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Energy

Tidal range electricity generation into the twenty-second century

David Vandercruyssen PhD, CEng, FICE, FIStructE, MCIHT
Research student, Lancaster University School of Engineering, Renewable Energy and Fluid Machinery Group, School of Engineering, Bailrigg, Lancaster, UK (Orcid:0000-0002-3474-3406) (corresponding author: d.vandercruyssen@lancaster.ac.uk)

Simon Baker MRes
Research student, Lancaster University School of Engineering, Renewable Energy and Fluid Machinery Group, School of Engineering, Bailrigg, Lancaster, UK

David Howard PhD, PGCE, MBES, MIALE, FRES
Fellow of UK CEH, UK Centre for Ecology & Hydrology, Lancaster Environment Centre, Wallingford, Oxfordshire, UK (Orcid:0000-0003-4494-7450)

George Aggidis PhD, Eur Ing, CEng, CMarEng, MASME, FIMarEST, FEI, FIET, FIMechE
Head of Energy, Lancaster University School of Engineering, Renewable Energy and Fluid Machinery Group, School of Engineering, Bailrigg, Lancaster, UK (Orcid:0000-0002-5175-4529)

Tidal range electricity generation schemes are designed to have a minimum operational life of at least 120 years, making it important to plan for changes such as sea-level rise (SLR). Earlier studies have shown that schemes can maintain the existing tidal range within the impoundment and protect areas from flooding. Here it is demonstrated that tidal range technology can maintain the current tidal extent despite SLR and suggests the operational strategies to achieve it. The approach is the only way to safeguard existing intertidal habitats. Mechanical and electrical plant requires a major overall, upgrade or replacement every 40 years; the levelised cost of energy is structured in 40-year periods reducing after the first period. Increasing the capacity or efficiency of the plant during the refits allows the protection of low-lying areas to be maintained and more electricity to be generated. The strategy requires energy to be used in pumping to achieve the current low tidal limits and the incoming tide to be curtailed to maintain the high tide extent, but there is very little effect on annual electricity production. Flexible operation can offer some protection from riverine flooding and existing inundation cycles can be maintained.

Keywords: coastal engineering/environment/power stations (non-fossil fuel)/renewable energy

1. Introduction

Earlier papers by the authors have described specific aspects of tidal range power generation in Great Britain. Their first paper compared case studies of a coastal lagoon and an estuarine barrage (Vandercruyssen *et al.*, 2022a). The paper used the Lancaster zero-dimensional (0D) tidal range model to estimate the annual electricity production (AEP) for various combinations of turbine numbers, generator ratings and sluice ratios. The second paper developed a cost model for tidal range schemes that can be used for initial estimates of capital costs so that schemes can be ranked in order of financial returns (Vandercruyssen *et al.*, 2022b). The cost model requires limited site-specific information and is intended for pre-feasibility estimates only. The third paper combines the first and second to show how the components of schemes can be optimised to find the lowest cost of energy (Vandercruyssen *et al.*, 2023). Funding mechanisms were discussed, and tidal range was shown as sufficiently economic for feasibility studies to begin in earnest. Here the consequences of sea-level rise (SLR) are investigated.

The most obvious consideration for such long-term tidal range projects is the impact of climate change on mean sea level. SLR is already a reality (IPCC, 2014). The Lancaster 0D model allows the user to specify a value for SLR and all values in the tidal cycle are then increased by this level. The tidal range may also be factored to increase or decrease. Thus, SLR can be modelled, and its effects simulated.

A barrage, if designed and operated appropriately, can mitigate the impacts of SLR on the intertidal zone and can help satisfy the government's legal commitment to protect valuable designated ecosystems. If the ecological and environmental considerations dictate that the tidal range within the barrage must be maintained at pre-SLR levels, then the design and/or the AEP may be compromised. Similarly, a barrage can be used to reduce terrestrial flooding by allowing free drainage into the impoundment.

2. Sea-level rise

The predictions over the next 120 years vary widely due to uncertainties in future net greenhouse gas emissions, and the environmental mechanisms involved. The Institution of Mechanical Engineers (IMechE) looking 80 years ahead recommended coastal developers to '… prepare for a minimum of a 1 metre rise in sea level this century but plan for 3 metres of rise' (IMechE, 2019: p. 5).

