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Integration of tidal range energy with undersea pumped storage

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The deployment of tidal technology is affected by the general bottlenecks associated with all new re-newables in respect of finance and integration with the grid. In this research, a development strategy is defined for tidal range projects based on geodynamics, civil engineering, and economics with the aim of assisting policy makers and industry. Criteria related to hydrodynamics, bathymetry, marine structure safety and cost recovery apply to relevant sites and to real data power prices. The case study described is that of the Bay of Bourgneuf on the French Atlantic coast, where a tidal range power plant of 900 MW could optimally be built with respect to sedimentation, water depth, and tidal coefficients. It has been determined that a 30 m-high artificial dam could maximise the harvestable energy (3 TWh). Numerical simulations show that a tidal plant sized at just 700 MW would be cost-efficient, due to the constraints of the grid and to high power curtailment rates (30%). The expected value of the Levelised Cost of Electricity would be around 200€₂₀₁₆/MWh. Integration into the grid could be improved through addition of an innovative underwater energy storage system, rated to one third of the size of the tidal plant. The economics would improve (the LCOE would drop to 170€₂₀₁₆/MWh) due to lower curtailment and to price arbitrage opportunities. Issues related to missing investor money (>3Bln€₂₀₁₆) and unquantifiable positive externalities such as flood protection, energy independency, and clean energy provision are discussed, underpinning the need for regulator support.

1. Introduction

Increased concerns about climate change, the scarcity of fossil fuels, and high energy prices have reinforced the interest of the European Union for deploying new technologies for renewable energy [1]. Among marine renewables, tidal and wave conversion systems are expected to be deployed the most due to their resource potential and their advanced technological status. By the end 2016, the installed capacities were cumulating 17 MW for tidal energy and 5 MW for wave energy [2,3]. The projections by 2020 are of 71 MW for tidal and 37 MW for wave energy [4].

Tidal energy has a strong potential to produce energy worldwide, but the technology remains largely unexploited [3], due to a set of technical and economic challenges [5]. In France, despite favourable political commitments [6], few initiatives are undertaken to deploy tidal energy, and there is a limited knowledge of the location of the optimal energy potential. This paper aims at

filling the knowledge gap related to the criteria involved in the tidal energy planning, such as the site selection, dam construction, the sizing of the plant, the channel length, dyke features, and basin area to maximise the harvested power. Multidisciplinary competences in geodynamics, civil engineering and economics are applied to a case study in the French region Pays de la Loire. This study expands on the existing literature by using tidal cycles' real data into a cost-benefit optimisation model such as to evaluate the output and to calibrate the storage needed to avoid curtailment.

The literature contains many techno-economic assessments of tidal energy potential and generation costs. The costs are found to be site-dependent, and can vary for example in the UK from 145€₂₀₁₆/MWh to 635€₂₀₁₆/MWh, corresponding to a very high and very low tidal resource potential respectively, in the area of the Bristol Channel and the Severn Estuary [7]. Costs depend on the tidal coefficients and on the opportunity to install sufficient capacity to obtain economies of scale. As a rule of thumb, at least 100 GWh are required to reduce the cost below 140€₂₀₁₆/MWh. One of the largest tidal power plants in the world at La Rance, France (240 MW), generates 500 GWh yearly at a low cost of 40€₂₀₁₂/MWh [8]. Bricker et al. [9] depict the economics of tidal stream energy at

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different locations in Japan and identify potential cost-efficient sites. At 10% discount rate, the cost ranges from 80 to 900\$2016/MWh depending on the scale of devices and the plant location.

Beyond economics, tidal energy planning needs to address the issue of traditional grids to cope with the variability of tidal loads. More stable output could be supplied by optimally distributing tidal arrays within a site or plants across sites with tidal cycles that are out of phase. For example, the tides of the Mersey and Severn estuaries in the UK are almost in anti-phase, with a 4-h delay [10]. However, continuous output can be achieved for only a limited number of days at suitable UK sites, e.g., during peak spring tides [11]; yet, some form of energy storage is needed to ensure constant output [12].

Two main factors drive tidal energy planning with regard to storage, namely the grid available to transport the tidal power and the power-energy quality requirements. Manchester et al. [13] simulated a tidal plant in the Bay of Fundy, Canada, which is one of the best sites in the world in terms of tidal energy potential, constrained by a distribution grid and a wind farm. Interestingly, the storage should represent 100% of the tidal plant capacity to avoid tidal power curtailment, but should be much less than this to avoid diminishing economic returns. Zhou et al. [14] rate storage at the greatest difference between the tidal power produced and the grid power. Storage must be 100% of the tidal plant capacity for providing long term stable output, but 140% of the tidal plant for short term power quality provision. Barbour and Bryden [15] simulated the operation of a tidal plant constrained by a grid rated at 40% at the tidal plant capacity and find that energy storage should represent 60% of the tidal plant in order to avoid the interruption to the tidal power output.

The study could be used to assist the industry in developing a greater understanding of tidal energy. The way this method could apply to other coastal areas depends on the tidal range and the need for dikes building, and on the local prices of raw materials for the infrastructure building. Other factors add such as the market power prices, and the grid network capability to integrate the tidal energy. The French site-specific conditions are 30 m water depth and tidal range velocity of less than 3 m/s. The tidal plant capacity is of 700 MW, and the capacity factor is of 32%. It has an infrastructure cost of 3.3 M€/MW, and faces an average market electricity price of 37€₂₀₁₆/MWh and a limited grid line of 450 MW.

2. Material: tidal range – storage principle

The technology assessed in this paper is a combination of a tidal barrage with a tidal stream device and an undersea pumped hydropower energy storage system. Fig. 1 shows the principle of a tidal barrage (left hand side) and the design of a storage system (right side).

Tidal range system design (Fig. 1 left). Tidal energy technologies can be classified into two categories: tidal stream and tidal range [16]. Tidal *stream*, or tidal current technologies, exploit currents using turbines similar to wind turbines, but stronger because water is much more dense than air. The term ‘tidal *range*’ expresses the vertical difference between high tide and the following low tide. Ideally, a tidal range plant should be located within a large gulf with a shallow basin, but where the tidal range may not be high enough (less than 5 m); an artificial dam can then be built across the mouth of the estuary or bay.¹ Tidal barrages are the more

mature type of tidal technology and comprise most of the capacity installed worldwide (South Korea 254 MW; France 240 MW; Canada 20 MW; China 5 MW, Russia 0.4 MW). The untapped potential is thought to be vast, from several hundreds of GW to 1 TW [8].

