Optimal Operation of a Tidal Lagoon as a Flexible Source of Electricity

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Abstract— **As the demand for electricity and the need for power systems flexibility grow, it is crucial to exploit more reliable and clean sources of energy to produce electricity when needed most. Tidal lagoons generate renewable electricity by creating an artificial head difference between water levels on the seaside, driven by tides, and water levels inside the basin, controlled by flow through the structure. Depending on the level of sea water, power generation from a tidal lagoon can be controlled, i.e. shifting power generation in time. This paper aims to investigate the operation of a tidal lagoon in response to the fluctuating electricity prices. By developing an optimal operation model of the tidal lagoon, its schedule in the day-ahead whole sale electricity market was optimized to achieve the maximum profit. The Swansea Bay tidal lagoon with ebb-only generation was used as a case study. It was demonstrated that by exploiting the flexibility offered by tidal lagoons, they can achieve a higher profit in the day-ahead market and provide energy system with flexibility, although their total electricity generation is reduced.**

Keywords—tidal lagoon, tidal energy, optimal operation scheme

I. INTRODUCTION

The United Kingdom faces an unprecedented challenge to provide reliable and clean energy in the coming decades. Many renewable energy resources (RESs), such as wind and solar energy, have been deployed to meet power demands with less greenhouse gas emission. However, the highly variable and unpredictable nature of these RESs often brings difficulties to the economical and secure operation of power system. In contrast, tidal energy is known for its high predictability. Many tide-related generation technologies can provide energy with less uncertainty, which could act as a reliable energy source for the power system. As the demands for power supply and system flexibility increase, it is wise to bring more tidal energy into the energy industry.

Tidal lagoon, a less-exploited power generation technology, has been brought up several years ago as an alternative to the tidal barrages. It captures the potential energy from the water level difference and generates electricity. Although one of the first lagoons proposed to be built, namely Swansea Bay Lagoon, was not approved by the British government in 2017, a new improved project at the same location has just been announced recently. This implies the great confidence from the government on this novel generation technology and is also a reminder for the academia and industry to dig deep into tidal lagoon.

Many studies on the design, control, simulation and analysis of tidal lagoons and its precedents have been carried out. Studies on the tidal energy resources, especially around the UK's western coastal area have been carried out decades ago [1], as well as the environmental and social impacts of this technology [2,3]. The design of tidal barrage, which is also used by tidal lagoons, has been developed in the 1980s [4]. There are also numerical models (e.g., 0-D model and 2-D model) that have been developed to simulate the optimal operation of tidal lagoon [5,6]. The contribution of tidal energy to the RES-embedded energy future of the UK has been assessed, too [7]. The existing researches focus on the tidal lagoon itself and normally pursue the maximisation of generation output. There has not been much discussion on how the tidal lagoon will integrate to the power system and react to the energy market. How much energy should a tidal lagoon provide during each time period? How to ensure a tidal lagoon generating power when energy is most needed, instead of simply maximizing energy production? How much energy can a tidal lagoon store and how does the energy storage change with the sea level going up and down? There are still some research gaps that haven't been explored yet.

To address some of the aforementioned challenges and lay the foundation for future studies on the tidal lagoon, this paper explores the optimal operation scheme of a tidal lagoon in response to wholesale electricity prices. By constructing an optimisation problem with the goal towards the maximum profit from power generation, a day-ahead operation scheme of a tidal lagoon is obtained. The head differences and number of active turbines are adjusted by the tidal lagoon during the operation to reach the optimum operating schedule. The energy stored by a tidal lagoon is also quantified in this paper to further reveal the contribution of a tidal lagoon to the power system. It should be noted that ebb-only generation was considered in this study. Further investigation of two-way generation will be conducted in future studies.

The remaining sections of this paper are organized as follows: Section II will give a brief introduction on the structure and operation scheme of the tidal lagoon; Section III will present the optimisation model for the tidal lagoon; Section IV will present the results and data analysis on a test run using the Swansea Bay Tidal Lagoon case; Section V will conclude this paper and provide directions for future work.