As water warms and expands and ice sheets melt there will be an increased volume of water in the seas. It is possible that tidal range and storm surges will also increase. Pickering *et al.* (2012) used the Dutch continental shelf model to estimate the effects of a 2 m rise in global average sea levels on the tidal range. They concluded there would be little effect on range (i.e. the difference in height between high and low water) in the North Wales (NW) to Liverpool Bay area. Surprisingly, the altered intertidal morphology suggests that the amplitude of the tidal range around the Severn estuary would fall to 91% of the current range. Khojasteh *et al.* (2022) describe the effects of SLR on estuaries. In the absence of more reliable estimates of this, the authors assume that the amplitudes of the tidal range remain constant. Without a barrage, much of the low-level intertidal areas in estuaries will be inundated with significant loss to the environment. Existing sea defences will prevent tidal encroachment inland, so the intertidal area will shrink.

There are upwards of 75 km^2 of low-lying land surrounding Morecambe Bay (MB) that are protected by ~50 km length of embankments plus one-way river flow gates and pumping stations. SLR threatens this infrastructure; embankments will need to be raised to prevent future breaches. Ultimately, the questions of cost of construction, the operational performance and multiple benefits must be answered by the UK government. When generation is suspended or reduced to prevent flooding, the cost of deviating from maximum energy generation needs to be offset in the valuation.

Climate change is also predicted to increase the likelihood and severity of storms, while they become less predictable (IPCC, 2014). The main catastrophic flood risk in the catchments surrounding MB at present is from rivers following heavy rain (EA and Cumbria County Council, 2017). The ability to drain the land is impeded by high tides and will become increasingly difficult with SLR. The benefits of a tidal barrage for flood protection were discussed in the paper by Vandercruyssen *et al.* (2022a).

3. Pumping

Pumping is the forced movement of water into or out of the impoundment against the existing direction of flow or stasis. It can increase the head before generation starts and is reported to increase the net AEP by 10% (Yates *et al.*, 2013). The operation usually employs the turbines as pumps against low heads, after slack tide, to increase the head available during the next generation sequence. However, it needs to be clear what is meant by pumping, as there are several modes of operation. For two-way generation without pumping, the range of water levels inside the impoundment, or lagoon, is less than the natural tide range over the same period. The equalisation of water levels occurs just after high or low tide. The following pumping scenarios are considered.

3.1 Cycle-by-cycle

The cycle-by-cycle (C-by-C) pumping scenario is used to maximise net power generation by pumping to try to match the natural tide level for each cycle. After generation, the sluices are opened to equalise levels as quickly as possible. The equalisation times for high and low tides inside the impoundment will be slightly behind the natural tide extremes. The pumps then attempt to bring the impounded water level to the previous natural tide limit. There is no guarantee that the natural tide levels will be achieved for all tides as there may not be sufficient time to achieve the goal.

3.2 Forced limits

The forced limit (FL) mode checks that the natural tide levels are matched. If not, then the sluices are opened early to allow sufficient time for the natural tide extremes to be met for each tide. There will be more power used in pumping compared with the C-by-C mode.

3.3 Pump storage/economic pumping

Another possible scenario is to pump to the maximum pumping head or mean spring tide levels. Exceptionally, in periods of high demand and low supply (e.g. no wind) it would be possible to pump to the highest or lowest astronomical tide level – effectively providing a small component of pumped storage capacity. This is constrained to specific times when energy can be captured and when it must be used within the next phase of the cycle. The stored head is low (say a maximum of 3 m) but with a surface area of 150–300 km^2, the potential is not insignificant. It would only be economic if the price of electricity for pumping is, say, 50–60% of the price at the next generation cycle, typically 2 or 3 h later; either early morning or afternoon before the morning and evening peak periods. This requires estimating the price of electricity 3 h ahead rather than the 24 h forward pricing used for most of the grid price bidding process. There is no point in pumping at 6 p.m. to obtain a lower price in the late evening or overnight. The approach is described by Harcourt *et al.* (2019), who suggested a 23% improvement of financial return is possible for Swansea Bay.

3.4 Maintaining pre-SLR levels

It is possible to maintain existing sea levels within the impoundment provided there is sufficient pumping capacity. At the end of generation on an ebb tide, the pumps are used to lower the impounded water to the desired low tide levels. On the flood tide the turbines and sluice gates are closed when the impounded water level attains the target for high tide; or earlier if a storm is expected. The adjusted operation changes the balance between the ebb and flood generation potential. There will still be a good head at the end of generation on the flood tide. Conversely, there will be more pumping energy used on the ebb tide. This effect may be more pronounced in coastal lagoons than estuaries that have much smaller wetted areas at low tides (Vandercruyssen *et al.*, 2022a).