The project assumes a generating system of a tidal range plant with a dyke built across a bay, with channels built over the dyke containing several lines of in-stream turbines. In this way, the barrage blocks the incoming and outgoing tides in the coastal basin, while tidal currents are intensified as the water is forced to flow through narrow channels. The tidal plant optimises the amount of harvestable energy using a two-way generating power system, and has a higher capacity factor than unidirectional turbines, e.g. 32% instead of 25% [8]. During the flood tide, the water enters into the basin through the turbines, creating electricity. During the ebb tide, when the water level outside the barrage has dropped sufficiently, water flows out of the basin through the turbines, again generating electricity. Power is thus generated during both emptying and filling; low tide corresponds to basin emptying, high tide to basin filling.

Undersea pumped hydropower energy storage system (Fig. 1 right). Tidal energy is variable, but unlike solar and wind power this variability is highly predictable, with clear and known daily, weekly and annual cycles. However, because there are 3–4 h during each tide where power generation is close to zero, there could be an economic interest in investing in some sort of storage system. This would regulate the output and could exploit any excess tidal power from by a limited power grid, or when the demand is low.

The storage system integrated in this virtual project consists of an artificial basin built along the dyke, a reservoir 25–30 m deep in the sea containing valves, a reversible pump-turbine, and a generator. The undersea pumping makes use of the pressure differential between the sea bed and the ocean surface, according to design of Sintef, a Norwegian research organisation [17]. Other innovative solutions are based on compressed air using underground cavities and balloons, as tested by the Canadian startup company Hydrostor,² or by means of pressure tanks and spheres, as tested by the Fraunhofer Institute in Germany [18].

Ideally, the pressure would be set using depths of 400–800 m, because the greater the depth, the higher the pressure differential. Here, the depth is linked to that of the tidal dyke, i.e., less than 30 m. The reservoir capacity and turbine size will be optimally calibrated against the size of the tidal plant, of the grid line capacity, and the power price volatility (see section 4.1).

3. Methods

3.1. Case study of a tidal-storage plant on the French Atlantic coast

The optimal site characteristics are first considered in terms of tidal range and water depth. The tide must be sufficiently high to drive the stream through the turbines, at a velocity of 3–4 m/s. To minimise the amount of investment required for the dyke, the water depth should be less than 30 m. As for the basin, the bigger the basin is, the larger the tidal energy potential. In practice, the specific nature of the shore topography could constrain the length and depth of the dyke. The technology for building breakwaters (e.g., Tangiers-Med port, Morocco, 2005), dykes, and wharfs in shallow waters (30 m) is mature [19].

For this case study, a number of sites along the French Atlantic coast have characteristics making them ideal for exploiting tidal

¹ The dam could also form a lagoon with an independent enclosure in highly tidal environments (projects are ongoing in the UK). Alternatively the dam could be an open structure built perpendicular to the coast to drive turbines exploiting the difference in the water level created.

² <https://hydrostor.ca/>.

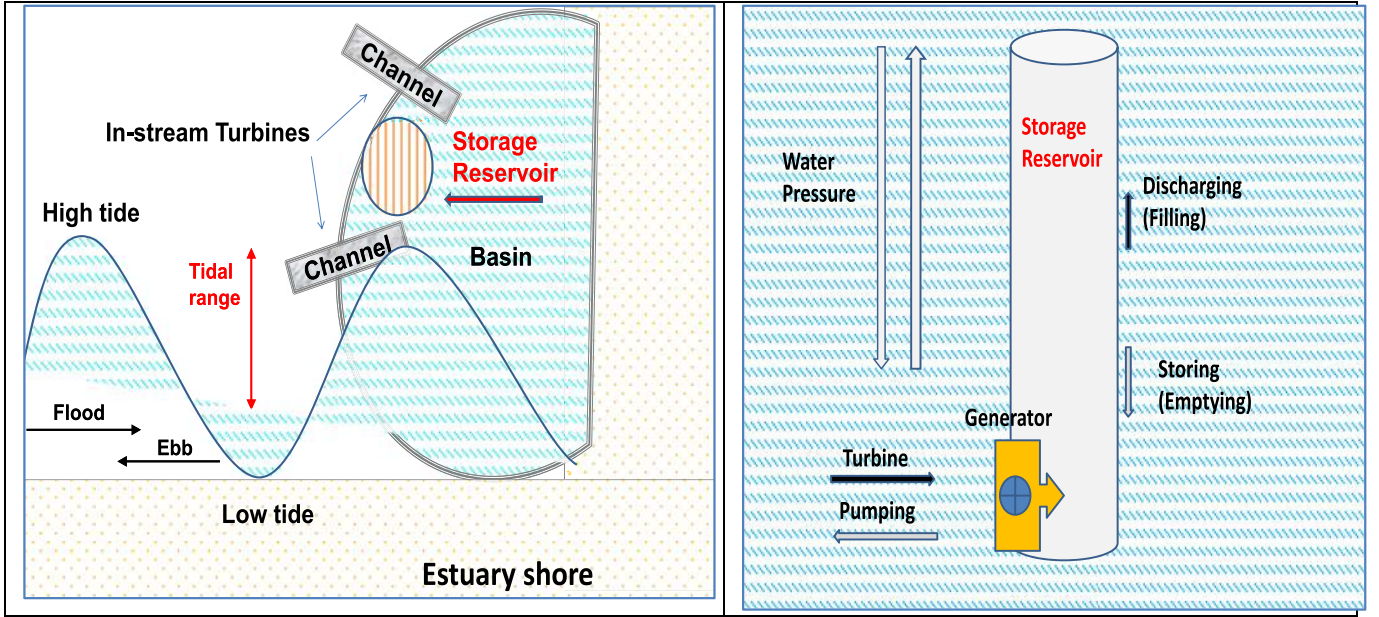


Fig. 1. Tidal range power system with channels over a basin and a storage reservoir (left). Pumped storage system (right).

range energy. Fig. 2 shows three embedded methodologies involving geodynamics, civil engineering and economics used for the site selection and plant sizing.

First, selection of optimal bays was achieved by applying technical filters to the hydrodynamics and bathymetry [20,21].

Secondly, civil engineering models have built the optimal marine structural design and tested the maintenance of the dam [22]. Tests were also conducted to optimise the impact between the dam, the tidal range, and the tidal cycle in the bay, using the software MIKE 21 [23]. It was found that Bourgneuf Bay meets virtually all the specific criteria of low sedimentation, 30–40 m water depth, and a high tidal range. Other sites were also considered, including Pertuis Breton.

Thirdly, the economics of the tidal plant has been simulated by means of technical-economic modelling. The best scenario in terms of investor returns has been ultimately selected for assessment and discussion.

