31**	**1.36**	**1.75**

Table 5. Annual energy balance of the the hybrid tidal range/PV power plant and desalination capacity only operated at full load (SEC= 4.8 kWh/m³) - A_{basin} = 3.0 km², A_{sluice} = 200 m², generator capacity 20 MW A_{basin} = 3.0 km², A_{sluice} = 200 m²; tidal generator capacity 20 MW (a single turbine) -.

PV generator	30 MWp		25 MWp		20 MWp	
Nominal desalination consumption (P_e^*) [MW]	**10**	**15**	**10**	**15**	**10**	**15**
Corresponding nominal capacity [m³/h] – SEC= 4.8 kWh/m³ -	2,083	3,125	2,083	3,125	2,083	3,125
Capacity factor - Figs.6-7 - [% y] (full load)	53	41	51	35	48	25
Water production [10^6 m³/y]	9.67	11.22	9.30	9.58	8.76	6.84
Cost associated to investment - 1,100 $/(m³/d), 15 y - [$/m³]	**0.38**	**0.49**	**0.39**	**0.57**	**0.42**	**0.80**
Total production - Fig. 4 - [GWh/y]	98.8	98.8	90.0	90.0	81.2	81.2
Solar PV production - Fig.4 - [GWh/y]	53.0	53.0	44.1	44.1	35.3	35.3
Tidal energy production - Fig. 4 - [GWh/y]	45.9	45.9	45.9	45.9	45.9	45.9
Energy consumed – associated to water production - [GWh/y]	46.4	53.9	44.7	46.0	42.0	32.9
Surplus energy – production minus actual consumption - [GWh/y]	52.4	44.9	45.3	44.0	39.2	48.4
Surplus to generated energy ratio	0.53	0.45	0.50	0.49	0.48	0.60
Cost of energy consumption [$/ m³]	**1.88**	**1.62**	**1.85**	**1.80**	**1.87**	**2.39**

Considering tables 4 and 5 as a whole, design recommendations for Australian desalination consumption range will be pointed out as follows. Recommended nominal power consumption of the desalination plant around a 50% of the nominal tidal power installed along with PV peak power around 100-125% of the tidal power. Under this design selection, the desalination plant is able to operate about one half of the year, thus avoiding excessive oversizing of the desalination plant. Besides that, the increasing of the PV size from 20 MWp to 30 MWp shows in both cases slight improvement of water production for desalination consumption of 10 MW. Therefore, greater PV systems are discarded.

Finally, tables 4-5 show that ratio of surplus energy to that consumed is quite high. Therefore, there are still opportunities of improving the preliminary design recommended by means of operating the desalination plant at variable power consumption.

3.4 Analysis of SWRO plant operation at variable power consumption

The comparison between annual surplus energy to that consumed allows to propose an adequate selection of operation strategy in the desalination plant having regard of methodology proposed – see section 2 -. Table 6 gives representative cases to study adequate plant sizing taking account of independent operation of auxiliary subsystems as permeate and raw seawater pumping. Note that generation of 10 MW is enough to drive the water production without simultaneous auxiliary pumping. Therefore, the time in operation throughout the year increases up to the value of the capacity factor shown in table 4 for 10 MW. Consequently, the water production significantly increases. The corresponding auxiliary pumping is possible within a power generation range of:

- ≥ 2.5 MW and < 5 MW or ≥5 MW and < 10 MW. Within these ranges only auxiliary pumping systems are able to operate thus allowing power consumption even if there are no water production. Therefore the use of power production increases.
- ≥ 12.5 MW and ≤ 15 MW. This interval of power production corresponds to simultaneous water production and operation of a single auxiliary pumping system.

If power production does not achieve the nominal power consumption (15 MW), those intervals result in higher energy consumption in comparison to the case analysed in table 4. Table 6 shows that the oversizing of the PV field in the case of 30 MW should be discarded since slight benefit in water production does not balance the surplus energy. Besides, the relevance of control strategies based on variable energy consumptions is clear by means of comparing tables 6 and 4.

Table 6. Annual energy balance of the tidal range/PV power plant and desalination plant operated at 2.5, 5, 10, 12.5, 15 MW (SEC= 3.5 kWh/m³) - A_{basin} = 3.0 km², A_{sluice} = 200 m², tidal generator capacity 20 MW (a single turbine) -.

PV generator	30 MWp	25 MWp	20 MWp
Desalination consumption [MW]	**2.5-15**	**2.5-15**	**2.5-15**
Corresponding nominal capacity [m^3/h]	4,286	4,286	4,286
Capacity factor - Figs.6-7 - [% y] (full load)	53	51	48
Water production [10^6 m^3/y]	19.90	19.15	18.02
Cost associated to investment - 1,100 \$/(m^3/d), 15 y - [\$/m^3]	**0.38**	**0.39**	**0.42**
Total production - Fig. 4 - [GWh/y]	98.8	90.0	81.2
Solar PV production - Fig.4 - [GWh/y]	53.0	44.1	35.3
Tidal energy production - Fig. 4 - [GWh/y]	45.9	45.9	45.9
Energy consumed – associated to water production - [GWh/y]	69.6	67.0	63.1
Surplus energy – production minus actual consumption - [GWh/y]	29.2	23.0	18.1
Surplus to generated energy ratio	0.30	0.26	0.22
Cost associated to total energy production [\$/m^3]	**0.91**	**0.90**	**0.91**