3.5 Pump performance

For commercial reasons, there is very little published information on the performance of hydraulic turbines used as pumps. The principle is well established as demonstrated by the Dinorwig pumped storage scheme (Baines *et al.*, 1983). The scheme uses six 300 MW reversible pumps/turbines that can pump to ~500 m head. Water is pumped at night for discharge the following day. For the tidal range in the UK, the maximum pumping head would be 3 or 4 m. The pump performance used in the Lancaster 0D is based on information from the La Rance scheme in France, where the turbines in pump mode are operated at a quarter of the rated generating power (Baker, 2021). The pump operates at a user-specified constant power with a linear relationship between head, flow and efficiency. Baker (2021) showed that for a turbine 8 m wide and 7.5 MW pumping power, for example, the flow rate starts at 380 m^3/s at zero head and drops to 240 m^3/s at a maximum head of 2.3 m. Higher flow rates and maximum head can be achieved with higher power at the expense of efficiency: the same turbine at 25 MW can pump 480 m^3/s at a head of 2.3 m, and can pump up to a head of 5.2 m. For this paper, pumping power has been limited to 7.5 MW.

4. Zero-dimensional model

The 0D model estimates power generation by simply using the volume of water moving with no consideration of the morphology of the impoundment; it assumes that the water inside the impoundment is always uniformly level. The approach is ideal for initial assessments for scheme development and component sizing. More complex models can be used when specific site data are available but are far more time-consuming to perform. The mathematics of the 0D model has been described by Aggidis and Benzon (2013) and Aggidis and Feather (2012), who provide the equations underpinning the model and the hydraulic characteristics of the turbine. A Hill chart describes efficiency and output under different discharge and flow conditions; in the Lancaster model the characteristics of an Andritz three-blade, bulb turbine were incorporated. The Hill chart is based on the performance of model tests. The equations relate the model to full-size machine operation.

To demonstrate the effects of SLR the authors continue with the two contrasting development schemes used in their earlier paper (Vandercruyssen *et al.*, 2022a). For estuarine schemes, such as MB, there are multiple overlapping environmental and ecological designations, aimed at protecting the whole ecosystem, specific components and their ecosystem services. In addition, there are specific areas allocated to shell-fishing, a long-standing traditional industry. Saltmarsh acts as an important carbon dioxide sink and should be protected where possible (Laffoley *et al.*, 2022). A coastal lagoon, such as NW, does not have the diversity of habitats and protected areas as an estuary and is currently considered easier to gain approval for development.

The presence of a barrage will change the nature of the intertidal zone that it impounds, but it is also an environmental management scheme that can safeguard and operate for the benefit of the ecosystem. Importantly, it can limit the height of the high tides to alleviate tidal flooding, mitigate riverine flooding and maintain the current tidal range, thus preserving existing habitats. The criterion of maintaining the current tidal range has been applied as part of the study as a proxy for an environmental requirement. The Lancaster 0D model allows the user to specify a value for SLR and a pumping option to match pre-SLR levels.

4.1 Assumptions

It is assumed that each site starts with the base configuration of the minimum levelised cost of energy (LCOE) described previously (Vandercruyssen *et al.*, 2023).

- The MB estuarine barrage will use 8 m wide turbines with 20 MW generators and a sluice ratio of 2.
- The NW coastal lagoon will use 8 m wide turbines with 15 MW generators and a sluice ratio of 2.
- In both cases, pumping power is limited to 7.5 MW using turbines as pumps.
- The tidal range does not change with SLR.

It is assumed that each scheme will have a minimum design life of 120 years and that major refurbishment or replants will occur every 40 years, phased over ±5 years.

The IMechE's prediction of 1.0 m rise in average sea levels by the end of the century, equates to a 0.5 m rise every 40 years. The approach is indicative of initial planning; more accurate figures will develop over time.

