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Life Cycle Environmental Impacts and Socio-Economic Implications of Tidal Electricity Generation and Storage in the UK

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ABSTRACT

Tidal range schemes (TRS) remain controversial as their sustainability issues are poorly understood. This study presents a first comprehensive life cycle assessment (LCA) of small, medium and large-scale TRS, considering their dual roles for electricity generation and storage. This is coupled with a discussion of their socio-economic implications and public acceptability. When used solely for electricity generation, tidal power has significantly lower environmental impacts than natural gas, wind and solar photovoltaics, but shows higher values against hydro and nuclear power. When used for both electricity generation and storage, TRS outperform wind electricity coupled with pumped hydro, batteries, compressed air or liquid air energy storage. If only half of the 20 proposed TRS replace natural gas and battery storage by 2050, they could reduce the climate change impact of grid electricity by 71%, saving up to 4.4 Mt CO_2 eq./y. Most other environmental impacts would be reduced by up to 24%. In addition, hundreds of thousands of jobs could be created, along with billions in gross value added. However, high costs and low public acceptability hinder the deployment. It is hoped that the findings of this study will contribute toward a better understanding of the sustainability of this emerging technology.

1 | Introduction

The UK is committed to the decarbonization targets set out in the Climate Change Act 2008 [1], which will require an energy mix composed predominantly of renewable and other low-carbon sources. In this context, tidal energy can complement these sources and make a valuable contribution to the net-zero targets [2]. Tidal energy, driven by the gravitational interactions of the Sun, Moon and Earth, can be harnessed in two main ways: through tidal stream and tidal range technologies [3]. The former are designed to extract kinetic energy from tidal currents, while tidal range schemes (TRS) harness potential energy from fluctuations in the sea level. TRS rely on solid structures, such as lagoons or barrages, to impound water at high tide and release it back to the ocean at low tide.

Owing to its geographical and oceanographic characteristics, the UK holds 10% of the global tidal resource, with significant potential for tidal energy generation—estimated to exceed 200 TWh/y [4, 5]. Moreover, the UK has the second-largest tidal range in the world, making it an attractive location for TRS [6]. Unlike solar and wind power, the timing and amplitude of tidal range power generation are highly predictable, as tidal patterns near potential TRS sites can be forecasted accurately many years in advance [7, 8].

FIGURE 1 | Proposed tidal range schemes (TRS) and their location in the UK. [Data from [6, 9]. The circle denotes the location of the three TRS considered in the study].

Despite the substantial global potential of TRS, only four tidal range projects are currently operational worldwide. Among them, two large barrages—Lake Sihwa in South Korea and La Rance in France—have capacities of 254 and 240 MW, respectively [7]. In the UK, a number of TRS projects have been proposed (see Figure 1), with a combined capacity of 37 GW, potentially generating 55 TWh/y [6, 9]—enough to meet 17% of the UK's current electricity demand. However, due to high initial capital costs, the levelized cost of electricity (LCOE) from TRS is relatively high [10, 11], hindering their further development.

Nevertheless, according to the projections by the National Energy System Operator (NESO), 0.5–4.3 GW of tidal range energy will be required by 2050 to help meet the net-zero targets [12]. In addition to being a generation technology, TRS can store a certain amount of potential energy during periods of low electricity demand and release it when needed, thereby functioning as short-term energy storage facilities [13]. This unique feature of TRS is particularly useful in addressing the supply and demand imbalances created by the growing use of intermittent energy sources, such as wind and solar. It is estimated that 14–19 GW of new electricity storage will be needed by 2030 and 34–47 GW by 2050 to balance the new solar and wind capacity in the UK [12]. Operating TRS as energy storage facilities could enhance their revenue streams and improve their financial viability. Therefore, it is essential to investigate TRS not only as renewable electricity sources but also as storage systems.