Dyke construction takes place in four main stages: soil preparation with a sand-and-gravel bed, installation of precast concrete caisson by flotation-ballasting and towing, filling the caisson with gravel and sand, and installation of the topside deck [19]. The construction process starts from the coast and the works proceed seawards, with each installed caisson serving as a basis for the installation of the next one.

In line with Lemperiere's (2014) estimate, the design of this tidal range plant maximising the energy potential consists of a 250 km² basin bounded by an artificial dam, and two channels dedicated to in-stream tidal turbines accelerating the velocity to 3–4 m/s. The two channels are 400 m wide and 3 km away from the storage basin. As in Lemperiere [24]; it is assumed that the maximum energy could be harvested by some 300 turbines each rated at 3 MW, installed in 10 rows of 15 turbines in each row in each channel. The turbines are distributed such that the flow rate and velocity are constant throughout the channels. Turbines can operate in either direction and generate at full power for 3 h of each tidal cycle. The tidal range plant and the dam are constructed without gates in order to preserve the intermittency of the natural tidal cycle and to minimise the environmental impacts.

3.2. Technical-economic optimisation process

The programme. A dynamic model is built to maximise the revenue of the tidal-storage operator under the technical and economic constraints of plant operation, tide cycles, transmission grid capacity, and market power prices.

The model is dynamic with 8760 time slices, simulating hour-by-hour the technology operation and the market transactions of the tidal range plant over a period of one year. The model uses linear programming implemented in the Gams software with the Cplex solver.³ The method used for solving the linear problem is a deterministic gradient-free method, where the objective function and the design variables are associated with bounds and constraints in order to ensure the global optimal solution. Symbols are listed at the end of the paper.

The objective function. The operator problem is maximisation of revenues from energy sales over one year, and their extrapolation to the project technical lifetime:

$$Fobj = \max \sum_{h=1}^{8760} p_h Z_h \quad (1)$$

The operator sells the power in the wholesale market under perfect information on electricity prices (p_h). The investor is assumed to be a price taker with no influence on power prices.

Constraints are as follows (Eqs. (2)–(8)):

$$Z_h = Yg_h + St_out_h \quad (2)$$

The hourly power sold on the market (Z_h) is either generated by the tidal plant in real time (Yg_h), or by the storage device (St_out_h).

³ The General Algebraic Modelling System (GAMS) is suitable for modelling linear optimisation problems, being especially useful with large database (<https://www.gams.com>). The GAMS solver Cplex is designed to solve large, difficult problems quickly. These advantages are fully exploited here to solve the power system specific problem of capacity sizing under hourly constraints over the year. Cplex optimizer helps setting the optimal solution of this detailed time decomposition model (more than 158,000 variables) in a short execution time (less than 1 min).

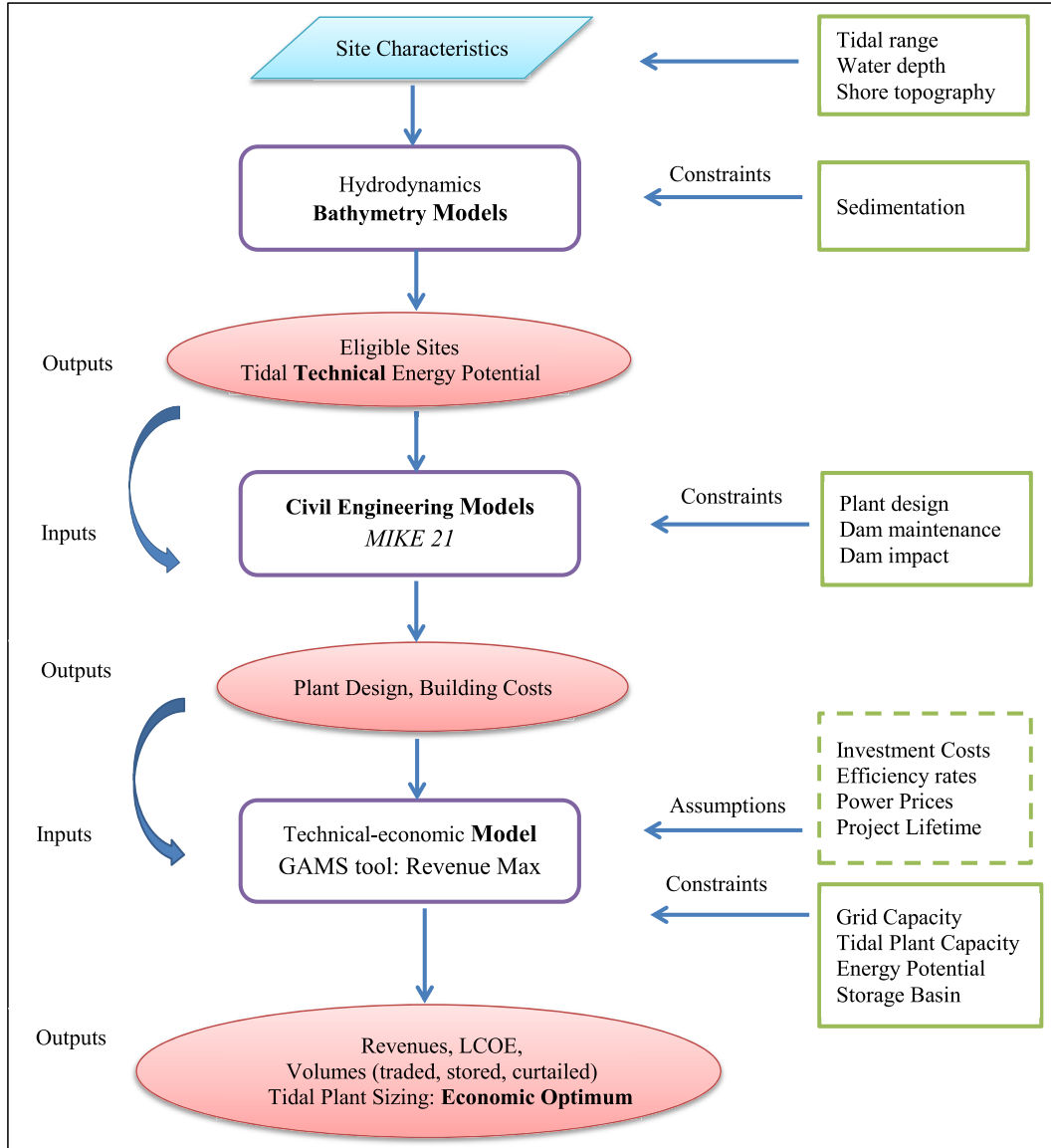


Fig. 2. Multidisciplinary methods used for the site selection and the tidal-storage plant sizing.

$$Y_h = Y_{g_h} + Y_{s_h} \quad (3)$$

The total tidal power (Y_h) is either sold (Y_{g_h}) or used to store the energy (Y_{s_h}).