5. MB estuarine barrage

In Britain, estuaries commonly contain important habitats and consequently have more designations and protected areas (e.g. Site of Special Scientific Interest (SSSI), Area of Outstanding Natural Beauty (AONB), Ramsar sites and Royal Society for the Protection of Birds (RSPB) sites) than other locations. MB has more than most, see Table 3 in the paper by Vandercruyssen *et al.* (2022a) for a detailed list and glossary. The strength of formal protection has been a major issue that has deterred the development of tidal range barrages across estuaries. There is a commonly held misconception that low-lying intertidal habitats will remain flooded within a tidal barrage. This perception was reiterated as recently as 2008 in the government-backed study of the proposals for the Severn estuary (DECC *et al.*, 2008). Contrary to these ideas, the analysis presented here demonstrates that two-way generation and pumping is the only way to protect sensitive areas from SLR while maintaining the dynamic tidal cycles.

With current average sea levels, the surface, or wetted, area of the impounded water is approximately the same for NW and MB at ∼150 km^2. The wetted area of MB at mean low water springs (MLWSs) is 50% of that for NW (Vandercruyssen *et al.*, 2022a). With a 2 m SLR, the wetted area of MB is still less than that of NW. Therefore, the pumping effort needed to maintain existing low water levels should be less for an estuary.

The Lancaster 0D model has been used to calculate the AEP expected from the estuary under various combinations of turbine and sluice numbers and pumping modes for SLR up to 2 m.

Table 1 shows the estimated AEP for 60 combinations of SLR, turbine and sluice numbers, and pumping regimes. The analysis demonstrates the power and flexibility of 0D modelling; it would be extremely time-consuming using two- or three-dimensional models. The blank cells for the FL mode show where the current model struggles to match the required minimum tide levels and the results are unreliable.

Figure 1 shows the data of Table 1 in graphical form. The initial configuration, using 8.0 m wide bulb turbines with 20 MW generators, and a sluice ratio of 2, was the optimum configuration suggested by Vandercruyssen *et al.* (2023). Other configurations employing 140 and 160 turbines were also considered previously and are used to show the consequences of increasing the number of turbines in line with SLR. The 8 m wide bulb turbine is considered the largest, and most efficient, currently available.

In Figure 1 solid lines represent the C-by-C pumping mode that maximises the power generated, whereas dashed lines represent the FL pumping mode. The separation between the solid and dashed lines shows the AEP loss due to maintaining pre-SLR tide levels – that is, the cost of fully mitigating SLR. In all cases (turbine numbers and SLR) the FL maintains the tides at their current cycle levels protecting the habitats until SLR attains 0.8 m. It is to be expected that once SLR exceeds 1.0 m, other measures will need to be taken.

For SLR up to 0.6 or 0.8 m, all scenarios (C-by-C and FL) demonstrate a slight increase in AEP. For the base case of 120 turbo-generators, it is apparent there is a significant and increasing cost to maintain existing sea levels when SLR exceeds 1.1 m. The larger installations of 140 and 160 turbines fare much better in meeting SLR up to 1.4 m. Thus, the proposed base case for MB should include at least 140 × 8 m wide turbines. Above 1.8 m of SLR the performance drops dramatically. It shows the necessity of designing for the future, either during the initial build or by providing an easy means to expand later.

To understand this rather complex graph, it is necessary to examine the tide and impoundment levels in detail. Figure 2(a) shows the water levels for a 12 day period of tides with 1.4 m of SLR. The blue lines are the sea levels and the red lines are the impoundment levels with the C-by-C pumping mode. The green dashed lines are the impoundment levels with the FL pumping mode. The existing high tide levels are easily maintained by stopping generation and closing sluices when the desired levels are met. The flat hold periods at neap tides are longer than those at spring tides. For the neap tides, the C-by-C mode fails to achieve the lower existing limit by ∼0.5 m. The FL mode starts its ebb generation slightly earlier and runs at a faster flow to achieve the pre-SLR low water levels. For the spring tides, the C-by-C mode is ∼0.9 m short of the desired low tide levels so more pumping is required. The FL

Table 1. Annual electricity produced in the MB estuarine barrage with 8 m wide turbines and 20 MW generators under various levels of SLR and numbers of turbines

MB barrage				Annual electricity produced: TWh										
		Sluices 15 × 15 m^2		Sea level rise: m										
Pumping mode	Number of turbines	Ratio	Number	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
C-by-C	120	2.0	54	5.39	5.43	5.45	5.46	5.46	5.47	5.47	5.45	5.42	5.35	5.27
	140	2.0	63	6.12	6.18	6.22	6.25	6.27	6.26	6.24	6.19	6.14	6.07	5.97
	160	2.0	71	6.69	6.75	6.79	6.83	6.82	6.82	6.74	6.72	6.64	6.53	6.45
FLs	120	2.0	54	5.26	5.34	5.41	5.43	5.41	5.36	5.26	5.07	4.81		
	140	2.0	63	6.15	6.21	6.24	6.27	6.28	6.27	6.20	6.08	5.88	5.65	
	160	2.0	71	6.72	6.77	6.80	6.83	6.86	6.84	6.81	6.73	6.58	6.41	