In spite of their significant potential, TRS remain controversial in the UK. One of the reasons for that is their environmental impacts, which depend on many factors, including whether they are barrages or lagoons, their location, scale and mode of operation. Over the years, a number of studies have considered the environmental impacts of TRS, most focusing on the immediate environment, such as loss of habitats, changes in flood risks and impacts on aquatic life. The most recent such study has been carried out for the Severn Estuary located in the southwest UK [9], where a number of TRS schemes are proposed (Figure 1). While the immediate environment is important, it is also essential that the impacts of TRS be assessed more broadly, across their whole life cycle, to determine their implications beyond the direct impacts and avoid any burden shifting. As each type of study captures different impacts, they complement each other and should be considered in parallel when considering TRS proposals, along with their socio-economic implications.

Some studies have already considered the impacts of TRS in the UK on a life cycle basis using life cycle assessment (LCA). Carried out between 10 and 20 years ago, they primarily considered barrage schemes in the Severn Estuary (Table 1). They were conducted as streamlined or screening assessments, focusing on only two indicators associated with electricity generation: the carbon footprint and energy payback period. The earliest study, carried out for the Cardiff–Weston Barrage (later known as the Severn Tidal Bar) in 2007 [14], estimated the carbon footprint of tidal electricity at 2.4 g CO_2 eq./kWh. However, it is important to note that it included construction of the TRS solely and excluded other life cycle stages, such as transport of materials to the site, operation, maintenance and decommissioning. Another screening study, also based on the construction-materials data for the Cardiff–Weston Barrage, estimated the carbon footprint of tidal electricity at 3.0–3.3 g CO_2 eq./kWh [15]. Subsequent studies of the same TRS [16, 17], which considered transport and operation but excluded maintenance and decommissioning, found that the

TABLE 1 | Summary of LCA studies of tidal range schemes.

Study	Scheme[a]	Life cycle stages considered	Carbon footprint (g CO_2 eq./kWh)	Energy payback period (years)
(SDC) Susstainable Development Commission [14]	Cardiff–Weston Barrage	Construction only	2.4	NA
Banerjee et al. [15]	Cardiff–Weston Barrage	Construction only	3.0–3.3	0.5
Kelly et al. [16]	Cardiff–Weston Barrage	Dredging, construction, turbines, transport and operations	10.5–80.4[b]	6
Hammond et al. [17]	Cardiff–Weston Barrage	Dredging, construction, transport and operations	9.5–11	7
Hammond et al. [18]	Shoots Barrage	Dredging, construction, transport and operations	8	6.6
Douziech et al. [19]	Annapolis Barrage (Canada)	Construction, transport, operations, maintenance and end-of-life	3.9	NA

[a]All schemes except Annapolis (Canada) are based in the Severn Estuary in the UK (Figure 1). The Cardiff-Weston Barrage is also known as the Severn Tidal Bar.
[b]The lower value is without flood pumping and the higher value is with pumping using electricity from coal.

operation stage was the most significant contributor to the energy and carbon footprints of the Barrage, mainly due to the use of electricity for flood pumping. Similar findings were reported in a study of the Shoots Barrage, located upstream in the Severn Estuary, as shown in Figure 1 [18]. In contrast, a screening LCA of the Annapolis Barrage in Canada, the only other LCA study outside the UK but also quite dated, found that the contribution of operation (along with maintenance and transport) was negligible [19]. Nevertheless, the estimated carbon footprint was higher (3.9 g CO_2 eq./kWh) than the values reported in any of the UK-based studies.

The above discussion highlights the absence of comprehensive LCA studies of TRS. Furthermore, none of the existing studies have considered the potential of TRS to function as both electricity generation and storage systems. Therefore, to fill these gaps, this study first aims to understand better the environmental sustainability of tidal energy by assessing for the first time the life cycle environmental impacts of small, medium and large TRS as electricity generators and comparing them with other generating technologies. Second, it evaluates the impacts of TRS as configurable grid-scale energy storage systems in comparison with other storage technologies, such as pumped hydro, batteries, compressed air and liquid air energy storage. This is followed by an assessment of the potential role of TRS in decarbonizing the UK grid and helping meet the net-zero targets, along with a discussion of their socio-economic implications and public acceptability.