II. INTRODUCTION ON TIDAL LAGOON

The tidal lagoon is an artificial reservoir built with turbine-embedded walls in the coastal area. It is designed to use the movement of the oceans to create energy. As the tides rise and fall water is channelled through turbines on a tidal lagoon's wall, which rotate to turn the potential energy into electricity.

The aerial view and structure of a tidal lagoon is demonstrated in Fig. 1 and 2. The wall encloses a certain area of the sea to form a basin, which stores sea water with varying water height level. A caisson embedded in the wall is a structure to provide a watertight seal to hold the water in or prevent it from entering the lagoon, usually consists of turbines and sluices. The turbines are submerged in the water

and are located in the walls of the lagoon. As the water rushes through the turbines due to the height difference between the water each side of the lagoon, the turbines are forced to rotate and then convert the kinetic energy into power. The sluices are openings in the lagoon's wall, which can be opened and closed and are designed to allow large volumes of water to pass into or out of the lagoon in a short period of time.

As the tidal lagoon generation depends on the rise and fall of the tides, there are two common generation methods of a tidal lagoon: one is one-way generation (generating energy with ebbing tides or flooding tides only) and the other is two-way generation (generating energy with ebbing and flooding tides both). In this paper, the ebb-generation (a kind of one-way generation) is used in the study. During flood tide the lagoon is filled through the sluice gates until the inside water level is high enough. The gates are then closed and as the tide goes back out it creates a head difference across the lagoon. The water is then released through the turbines going in the same direction as the ebb tide. As the turbines rotates due to the rush of water, it converts kinetic energy into electricity. When the water level inside the lagoon is no longer high enough to support the turbine generation, the turbines will stop generating and water will keep flowing through these idle turbines or sluices as the tide fall or rise. This process can be seen in Fig.2.

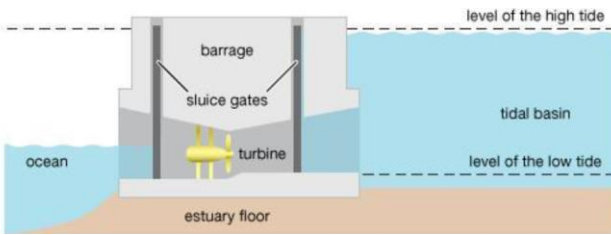

Fig. 1.   The aerial view of a tidal lagoon

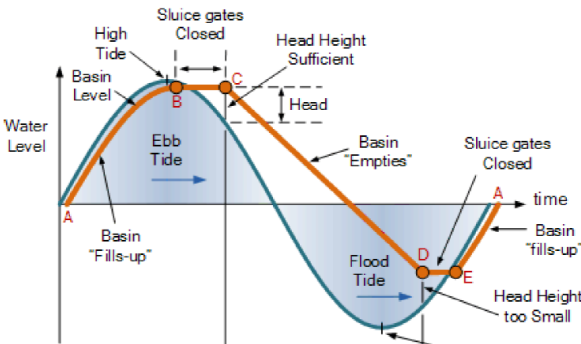Fig. 2.   The structure of a tidal lagoon's caisson

Fig. 3.   The operation scheme of a tidal lagoon

III. THE FORMULATION OF TIDAL LAGOON'S OPTIMAL OPERATION SCHEME

In this paper, we formulate the operation of a tidal lagoon as two different optimisation problems. In the first optimisation problem, the objective function is to maximise the generation of electricity over a 24 hours. The objective function of the second optimisation problem is to maximise the profit of the tidal lagoon by selling its electricity to the day-ahead wholesale electricity market. . The objective is the total amount of energy profit made by the turbines:

$$\max \sum_{t \in T} \left(C_t^{E} \cdot E_t^{TL} \right), \tag{1}$$

where C_t^{E} (£/MWh) and E_t^{TL} represent the electricity price and the energy production (MWh) of the tidal lagoon at time t, respectively.