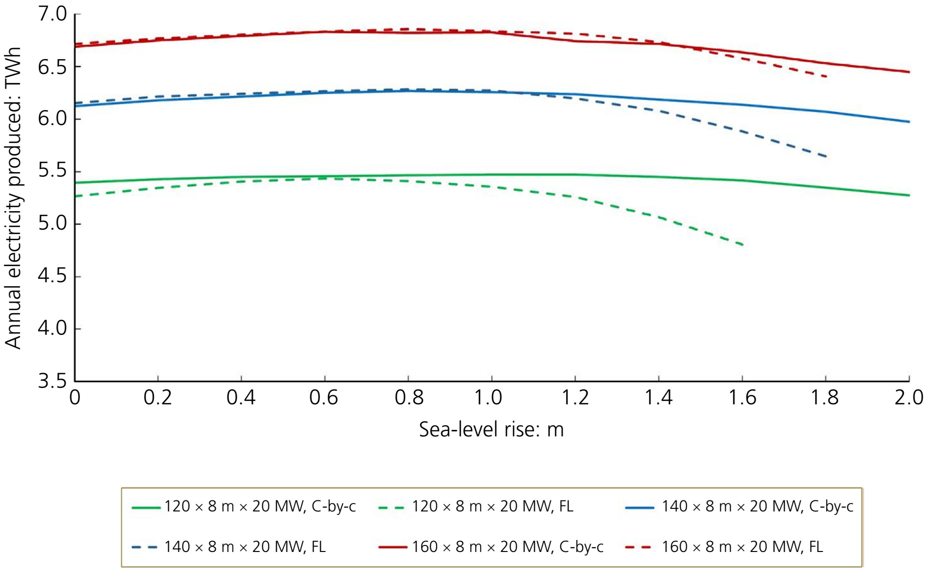

Figure 1. Annual electricity produced in the MB estuarine barrage under various levels of SLR and plant configurations