2 | Methods

The environmental impacts are estimated via attributional LCA, in accordance with the ISO 14040 and ISO 14044 standards [20, 21]. The systems have been modeled in the "LCA for Experts" software, formerly known as GaBi [22]. The subsequent discussion on the role of TRS in decarbonizing the UK grid and related impacts is derived from the LCA results. In contrast to the LCA, a comprehensive assessment of the socio-economic implications and public acceptability of TRS is not carried out, as it has been well documented in other studies. Instead, they are discussed with reference to the published literature.

The following subsections outline the goal and scope of the study, detail the life cycle inventory data and outline the impact assessment methodology used to calculate the impacts.

2.1 | Goal and Scope of the Study

The study has four goals:

i. To evaluate the life cycle environmental impacts of electricity generation from TRS in the UK considering their different scales (small, medium and large) and compare them to other sources contributing to grid electricity;

ii. To assess their environmental impacts when operated for both electricity generation and storage in comparison with some other electricity generating and storage technologies;

iii. To consider the potential role of TRS in decarbonizing the UK grid by 2050 and determine the associated life cycle impacts; and

iv. To explore public acceptability and other socio-economic issues associated with their deployment at the UK level.

In the first objective, the impacts of TRS are compared to the following main electricity sources present in the UK grid: wind, solar photovoltaics (PV), hydro, nuclear and natural gas. Furthermore, the impacts of the proposed TRS designs are compared with configurations optimized to maximise both electricity generation and storage. Additionally, the first objective aims to identify

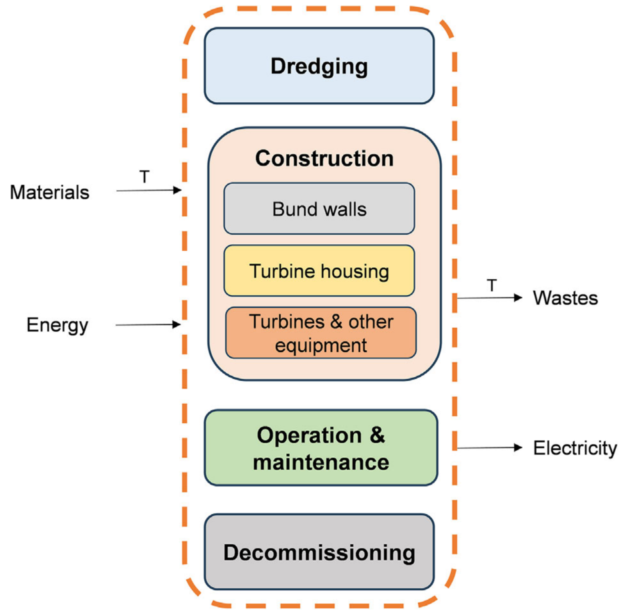

FIGURE 2 | System boundary for electricity generation and storage by tidal range schemes.

environmental hotspots within the TRS systems that could inform strategies for reducing their impacts. For the second objective, the environmental performance of TRS serving the dual function of energy generation and storage is compared with wind electricity coupled with one of the following storage technologies: pumped hydro, batteries, advanced compressed air energy storage (A-CAES) and liquid air energy storage (LAES). Wind is selected for comparison as the renewable electricity source with the highest share in the grid, while the storage options are chosen based on their relevance for the UK [12]. In addition, two sources are considered for pumping to evaluate the effect on the impacts of the TRS: grid and wind electricity. The third objective considers potential deployment of the proposed TRS by 2050 to determine their contribution to the net-zero targets at the UK level and any trade-offs with other life cycle impacts. The final objective broadens the discussion to key socio-economic aspects of TRS, along with public acceptability, to provide a more complete picture of their sustainability and help inform decision makers and other stakeholders.

The scope of the LCA study is from cradle to grave. The system boundary, illustrated in Figure 2, comprises dredging, construction (civil works and manufacturing of electromechanical equipment), operation, maintenance and decommissioning. It also accounts for transport of materials and management of waste across the life cycle. Based on the first and second goals of the study, two functional units are defined, respectively: (i) generation of 1 MWh of electricity, considered here as the base case; and (ii) generation and storage of 1 MWh of electricity, considered as the optimized case. The split between generation and storage in the second functional unit is 0.8 and 0.2 MWh, respectively, based on the inventory data for the TRS considered in this study, as explained in Section 2.2.3.