The constraints are formulated based on a 0-D representation of a tidal lagoon as below:

$$z_t^{in} = \begin{cases} z_t^{out} & t=1 \\ z_t^{out} - \dfrac{Q_t^{TL}}{A}\Delta T & \text{else} \end{cases}, \tag{2}$$

$$H_t = z_t^{in} - z_t^{out}, \tag{3}$$

$$Q_t^{TL} = n^{S}Q_t^{S} + \sum_{i \in S^{T}} \delta_{i,t}^{T} \cdot Q_{i,t}^{T}, \tag{4}$$

$$P_t^{TL} = \sum_{i \in S^{T}} \delta_{i,t}^{T} \cdot P_{i,t}^{T}, \tag{5}$$

$$E_t^{TL} = P_t^{TL} \cdot \Delta T, \tag{6}$$

where z_t^{in} and z_t^{out} represent the water head level (unit??) inside and outside the tidal lagoon, respectively; Q_t^{TL} represents the total amount of water flowing through the tidal lagoon; ΔT is the time step; A is the surface area of the tidal lagoon; H_t represents the head difference between the inside and outside; Q_t^{S} and $Q_{i,t}^{T}$ represent the amount of water flowing through each sluice and turbine, respectively; n^{S} is the number of sluice gates; $\delta_{i,t}^{T}$ is a binary variable indicating the status of the i th turbine; $P_{i,t}^{T}$ represents the power output of the i th turbine; P_t^{TL} and E_t^{TL} represent the power output and energy production of the whole tidal lagoon, respectively.

Constraints (2) to (4) describes the relationships between the water head level inside/outside the tidal lagoon and the water flow rate through the sluices/turbines. Constraint (2) sets the water level inside the tidal lagoon at the initial time period and relates z_t^{in} of other time periods to the amount of water flowing out of the tidal lagoon. Constraint (3) defines

the head difference in the tidal lagoon operation. Constraint (4) defines the total amount of water flowing through the tidal lagoon. Constraints (5) and (6) pertain to the energy generation, defining the power output and energy production of the whole tidal lagoon. The calculation for Q_t^S, $Q_{i,t}^T$ and $P_{i,t}^T$ are given as follows.

For the calculation of Q_t^S, a nonlinear equation is used:

$$Q_t^S = C^S A \sqrt{2gH_t}, \qquad (7)$$

where C^S is the discharge coefficient (normally set as 1.0) and g is the gravitational acceleration. To lower computation complexity, Constraint (7) was approximated as a linear equation:

$$Q_t^S = 4C^S A H_t. \qquad (8)$$

During the simulations in previous studies [5], a hill chart has been made to show how turbine flow rate and power generation change with the head difference. As shown in Fig.4, both $Q_{i,t}^T$ and $P_{i,t}^T$ start when $H \geq H^{min}$ ($H^{min} = 1$ m). $Q_{i,t}^T$ reaches the maximum when $H_t = 5$ m and decreases then, while $P_{i,t}^T$ steadily climbs until it meets the rated power capacity. Based on the curves of this chart, $Q_{i,t}^T$ and $P_{i,t}^T$ are also approximated:

$$Q_{i,t}^T = \begin{cases} 80|H_t| & H_t \leq 5 \\ 625 - 45|H_t| & H_t > 5 \end{cases}, \qquad (9)$$

$$P_{i,t}^T = \begin{cases} 4.1667 \cdot H_t & H^{min} \leq H_t \leq 6 \\ 25 & H_t > 6 \\ 0 & else \end{cases}. \qquad (10)$$
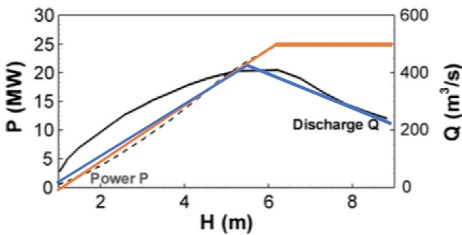