$$Y_h \leq Y_{cap} \quad (4)$$

$$Y_h \leq Eff_t \cdot (1 - loss_c) \cdot Y_{p_h} \quad (5)$$

Tidal power generation is constrained by the plant capacity (Y_{cap}), and by the natural water inflow, which yields the maximum hourly harvestable energy (Y_{p_h}). To this applies the efficiency of the tidal turbines, set at 85%, and hydro losses recorded in the channels, set at 20%. The farm efficiency is of 68% such as documented in Lempriere [24]; where turbines and rows are tuned to the tidal velocity to maximise the farm's output. The plant potential becomes a function of the turbine's fluid dynamic efficiency, as soundly described in Vennell [25]. Here turbine efficiency is near 90% and losses in the channel can go up to 70%

function of the occupancy rate. Similarly Angeloudis and Falconer [26]; Lisboa et al. [27] assume a turbine hydraulic efficiency rate of 90% in ideal inflow conditions, and losses of 15% due to mainly water friction and turbine unavailability.

$$Z_h \leq G \quad (6)$$

The power sold in the market is limited by the electricity grid line capacity for transmitting the flow to the System Operator (G). The grid is exogenously set at 450 MW, which is the cable capacity planned by the French System Operator [28]; p.26).

Power generation. Tidal power generation is a proportion of the total harvestable energy that could theoretically be generated. The tidal energy potential is given by the difference in water level between the sea and the basin. The harvestable potential is estimated based on the basin area, the efficiency of the tidal turbines, and the real data on hourly tidal coefficients for the year 2014 as documented by the French Hydrographic and Oceanic Marine Service (SHOM). Fig. 3 shows the estimated harvestable energy

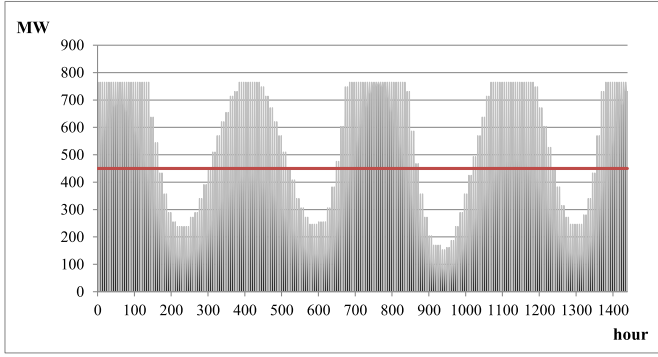


Fig. 3. Harvestable energy potential of a 900 MW tidal range plant (grey area) constrained by a grid line of 450 MW (bold line) during January–February.

potential for January and February 2014.

The effective generation is obtained from the overlap between the area of harvestable energy potential and the area below the grid capacity, i.e., the grey area below the bold line. The energy in excess of grid capacity (i.e., above the bold line) will not be generated because it cannot be transported. Note that the theoretical generation is not constant and depends on the tidal intensity. Cycles of almost 6 h (for semi-diurnal tides like those on the French Atlantic coast) correspond to the rise and fall of tides. Longer fluctuations depend on the tidal intensity varying between weeks or months due to the inclination of the earth related to the sun and the moon.

Storage operation. The dynamic operation of the charging-storing-discharging program implies pumping water out to empty the reservoir (charging), or allowing the water in to generate the electricity (discharging):

$$St_h = St_{h-1} + (Ys_h \times Eff_p) - St_{out_h} / Eff_g \quad (7)$$

When tidal power is in excess and cannot be fed into the grid, the electricity is used to *charge* and *store* the energy by pumping the water out of the storage reservoir through valves, back into the main basin. When power is required, the storage system is in a state of *discharge*: the valves are opened in the empty reservoir and the water flows in, turning the turbines and generating electricity. The discharging ends when the reservoir is full. A reversible pump-turbine system is designed to operate alternately as a pump and a turbine. Hence at efficiency rates of 0.9 for each Eff_p and Eff_g parameters, the round-trip efficiency of the storage system is of 0.81 [17].

Full storage occurs when the reservoir is empty:

$$St_h \leq St_{cap} \quad (8)$$

The size of the reservoir (St_{cap}) is limiting the capacity to store the energy, and it is optimally determined by the income maximisation investor program. It is assumed that the storage plant is charged for free from the tidal plant, since the same entity invests in both the tidal plant and the storage system.

$$Curt_h = Yp_h - Y_h \quad (9)$$

When the tidal range power exceeds both the storage reservoir and the electricity grid capacities, the tidal energy is curtailed and tidal range turbines are stopped.

3.3. Cost calculation

The economics of the tidal range project is assessed using two indicators, one based on costs, and one based on both costs and revenues. The former indicator is the Levelised Cost of Electricity

(LCOE) and the latter includes the Net Present Value (NPV) of the benefits (see the Appendix for details). The LCOE minimisation program is used for capacity sizing of each tidal plant, storage reservoir, and pumping turbines. The NPV maximisation programme is used to optimise the tidal-storage operation based on the price volatility in a given year. Prices in the very long run are of course subject to uncertainties, thus revenues and NPV might be highly unpredictable.

Alternative indicators could be used such as the additional costs with balancing services and grid reinforcement, or the avoided cost, which a system would face for installing other generators (EIA, 2017; IEA, 2015). Yet, estimating system-wide cost would require dispatching models of all technologies in the electricity mix, such as to compute the cost when the system operates without the tidal energy option under evaluation. Existing studies do not integrate however specifically the tidal energy due to large uncertainties about its development pathway and the site location.

This study is focused on the generation cost of the tidal energy from the perspective of an investor, while admitting that numerous factors are not considered. For instance, the LCOE will be used to evaluate the tidal energy in both cases, with and without storage. In fact, the two cases are not directly comparable from the grid perspective, since the storage provides more stability and has therefore a different system value, e.g. higher.

Tidal facilities have very high infrastructure costs. To set up a tidal plant of 1050 MW would cost about 1.2Bln\$, mainly due to the construction of the barrage. The proposed 8000 MW Severn Estuary barrage system in the UK would cost US\$15 billion, the 2200 MW tidal project in San Bernardino Strait in the Philippines would cost US\$3 billion [29], and the tidal lagoon scheme in Swansea Bay is estimated at £1.3 billion [30]. The construction costs for La Rance were around USD₂₀₁₂ 340/kW, resulting in a low electricity production cost of 40€₂₀₁₂/MWh due to the natural site conditions minimising the need for artificial infrastructure [8].