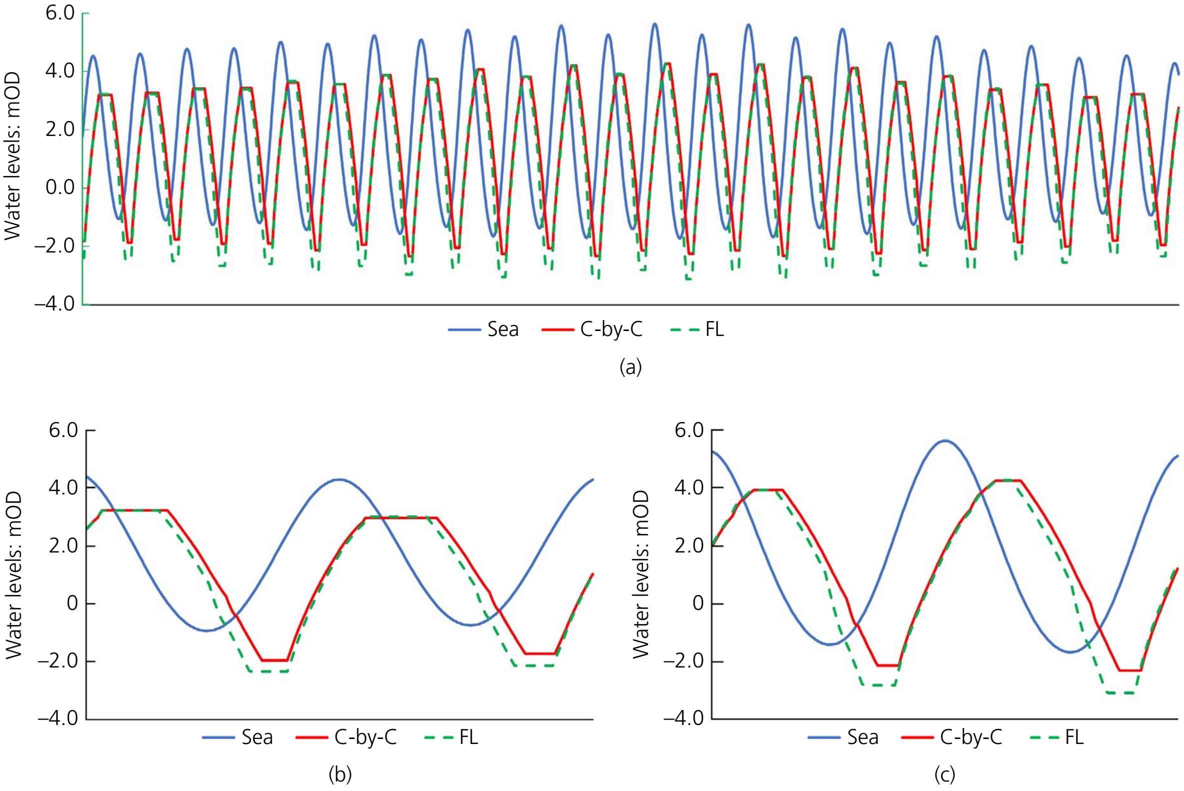

Figure 2. MB estuarine barrage using 140 × 8 m × 20 MW, 1.4 m sea level rise: (a) 12 day seas and impounded water levels, (b) neap tides and (c) spring tides

mode achieves the required current low levels with an additional loss of only 2% of the AEP. Spring low tide inside the impoundment lags the natural tide by 2 h 36 min for C-by-C and 2 h 0 min for FL modes.

6. NW coastal lagoon

The surface area of the impounded water at low tide for a coastal lagoon, such as this case study site, is a higher proportion of the area at mean tide than a typical estuary. This means the flood generation mode is more significant than for a similar-sized estuary. Consequently, the coastal lagoon will require more pumping effort to achieve existing low water levels and maintain them against SLR. However, there are no environmental designated areas within this proposed scheme. Thus, it could be argued that maintaining existing low water levels is less important compared with estuaries. However, protection is still possible.

The Lancaster 0D model has been used to calculate the AEP expected from the lagoon under various combinations of turbine and sluice numbers and pumping modes for SLR up to 2 m, see Table 2 and Figure 3.

As with MB, all the curves in Figure 3 show a slight increase in AEP with SLR of 0.2–0.4 m and then all start to decline. For the case of 125 × 8 m wide turbines, the loss of AEP becomes significant for SLR exceeding 1.4 m. For the 140 and 160 turbines, the AEP loss becomes significant after slightly higher SLR. When SLR attains 1.6–1.8 m the system struggles to match the pre-SLR low tide levels.

Table 2. Annual electricity produced in the NW coastal lagoon with 8 m wide turbines and 15 MW generators under various levels of SLR and plant configurations

NW coastal lagoon				Annual electricity produced: TWh										
		Sluices 15×15 m^2		Sea level rise: m										
Pumping mode	Number of turbines	Ratio	Number	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
C-by-C	125	2	56	4.37	4.39	4.39	4.34	4.28	4.22	4.12	4.00	3.89	3.76	3.59
	140	2	63	4.68	4.72	4.71	4.68	4.61	4.53	4.42	4.29	4.15	4.00	3.85
	160	2	72	5.00	5.03	5.01	4.97	4.91	4.83	4.73	4.59	4.44	4.29	4.14
FLs	125	2	56	4.33	4.36	4.36	4.32	4.25	4.16	4.05	3.85	3.56		
	140	2	63	4.68	4.72	4.70	4.64	4.57	4.53	4.40	4.26	4.04	3.67	
	160	2	72	5.01	5.03	5.02	4.97	4.92	4.83	4.72	4.60	4.44	4.24	