Fig. 4.   The hill cahrt for turbine flow rate and power generation

Constraints (9) and (10) could be built in a linear form using binary variables. For Constraints (4) and (5), the product of a binary variable and a continuous variable could be linearized as well. Taking Constraint (4) as an example, the replacement constraints are written as below:

$$z_{i,t}^Q \leq \delta_{i,t}^T \cdot \overline{Q}_{i,t}^T, \qquad (11)$$

$$z_{i,t}^Q \leq Q_{i,t}^T, \qquad (12)$$

$$z_{i,t}^Q \geq Q_{i,t}^T - \left(1 - \delta_{i,t}^T\right) \cdot \overline{Q}_{i,t}^T, \qquad (13)$$

$$z_{i,t}^Q \geq 0, \qquad (14)$$

where $z_{i,t}^Q$ is a new ancillary variable introduced to linearise the constraint and is the maximum bound of $Q_{i,t}^T$. In this way, the optimisation model was fully converted into a mixed integer linear problem, which saves a considerable amount of computation time.

IV. CASE STUDY

To validate the proposed optimisation model of optimal operation scheme for a tidal lagoon, a test run is carried out using the Swansea Bay case. This test case is a tidal lagoon with rated capacity of 225 MW (containing nine turbines with maximum generation capacity of 25 MW for each). The surface area of the tidal lagoon is 11.5 km2 while the total area of sluice gates is 2250 m^2. The optimisation problem aims to provide a 24-hour operation scheme with a 30-min time step, which is modelled in Python and solved by Gurobi. Detailed results and data analysis are given as below.

A. The result of maximum profit

To demonstrate and analyse the proposed optimisation model, the details of the one-day operation scheme are demonstrated in Fig. 5 to 7. Fig. 5 shows how the water level inside the lagoon steadily changes with the ebb and flood. As the ebb tide begins, sea water gradually flows out of the lagoon, maintaining a certain of head difference until the inside and outside water levels are the same. When turbines are generating energy, the sluices are closed and the water runs through the turbines; while in other periods both turbines and sluices are open to ensure the lagoon can raise the inside water level in a short time length and start generation in time. The water flow rate through the turbines and sluices are presented in Fig. 6. When the ebb tide begins, the water realeased from the lagoon will only run through the turbines to ensure the maximum utilization of the head difference. The power generation and profit made in each time period are demonstrated in Fig. 7. As the power production is determined by head difference, these two shares the same trend throughout the operation.
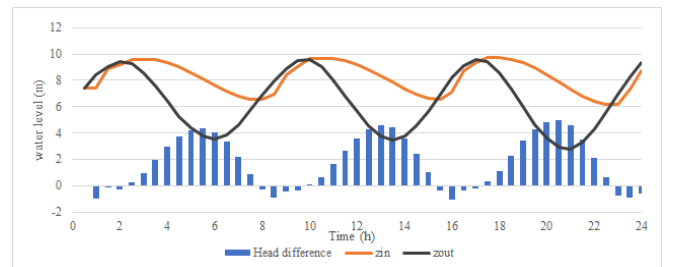

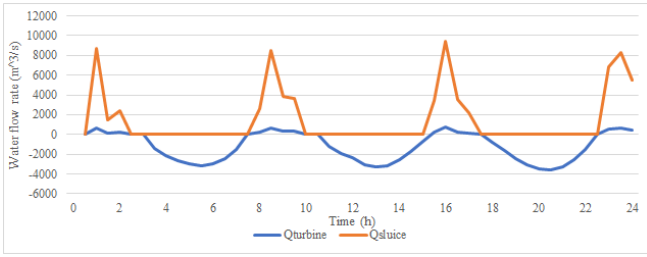Fig. 5.   Head difference and water levels

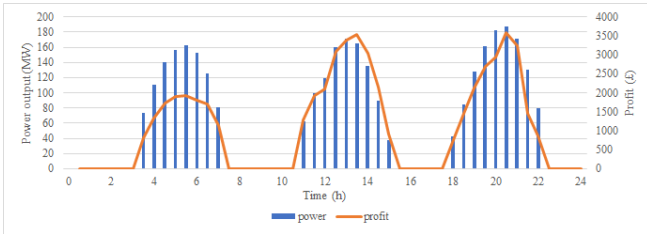Fig. 6.   Total amout of water flowing thourough turbines and sluices