Costs can vary over time, either upwards due to the increased costs of failure, or downwards due to learning effects [4,31]. Tidal energy devices can be evaluated on a scale of technological ‘readiness’ at around 6 out of a maximum of 9 for mature technologies like natural gas turbines or some on-shore wind power devices, so further improvements could be made. Although some estimates show tidal range plants close to commercial viability [4,32], the cost of construction can still make projects unprofitable, especially in deep water, where the cost of the dam alone can amount to two thirds of the total project cost

The cost of a 900 MW tidal plant with a basin could amount to 4400€₂₀₁₆/MW (see Table 1), which is close to the level for tidal

Table 1
Tidal range-storage cost structure, by component.

Plant	Cost	Technology	Size	Total Cost M€
Tidal + Dam	Capex	Tidal range farm		
		Tidal turbines	900 MW	1200
		Basin		
		Two Channels	2 × 800 m ³	750
		Channel Dyke	4 km	200
		Coastal dyke	6.4 km	640
		FOM		
(% of Capex)	Tidal range farm	10%	120	
	Basin	8%	96	
	Total cost of the tidal plant without storage		3006	
Storage	Capex	Reservoir	1 GWh	150 M€
		Pumps + Generator	1 MW	0.8–1 M€
	FOM	Reservoir	8%	
		Pumps + Generator	8%	

Source: Lemperiere [24].

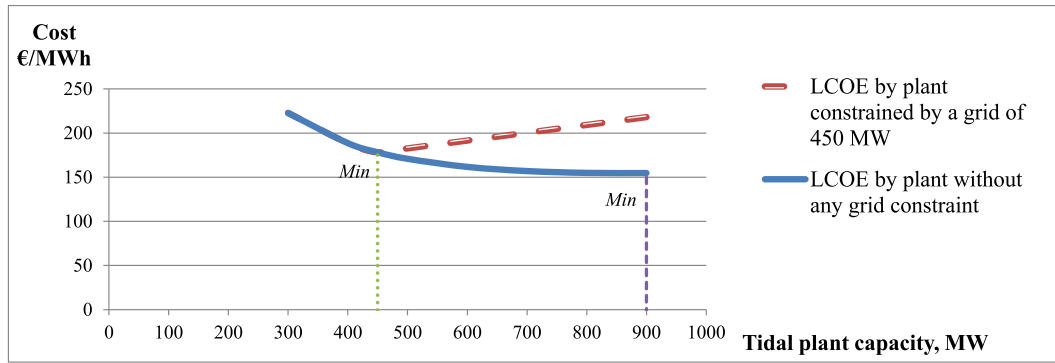


Fig. 4. LCOE of the tidal plant constrained by the grid at different capacity rates (dashed line) and LCOE of tidal plants without any grid constraint (bold line).

stream plants in their commercial phase as documented in Vasquez and Iglesias [33]; but much lower than the levels documented in Ademe [34]. Johnstone et al. [35] defend tidal cost projections of about $4000\text{€}_{2012}/\text{MW}$, but high opex costs can also apply due to expensive maintenance requirements for complex engineering systems, device operation, and environmental control systems.

In this economic model, the tidal plant has variable operating costs close to zero, but significant fixed costs (FOM), involving staff with specific skills in marine environments, expensive equipment, vessels and materials. These costs depend on the site specificities (tidal velocity, weather, offshore distance), and on the system geometry and fatigue [36,37]. To these add decommissioning (2.5% of the capex), interconnection to the grid ($1000\text{€}_{2016}/\text{MW}$ in Ref. [34], and the cost of marine environment impact studies (3M€_{2016}).

Construction of the channels includes 1 m of soil coating, 25 gates for each channel, and 4 km of lateral dyke, for a total cost of 750M€ , covering the cost of feasibility studies and unpredictable delays during construction (20%).

The storage reservoir has a unitary cost of $30\text{M€}/\text{km}$ of dyke. To determine the cost of the storage capacity, it is assumed that 1 GWh of storage requires 150M€ [24]. The total cost of storage is based on a unitary cost and for the sake of simplicity does not include economies of scale.

The lifetime of tidal turbines is around 30 years, while that of the barrage is 120 years. Additional investments are foreseen to replace the turbines once every 30 years, i.e., the plant will be renewed three times during the lifetime of the barrage.

The tidal range plant investor is assumed to share the total amount of capital between the company's own capital and debt. The Weighted Average Cost of Capital (WACC) includes the cost induced by borrowing the capital, and represents the minimum return that the investor must earn on the expected asset base. The heavy and risky investment required by the tidal project leads to levels of 10% for each WACC and the discount rate. This is relatively higher than the social discount rate (around 3.5%) or the private discount rate e.g., 6.5% in Ref. [32].

The power price database is composed of the real hourly power prices data in the year 2016 on the spot market (Expexspot⁴). The data show large extreme values such as high peak prices ($874\text{€}/\text{MWh}$) and negative values ($-10\text{€}/\text{MWh}$), but with relatively low average ($37\text{€}/\text{MWh}$).

4. Results

Inputs to the model are the technological parameters of the

tidal-storage system (plant size, efficiency, lifetime, costs) and external factors to the plant such as the network grid and the market power prices. The model assumes successively fixed rates of the tidal plant capacity (from 900 MW down to 300 MW) and endogenous storage volume.

Outputs of the model are the optimal capacity of the tidal plant constrained by a grid line and the storage volume which would maximise the revenues of the tidal operator. Hourly results are the output of the tidal-storage system, the power curtailed and the price arbitrage of the operator between selling the power on the market and storing it for later use.

4.1. Tidal-storage sizing

Engineering optimisation shows that construction of the dam would allow installation of 900 MW of tidal range turbines to harvest the entire energy potential. Nevertheless, combining the hourly technological potential with the economic criteria leads to a tidal plant capacity of less than 900 MW. Fig. 4 shows the economic outcome of successive tests conducted for different tidal range capacities (LCOE).⁵

For a given grid line of 450 MW, the best cost-efficient configuration is the tidal range capacity equivalent to the grid line of 450 MW, yielding a unitary generation cost of $178\text{€}/\text{MWh}$. Fig. 4 shows that without any grid constraint, the generation cost decreases with the capacity installed, due to important economies of scale.

The system design needs further trade-offs between the investment into the grid reinforcement and the grid usage rate. In principle, the higher the interconnection capacity, the lower the usage of the line, as shown in Table 2.

The capacity factor indicates the usage of the asset over one year and is calculated by dividing the yearly power generation by the capacity installed and the number of hours in the year. Calculations were undertaken for a 900 MW tidal plant for different grid line sizes.