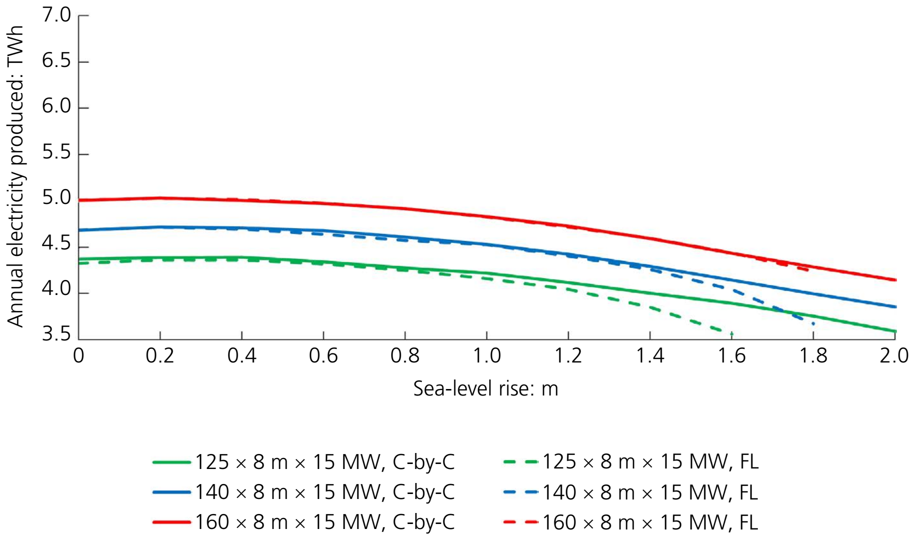

Figure 3. Annual electricity produced in the NW lagoon under various levels of SLR and plant configurations

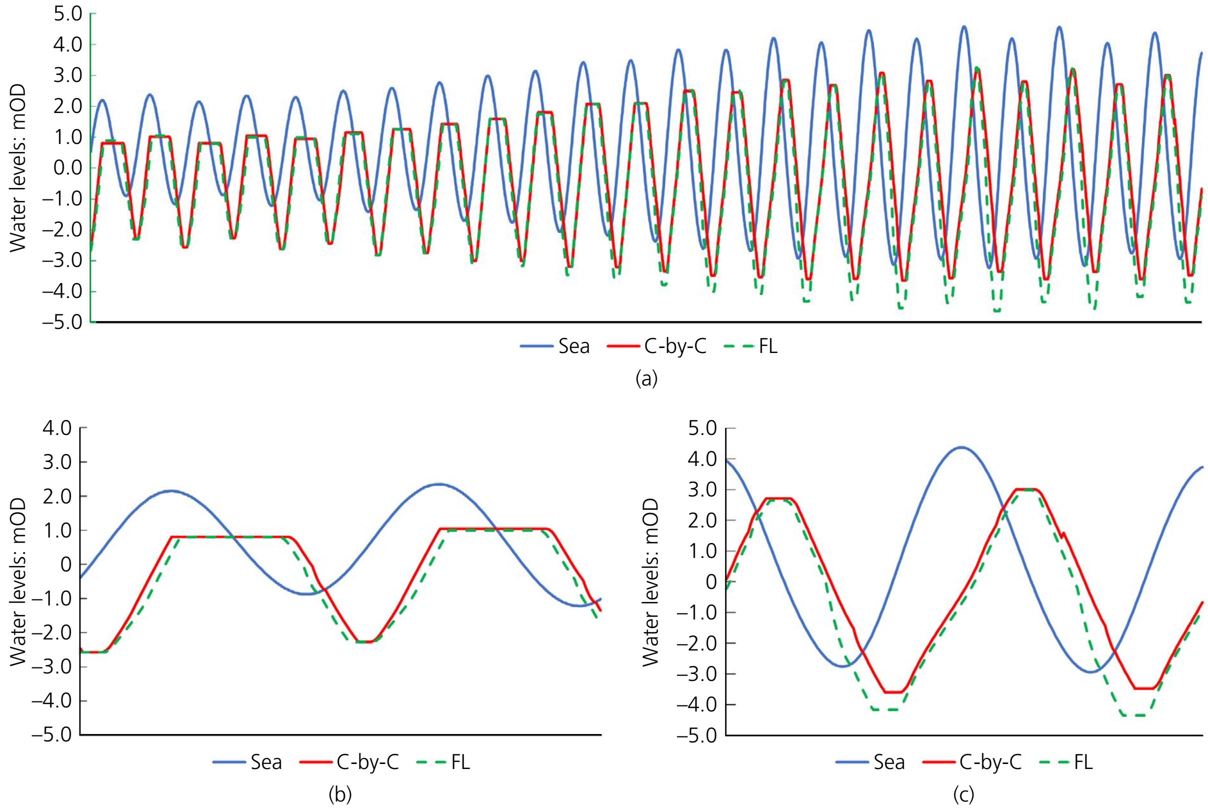

Figure 4. Water levels in the NW coastal lagoon with 125 × 8 m × 15 MW, 1.2 m sea level rise: (a) 12 day seas and impounded water levels, (b) neap tides and (c) spring tides