Fig. 7.   Power output and energy profit

B. *Comparison between different electricity price profiles*

To reach maximum profit, the tidal lagoon can adjust its power generation, which is normally achieved by controlling the number of active turbines. To show how tidal lagoon react to the fluctuation of energy prices, the optimal scheme of the same tidal lagoon (with the same tidal pattern) under different price profiles were calculated and analysed. In this section, we use the result from the optimal scheme with the goal of maximum power generation as the benchmark to demonstrate tidal lagoon's response to energy price (shown in Fig. 8).
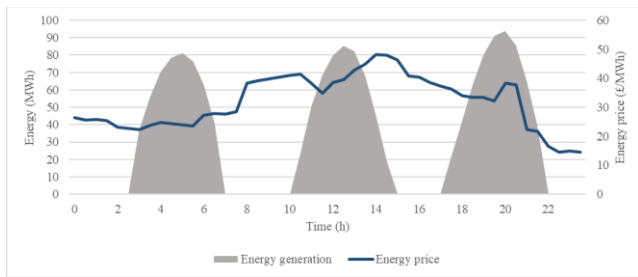
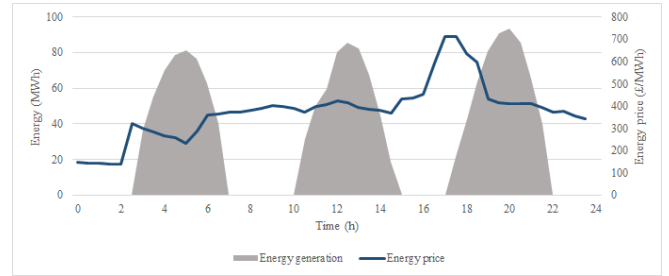(a) Energy generation and price profile
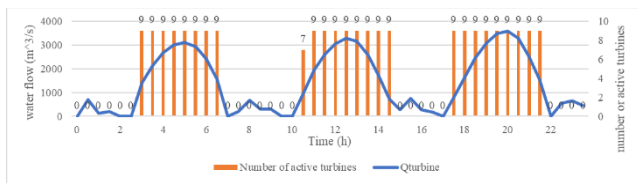
(b) Number of active turbines and water flow rate through turbines

Fig. 8.   Operation scheme for maximum energy production

The results of the proposed optimisation model under two different price profiles are demerstrated in Fig. 9 and Fig. 10. When in pursuit of maximum profit, the tidal lagoon adjusts the number of active turbines to control the amount of water released back to the sea and the speed of lowering the water level inside the lagoon. As shown in Hour 11 to 12 in Fig. 9, Hour 3 to 6 in Fig. 10, when electricity price is high, the tidal lagoon opens the maximum number of turbines to reach the maximum power output. When electricity price is lower than privous or latter ones, the tidal lagoon will shut down a certain number of turbines to contain the water level inside the

lagoon, saving the available energy for time periods with higher energy prices.

During each ebb tide, the tidal lagoon tends to have more ability to adjust its power generation at the beginning of the ebb tide than in the last couple of hours. Most of the adjustments are made during the first half of the ebb tide, e.g., Hour 3 to 6 in Fig. 10. As the water level inside the lagoon lowers, the tidal lagoon has less and less potential energy that could be converted into electricity. So the number of active turbines in the tidal lagoon normally maintains the maximum for the maximum power production and energy profit.
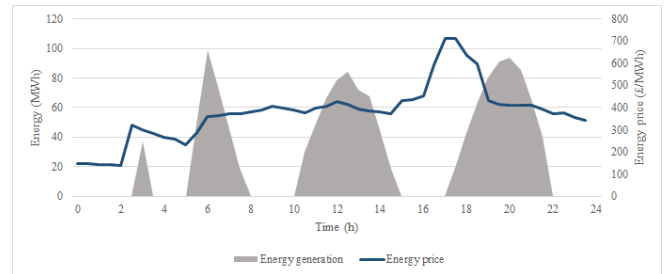