Selection of desalination plant size and peak power of the PV plant require further analysis. To this end, table 7 analyses a second case of variable energy consumption considering a nominal energy consumption of 20 MW (5,714 m^3/h). Assumption adopted in relation to total SEC consists in main consumption of 2.34 kWh/m^3, plus 0.58 kWh/m^3 due to permeate pumping plus 0.58 kWh/m^3 for raw seawater pumping. Depending on the power available, the desalination plant consumes:

- 3.3 MW, attributable to either, raw seawater pumping or permeate pumping.
- 6.6 MW, corresponding to simultaneous operation of aforementioned pumping.
- 13.4 MW due to the operation of the core of the process, thus resulting in water production.
- 16.9 MW also with fresh water production and only one of the auxiliary pumping systems.
- 20.0 MW considering full plant operation.

Table 7 in comparison with table 6 points out that the increase in nominal capacity of the desalination plant does not improves results obtained. However, other control strategies might result in enough reduction of surplus energy to achieve better energy balance. Therefore, both control strategy and desalination plant size should be analysed as a whole. Finally, based on tables 6-7, recommended peak power of the PV plant ranges from 100% to 150% of the nominal power of the tidal range plant.

Table 7. Annual energy balance of the tidal range/PV power plant and desalination plant operated at 3.3, 6.6, 13.4, 16.9, 20 MW (SEC= 3.5 kWh/m^3) - A_{basin} = 3.0 km^2, A_{sluice} = 200 m^2, tidal generator capacity 20 MW (a single turbine) - .

PV generator	30 MWp	25 MWp	20 MWp
Desalination consumption [MW]	**3.3-20**	**3.3-20**	**3.3-20**
Corresponding nominal capacity [m^3/h]	5,714	5,714	5,714
Capacity factor - Figs.6-7 - [% y] (full load)	41	37	25
Water production [10^6 m^3/y]	20.52	18.52	12.51
Cost associated to investment - 1,100 $/(m^3/d), 15 y - [$/m^3]	**0.49**	**0.54**	**0.80**
Total production - Fig. 4 - [GWh/y]	98.8	90.0	81.2
Solar PV production - Fig.4 - [GWh/y]	53.0	44.1	35.3
Tidal energy production - Fig. 4 - [GWh/y]	45.9	45.9	45.9
Energy consumed – associated to water production - [GWh/y]	71.8	64.8	43.8
Surplus energy – production minus actual consumption - [GWh/y]	27.0	25.2	37.4
Surplus to generated energy ratio	0.27	0.28	0.46
Cost associated to total energy production [$/m^3]	**0.88**	**0.99**	**1.31**

4 Conclusions and recommendations

Analyses conducted within the framework of this paper proves that SWRO desalination powered by hybrid tidal/PV systems in a favourable location achieves actual water production of one half of nominal production with adequate selection of design parameters. Besides that, considering the predictable nature of tidal range resources and that the surplus energy is mainly produced during the daylight, this RE-desalination technology shows interesting market prospects at medium-large capacity range.

Recommended preliminary selection of main parameters as reasonable values for water desalination studies of conventional seawater desalination plants in Australia (SEC, 3.5-4.8 kWh/m^3) – tables 4-5 - are the following, based on 20 MW of power output: basin area, 3 km^2; sluicing area, 200 m^2; starting head, 2.0 m; ratio of nominal consumption to nominal tidal power around a 50%, and ratio of the PV peak power to tidal power within a range 1.0-1.25 (20-25 MWp). In those conditions, considering 0.28 $/kWh of tidal power production and 0.10 $/kWh of PV power production, costs associated to energy consumption ranged from around 1.35 to 1.85 $/m^3 in off-grid systems whereas the desalination capacity required is double size than that of a conventional energy plant with similar annual water demand.

Besides that, operation strategies that allows variable power consumption of the desalination plant are recommended, if possible, by means of managing the operation of either, the core of the desalination plant or auxiliary pumping – i.e. raw seawater pumping and product pumping -. In this case – tables 6-7 - the recommended ratio of nominal consumption to the nominal tidal power is around 75% with a ratio of PV peak power to tidal power of 1.0-1.25. In this option, the desalination plant is able to operate around the 50% of the year. The cost associated to the hybrid energy generator would be around 0.90 $/m^3 in off-grid systems.

To sum up, per each 100,000 m^3/d of nominal desalination capacity and specific energy consumption of 3.5 kWh/m^3, the recommended hybrid energy generator corresponds to:

- 19.4 MW of nominal tidal power and 19.4-24.33 MW of peak PV power if the desalination plant is able to operate at variable power consumption as described and its nominal consumption is 3.5 kWh/m^3 – table 6 -. At Broome, the expected annual water production would be around one half of the nominal production.
- 29.2 MW of nominal tidal power and 29.2-36.5 MW of peak PV power if the desalination plant operates only at nominal power consumption – table 4 -, being the expected water production at Broome also about one half of the nominal production.

Estimations of water costs require a case by case analysis based on considering the specific scenario of energy resources, economic and financial parameters along with optimising design and operation strategy of the desalination plant, which is out of the aim of this paper.

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