Figure 4(a) shows the sea and impoundment levels for the base case installation with 1.2 m of SLR. The truncated tops of the scenario curves show that pre-SLR high tide limits are easily achieved by simply closing sluices and stopping generation or pumping when the existing high tide level is attained. Pumping is necessary to achieve the pre-SLR low tide levels. At neap tides, there is little or no difference between the efficient C-by-C operating mode and the FL mode, which means there is no cost to achieve existing low tide levels. At spring tides, the FL mode starts ebb generation slightly earlier than the C-by-C mode and the rate of discharge and turbine speed is slightly greater. The amount of pumping required at low tide is similar, but the FL mode starts earlier. The FL mode achieves the required current MLWS levels with an additional reduction of 1% of the AEP. Spring low tide inside the impoundment lags the natural tide by 2 h 36 min for C-by-C and 2 h 0 min for FL modes.

7. Discussion

Comparing Figures 1 and 3, it appears that it is easier to maintain pre-SLR levels in the coastal lagoon than in the estuarine barrage despite the lagoon having a greater wetted area at low tide. This result was unexpected and may be due to the specific characteristics of the two sites with a lower tidal range in the lagoon and a higher proportion of flood generation.

The analysis presented by Vandercruyssen *et al.* (2023) assumed there are major plant refits or replacements every 40 years. The LCOE following refits was estimated at 57% of the LCOE for the first 40 years. Thus, there is scope for upgrading the installation and generating more electricity. Options available include the following.

- Increasing the number of turbo-generators.
- Increasing the diameter of the turbines and/or generator ratings.
- Increasing the pumping power or installing dedicated submersible pumps.
- Increasing the initial sluice ratio to provide installation sites for additional turbines.

Increasing the number of turbines or sluices once the barrage is operational is possible but difficult and would require cofferdams. It is possible to retrofit turbo-generators into dual-purpose sluices although this saves little money during the initial construction and diminishes the sluicing capacity when the additional turbogenerators are installed. A better option may be to increase the diameter of the turbines by refitting the draught tube within the turbine caisson. It is assumed that larger turbines will be developed as the tidal range industry grows.

Increasing the pumping power is possible, but without specific operating information on the design of low-head turbines as pumps the results are currently unpredictable. Installing dedicated pumps may be a better option in situations where the turbines find it difficult to pump to the current low tide levels; their efficiency is considerably higher than using turbines as pumps.

Increasing the initial sluice ratio is also possible but this will be a fine balance between the initial capital cost and the additional AEP provided by the sluices.

Changes in the tidal dynamics of an estuary need detailed and bespoke investigation. However, the benefits include not only reduced carbon dioxide emissions from sustainable power but also securing supply against power failure. In August 2019, a million people across the UK were plunged into darkness after two national grid generators spectacularly failed (Pike and Allen, 2019). Large parts of London, the south-east, Liverpool, Glasgow, Wales, Gloucestershire and Manchester all lost power. Parts of the railway network could not re-boot, trapping many people on trains for up to 6 h. Ipswich Hospital was also affected when its backup generator failed to work.

Storm surges will be discussed in a subsequent paper. They make little difference to the AEP as the effects of high or low air pressures usually last longer than a full tide cycle of 12.3 h. For a low-pressure area, the average sea level will be higher, and winds can increase wave heights. Consequently, there may be slightly more generation on the flood/ebb tide that will be offset by a slight fall in the electricity generated in the following ebb/flood.

8. Conclusions

During the initial years of SLR after construction, the flood generation will increase slightly due to SLR. Generation during the flood tide will need to stop earlier to limit the maximum sea level but the head at this point will be higher, yielding increased efficiency. Conversely, the ebb generation mode will be somewhat less due to the restrictions at high tide and the additional pumping required to achieve the low tide levels.

For an average SLR of up to 0.5 m for the coastal lagoon example and 0.8 m for the estuary example, the impounded water can be maintained at pre-SLR levels with no significant reduction in annual generation. As the SLR increases further the AEP falls in both C-by-C and FL operating modes. To safeguard the environment from SLR greater than 1 m, it requires increasing the number or size of turbines during planned refits at a future date. It is also possible that design and manufacturing developments over the next 40 or 80 years could utilise the same number of larger and more efficient turbines. The addition of dedicated submersible pumps may be necessary and efficient for the higher ranges of SLR. These will be investigated in a subsequent paper.

Disclaimer

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