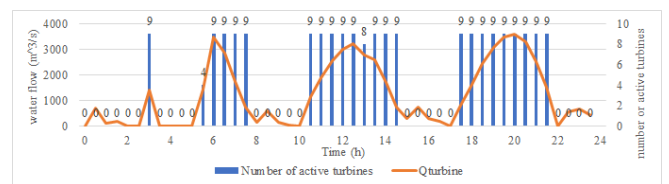(a) Energy generation and price profile
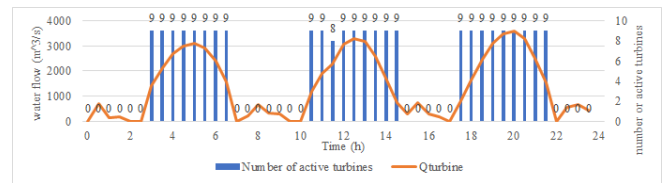
(b) Number of active turbines and water flow rate through turbines

Fig. 9.   Operation scheme under price profile #1

(a) Energy generation and price profile

(b) Number of active turbines and water flow rate through turbines

Fig. 10.   Operation scheme under price profile #2

C. *Quantification of energy storage*

When the water level inside the lagoon is higher than the outside, the tidal lagoon holds a certain amount of potential energy that could be converted into electric energy. As long as the tidal lagoon maintains the high water level without generating power, its capability of generating remains and

could be regarded as some sort of energy storage system. Similar as battery energy storage, the tidal lagoon could provide and storage energy as demanded. But different from the battery, the level of energy storage of tidal lagoon varies in different time periods as it depends on the sea water level outside the lagoon.

To explore how much energy stored by the tidal lagoon in different time periods, we define the level of storage in a tidal lagoon as the maximum energy it could produce in one time period. The inner water level is set to the highest during all time periods while the sea level goes up and down, and the maximum possible gneration output is calculated based on the varying head difference. As shown in Fig. 11, the head difference shows the same trend as in other figures, but with greater values. The level of storage is mostly proportional to the head difference. Due to the limited rated capacity of turbines and the startup threshold of head difference, the energy storage always stays within the maximum bound though sometimes the head difference is larger than 6 m (e.g., Hour 20), and stays as zero when head difference lower than $H^{\min}$ (e.g., Hour 8 to 10). During the most of the time, the tidal lagoon holds a certain amount of energy storage which can be provided to the power system. Although the storage capability of one single tidal lagoon is greatly imapcted by the tides, the coordination of multiple tidal lagoons in different locations (operating under different tidal ranges) will help fill the valleys in energy storage, and probably provide the power system a continuous and reliable sources of flexibility.
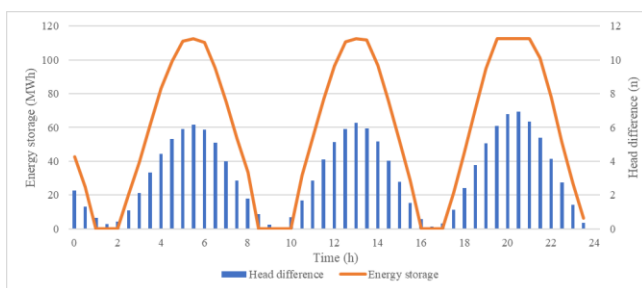

Fig. 11.   The fluctuation of level of energy storage and head difference

V. Conclusion

This papper proposes an optimal operation shceme of a tidal lagoon to maximize its profit from selling generated electricity. First the optimisation problem is modelled based on a 0-D tidal lagoon model and fully linearised to a MILP form for less computation complexity. Then the tidal lagoon's reaction to the fluctuating energy prices is studied to provide more insight on how tidal lagoon joins the operation of power system. Results shows that the tidal lagoon can adjust its power generating by controlling the water level inside the lagoon according to the energy prices, so more energy could be provided when it's most needed by the power system. The energy stored by the tidal lagoon is also evaluated and data show that the level of energy storage goes up and down as influenced by the tide outside the lagoon. Future work will focus on the coordination of multiple tidal lagoons and how they will provide flexibility to the power system to suuport the integration of intermittent renewable energy sources.

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