Two investors have opposing interests, namely the System Operator who owns the grid line and the energy operator who owns the tidal plant. The aim of both parties is to maximise the usage rate, but their programmes are inter-related. For a maximum capacity grid of 900 MW, the entire power flow can be transported, implying a zero curtailment rate, but a low capacity factor of the grid, 32%. A low grid capacity of 300 MW improves the capacity factor of the grid but decreases the usage of the tidal plant.

⁴ https://www.epexspot.com/fr/donnees_de_marche/intradaycontinuous (last accessed February 2018).

⁵ Optimisation results have been generated with the software Gams and exported to Excel 2013. All the tables and figures which are next displayed have been created in Excel based on the results obtained with the software Gams.

Table 2
Grid line capacity and effects on power transported for a tidal project of 900 MW.

Grid, MW	900	800	700	600	500	450	400	300
Tidal power generation, GWh	2553	2446	2312	2145	1937	1811	1669	1342
Capacity factor, Grid	32%	35%	38%	41%	44%	46%	48%	51%
Capacity factor, Tidal	32%	31%	29%	27%	25%	23%	21%	17%
Curtailment rate	0%	4%	9%	16%	24%	29%	35%	47%

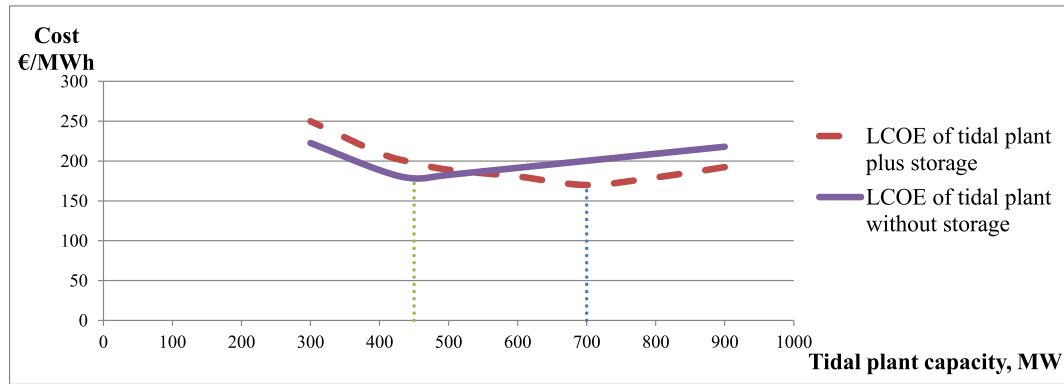


Fig. 5. LCOE of the tidal plant with storage (the dashed line) and without storage (the continuous line) at different capacity rates of the tidal plant under the constraint of a grid of 450 MW.

The implementation of a sea storage plant allows using the excess power. The optimisation of the new tidal-storage system is done by successive tests of different tidal plant capacities, again from 900 MW down to 300 MW. The storage volume is endogenously set at the highest revenue level of the system operator.

Fig. 5 shows the cost optimisation for different power plant sizes with and without storage, under the constraint of the grid line. Results show that a 700 MW tidal range plant equipped with storage would return the best economics, i.e., the lowest LCOE (174€/MWh). The outcome in terms of infrastructure is a volume of storage of 624 MWh or 19 Mm³ (0.75 km²), and pumping-generating turbines of 250 MW. The optimal size of 700 MW tidal range plant will represent next the study case.

4.2. Tidal-storage operation

Installing 250 MW of storage generator next to the 700 MW tidal plant would allow the system to absorb 293 GWh of tidal power, and to supply 2.5 h continuously at full power. Note that without storage, the curtailment flow is 308 GWh due to the grid line limit, while adding storage reduces the curtailment to 30 GWh.

Aggregated results show that a 700 MW tidal range plant without storage would generate 2.3 TWh yearly. The 450 MW grid line restrains the load factor to 33%, while the storage increases it to 37%. Fig. 6 shows that storage allows the tidal operator to have a firm capacity of 250 MW locally, or a continuous power supply of both the tidal plant and the storage discharge. The number of hours with more than 250 MW supply increases by 34% with storage support.

It must be noted that the selection of March for representing the operation of the tidal-storage plant is made with respect to low tides during this period, in order to highlight the mechanism of the model. During this month, the operator makes more frequent use of the arbitrage option between the market and the storage.

Tidal range being coupled with storage, the plant operator can make the arbitrage between selling the tidal power to the market or storing it for free and selling it when prices increase. Due to losses incurred during charging and discharging, priority is given to the

tidal power fed into the grid. The storage of the power in excess represents the highest proportion of the energy stored (95%), while the remaining flow (15 GWh) represents the power stored in response to the power price differential and to strategic market decisions. A loop into hourly arbitrage shows the energy flow optimisation triggered by the price vector.

The plant operator complements the output of the tidal range plant with the storage discharge in particular during local high-price periods, as seen in Fig. 7. The tidal range power is stored whenever there is an excess provided that the storage can absorb the flow. Charge-storage-discharge cycles are performed during short-time periods and have no long-term purpose, over seasonal cycles for instance. Since the tidal operator has no commitment to supply power continuously, it might occur that a proportion of the tidal power is stored instead of being sold to the spot market; or during periods of low power prices, the power stored might not be discharged due to price increases forecast in the short term.

4.3. Economics of tidal range-storage power plant

Numerical simulations show that adding a storage system to the tidal plant improves the unitary cost (the LCOE decreases from 200€/MWh to 174€/MWh; see Table 3). This means that the avoidance of a significant power curtailment such as 293 GWh outweighs the investment cost associated with the storage-generation infrastructure. The capacity factor of the storage basin is rather low, 13%, which allows some room for improvement if additional projects with variable inflows are connected to the system, such as offshore wind farms for example. However, the amount of power stored seems sufficiently valuable to decrease the tidal generation cost.

The market power price is a key driver for the tidal-storage profits, which are here expressed in terms of NPV. Price level is on average rather low (37€/MWh in 2016) compared with the levelised net present value of the benefits. The levelised NPV indicates that the loss of the operator by unit of output (-137€/MWh). The aggregated present value of the benefits is negative, with or without storage, due to the high infrastructure costs and

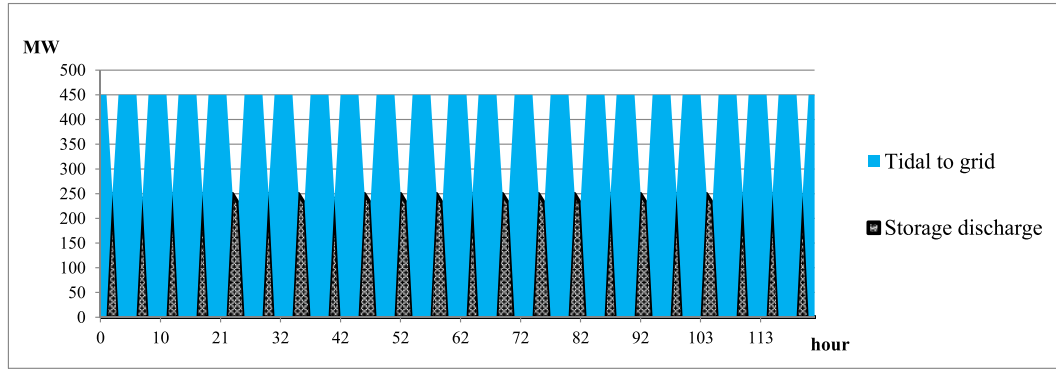


Fig. 6. Selection of 5 days in March with continuous supply of the tidal-storage plant.

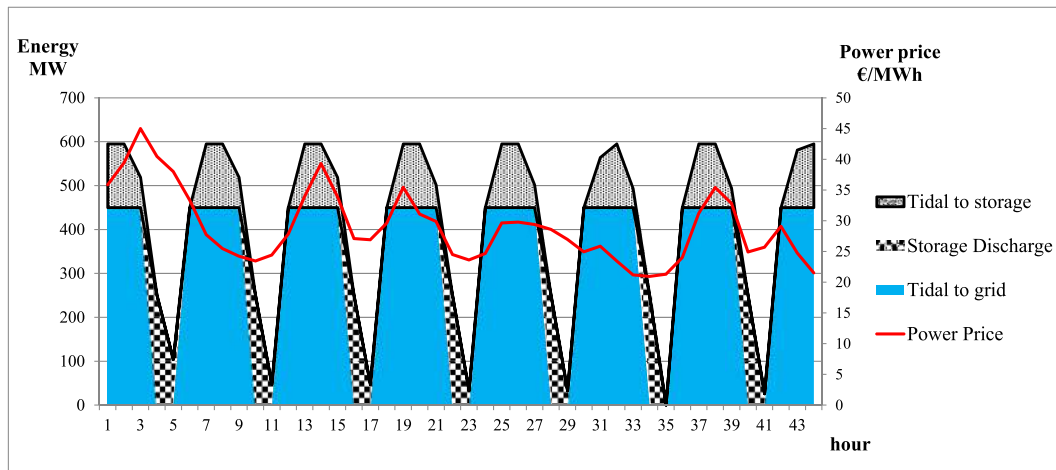


Fig. 7. Price arbitrage between the energy sold in the market and the energy stored over 48 h.

low market power prices. The levelised NPV shows better values in the case of storage, due to a higher power volume (+14%) over which the loss is spread.

Storage allows better integration of the energy. Power curtailment, which is a cut in the tidal power generation due to the grid line limit, is higher before installing storage (13% of the harvestable energy), and improves with storage installation (1%). The usage rate of the grid improves as well, increasing from 51% to 57%.

Our results are in line with the cost projections of similar studies. The current demonstration projects have high generation costs, in the range of 250–470€/MWh [8], but these are expected to decrease with capacity deployment and the improvement of the load factor. Poyry [32] defends an LCOE in the range 129–235€/MWh for tidal plants located in the UK. JRC [4] sets an LCOE between 500 and 700€/MWh for the current installed capacity, but estimates lower levels in the future, of 100–150€/MWh. Johnstone et al. [35] show projected values between £138/MWh and £222/MWh for return on investment rates ranging from 0 to 12%, while Vasquez and Iglesias [33] consider that a strike price of £280–300/

MWh is required to make the technology financially attractive.

Costs are site-specific and vary with their location, labour and capital costs, national regulations, and administrative procedures. For comparison, wind and solar power have generation costs in the range 70–125€/MWh (onshore wind), 110–165€/MWh (offshore wind), and 100–300€/MWh (solar). The current cost of tidal power is obviously much higher, but the comparison must also be considered with respect to regional potential, predictability, technological readiness level, and the diversity of the technological mix.

The amount of investment preventing the operator from attaining profitability is generally referred to as the *missing money* [38]. The high level of missing money is largely due to the capital required to start construction of the barrage and could block project deployment. Moreover, the project might not be attractive due to its long payback periods. This problem could be solved by government funding. In this way, once the construction of the barrage is complete, the only investment costs are in the generation turbines. Assuming that the government gives financial support to dam building, the LCOE for the tidal operator is 56€/MWh without

Table 3
Aggregated economic indicators for a 700 MW tidal plant.

Study case	LCOE €/MWh	NPV M€	Levelised NPV €/MWh	Capacity factor, Tidal plant %	Capacity factor, Storage %	Curtailment rate %
Tidal plant with storage	174	-3126	-137	37%	13%	1%
Tidal plant without storage	200	-2873	-143	33%	-	13%

storage, which is comparable to the costs of conventional and mature technologies.

5. Discussion

The impacts of tidal-storage plants are regional, but their effects are also notable at the system-wide level, from social and political perspectives.

Locally, impacts would be positive in terms of the regional dynamics, on jobs, education, tourism, flood defence, and the protection of human life, housing, buildings, and mooring space for boats. The power system operator could benefit from a secure energy supply with high forecast precision of the variability of the tidal energy. A tidal range plant with storage would supply balancing reserve and both base-load and peak-load, thereby replacing gas- or coal-fired power plants. Society in general would benefit from clean energy generation and higher national energy independence, given that most primary energy in France is imported.

Local impacts could also be negative, however, in particular with concern to the fishing industry and to the environment. Further work is needed to simulate the impacts on the ecosystem and to consider the experience gained from the French tidal plant at La Rance on sediment deposition and site maintenance. However, projects such as the tidal lagoon scheme in Swansea Bay (in Wales, UK) have succeeded in attracting the consent of the marine industry, local authorities and the general public [30]. This 240 MW project could exploit the opportunities afforded by lagoons by implementing marine community farms and reef regeneration, and developing tourism, cultural activities, cycling, sailing, and so on.

Tidal barrages could be less popular locally; the barrage project in the Severn Estuary in the UK was eventually rejected due to a lack of clarity on environmental and economic impacts [39]. *In-stream* tidal energy instead enjoys better social acceptability as shown by the survey conducted among residents of the Puget Sound area in the USA who broadly support tidal energy R&D [40]. By means of a choice-based experiment conducted in the Ria de Ribadeo estuary in Spain, Vasquez and Iglesias [7] found general support from households in the area, although by disaggregating the responses of residents they revealed that individuals living in the immediate vicinity of the estuary showed a certain degree of opposition (the NIMBY effect). For tidal barrage projects to be accepted, other benefits must be made clear [8], such as flood defence in the Netherlands (the Tidal Testing Centre at Grevelingen lake), flood mitigation and agricultural applications in South Korea (Sihwa lake barrage), or road transportation in France (the highway over the tidal barrage at La Rance).

Related to the climate change-related events, bays and estuaries such as the Bay of Bourgneuf are of particular concern, because they are more vulnerable than other coastal systems [41]. On a global scale, they are hotspots of coastal vulnerability, in that rising sea levels have already had a strong impact on the coastal landscape, in terms of coastal retreat [42]. Topography, sand bays and the location of real estate in estuaries due to intense tourism and urbanisation are among factors of vulnerability. The effects of sea-level rise may be aggravated when associated with flooding, as noted for the Pays de la Loire region where several coastal communities are facing marine submersion hazards. In 2010, storm Xynthia submerged many low-lying areas below an altitude of 4.50 m, and caused considerable damage to homes as well as the death of 41 people [43].

When barrages are seen as a public good, the State can involve by means of credits, loan schemes and subsidies for dam building. Examples of state support are the green loan guarantee program in the U.S. [40], contracts for difference, or feed-in tariffs in the UK

[44]. In France the feed-in tariff level for tidal energy projects support a level of 150€/MWh, which is guaranteed for 20 years [45], although this is still less than the amount needed for investors to achieve profitability.

Ultimately, decisions on deployment tend not to be market-oriented, because the power market signals are too weak to trigger investments. Politics and the support of the general public are essential for deploying tidal energy technologies. In the absence of any action on climate, the social cost will increase due to higher costs related to energy dependency, carbon emissions and climate change; their reporting should therefore complement the information on the benefits of tidal energy while planning for development consent progresses.

6. Conclusions

Any assessment of tidal range energy must include complex research on available technologies, hydrodynamics, bathymetric surveys, simulations of marine structures, and economic estimations. The application of a technical economic tool to the French Atlantic coast shows that a tidal range power plant could be built in the Bay of Bourgneuf, optimally selected with respect to sedimentation, water depth, and tidal coefficients. Economically, a 700 MW tidal range plant would record the lowest generation cost, which could further be reduced by implementing an undersea pumping and storage system, based on an innovative approach exploiting ocean pressure differentials.

A dynamic optimisation model simulating the operation of a tidal range-storage plant shows that the annual harvested power flow would be 2 TWh. The use of highly predictable tidal energy and associated technologies can contribute to the accurate sizing of the components. 250 MW of storage would allow the system to absorb some 290 GWh, which would otherwise be cut due to the grid line limit. The curtailment rate is reduced from 13% to 1% with storage support. The unitary cost decreases from 200€/MWh to 174€/MWh, but discounted losses remain high, more than 3Bln€, because of low market power prices.

Cost indicators might not be the only performance indicator used when considering tidal energy, however, because several societal exist, such as competitiveness, growth and climate mitigation.

Supportive regulatory policies could take the form of public-private partnership as a means of financing the heavy investment of dams, or market-based tools could be used such as contracts for difference or feed-in tariffs. Without basin investment for instance, an investor would record a generation cost of 56€/MWh, which is of the same order as mature energy plant costs.

Tidal technology deployment faces the general bottlenecks of new technologies related to finance and markets, as well as more specific ones related to ecological implications. State support for research activities and large-scale demonstration projects could contribute to a further reduction of upfront costs and market risks, while public information on the experience of the La Rance tidal plant could improve understanding of the impacts on the ecosystem. French know-how in building and operating tidal plants is well established, as has been proved by the construction of the first and largest tidal plant in the world at La Rance in the 1960s. French experience in civil engineering, hydropower systems, and large energy storage, together with various projects currently being undertaken offshore are some of the assets that justify state involvement in tidal energy deployment. New industrial perspectives could open up in front of the significant tidal energy potential, estimated at several hundreds of GW worldwide [8].

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Nomenclature

Symbols, Index

h hours over one year (1–8760)

Variables (Outputs)

$Fobj$ the objective function of the tidal operator
 $Curt_h$ output suppression (MW·h)
 St_{out_h} hourly power generated with the storage system (MW·h)
 St_h energy stored at hour h (MW·h)
 St_{h-1} energy stored at hour $h-1$ (MW·h)
 Z_h hourly power sold on the market (MW·h)
 Y_h hourly tidal power generated (MW·h)
 Yg_h hourly tidal power sold to the market (MW·h)
 Yst_h hourly tidal power stored (MW·h)

Fixed Variables (Inputs)

G grid line capacity (MW)
 ph hourly market power price (€/MWh)
 St_{cap} the size of the reservoir (MWh), St_{cap} – the size of the reservoir (MWh)
 Y_{cap} tidal power plant capacity (MW), Y_{cap} – tidal power plant capacity (MW)
 Yph hourly tidal energy potential (MW·h)

Parameters

Eff_t efficiency of turbines of tidal range plant
 $loss_c$ hydro loss rate in the channels
 $Effp$ efficiency of the turbines pumping the water
 $Effg$ efficiency of turbines generating the energy stored

Appendix A

Levelised cost of electricity (LCOE). The LCOE is the net present value of the total cost of the project divided by the quantity of energy produced over the system lifetime. It reflects the cost of generating 1 MWh and it is expressed in €/MWh:

$$LCOE = \frac{\left(\sum_{t=1}^T \frac{Opex_t}{(1+r)^t} \right) + CAPEX \times WACC}{\left(\sum_{t=1}^T \frac{EG_t}{(1+r)^t} \right)}$$

Opex represents the variable costs which in case of renewables relate mostly to operational cost than to input costs. CAPEX indicates the costs related to capital, including fixed costs for operating and maintaining the tidal-storage plant, and EG is the energy sold on the market.

The Weighted Average Capital Cost is as follows:

$$WACC = \frac{A}{A+E}r + \frac{E}{E+A}i = \omega_A r + \omega_E i$$

The investment is $A + E$, where A is the investor capital, E the debt amount, r the discount rate, i is the own capital discount rate, ω_A is the proportion of own capital, and ω_E is the proportion of debt, set at 0.75 and 0.25, respectively.

Net present value (NPV). The NPV indicator is the discounted value of all revenues during the economic lifetime, net of fixed and variable costs, related to capital, operation and maintenance.

$$NPV = \sum_{t=1}^T \frac{Revenues_t - Opex_t}{(1+r)^t} - CAPEX \times WACC$$

A derivative indicator is also used to set the economic value for the investor per MWh of energy produced, termed the specific NPV:

$$NPV_{specific} = \frac{\left(\sum_{t=1}^T \frac{Revenues_t - Opex_t}{(1+r)^t} \right) - CAPEX \times WACC}{\left(\sum_{t=1}^T \frac{EG_t}{(1+r)^t} \right)}$$

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