2.2 | Inventory Data and Assumptions

This section presents the life cycle inventory (LCI) data and assumptions for the TRS and the other electricity generation and storage technologies considered in the study. Primary data for the TRS have been obtained from design documentation and project developers, supplemented with government reports and literature. Background LCI data are sourced from the Ecoinvent v3.10 database [23]. The following sections describe the TRS systems selected for analysis and the data used for the LCA modeling, followed by a description of the other electricity generating and storage technologies.

2.2.1 | Description of the Tidal Range Schemes

The following three TRS are selected for consideration as representative cases across the sizes, all based in the Severn Estuary (Figure 1):

1. Small: Swansea Bay Tidal Lagoon (SBTL);
2. Medium: West Somerset Lagoon (WSL); and
3. Large: Severn Tidal Bar (STB) (previously known as the Cardiff-Weston Barrage).

These TRS are selected for two reasons: to cover a range of sizes and due to data availability. Regarding the latter, most of the proposed TRS are at a conceptual stage, and data needed for LCA are not available. These three schemes are the exceptions, with the SBTL and STB being designed in detail and submitted for planning approvals, and the WSL being at a preliminary design stage. Table 2 provides an overview of their key design parameters, with their brief description provided in the next sections.

2.2.1.1 | Swansea Bay Tidal Lagoon (Small Size). Swansea Bay is situated on the South Wales coastline in the Bristol Channel. Since 2004, various companies have been proposing tidal lagoon developments in the area. In the most recent proposal [24], the lagoon is designed to encompass 11.5 km^2 of tidal area. It would be constructed using a 9.5 km U-shaped breakwater sea wall. The proposed lagoon includes an 800 m^2 sluicing area and 16 bulb turbines, with a total installed capacity of 320 MW. The net annual power generation is estimated at around 534 GWh. Although the SBTL proposal was strongly recommended by an independent review commissioned by the UK government in 2016 [6], it was ultimately not supported due to high projected costs. However, efforts to revive the project through private sector funding are ongoing [28].

2.2.1.2 | West Somerset Lagoon (Medium Size). This TRS is based in the Bristol Channel, off the coast of West Somerset [25]. The lagoon features a semi-circular breakwater with a total perimeter of 22 km and an enclosed area of 80 km^2. It is proposed to construct the TRS using prefabricated reinforced concrete caissons. A total of 125 bulb turbines are envisaged, each with a diameter of 7.2 m and a capacity of 20 MW, resulting in a total installed capacity of 2500 MW. The WSL is designed to generate

TABLE 2 | Main design parameters for the three tidal range schemes considered in the study.

Design parameters	Swansea Bay Tidal Lagoon [24]	West Somerset Lagoon [25]	Severn Tidal Bar [26]	Units
Installed capacity	320	2500	6500	MW
Annual electricity output	534	6500[a]	16 500	GWh/y
Lagoon perimeter/barrage length	9.5	22	18	km
Lagoon area	11.5	80	NA	km^2
Turbines	16	125	1026	number
Sluice gates	6	160	53[b]	number
Design lifetime	120	120	120	years

[a]Without pumping, the designed output is 5780 GWh/y [27]. However, pumping would be needed to maintain the water levels in the lagoon to minimise the loss of intertidal habitat, which would increase the electricity output to 6500 GWh/y [25].
[b]Sluice caissons.

electricity during both ebb and flood tides, with an estimated annual output of 6.5 TWh.

2.2.1.3 | Severn Tidal Bar (Large Size). This scheme, also known as the Cardiff–Weston Barrage, was originally proposed in 1981 and a comprehensive feasibility report was published in 1989 [29], evaluating the project from the technical, economic, social and environmental perspectives. This remains the most detailed study of any TRS in the UK.

In 2010, the then Department of Energy and Climate Change (DECC) published a series of detailed reports on the feasibility of the STB, concluding that there was no compelling case for public investment in a TRS in the Severn Estuary [30]. However, in 2011, a private consortium submitted a business plan to the government with some modifications to the original proposal [31]. The consortium proposed to construct an 18 km tidal barrage with an estimated annual generation of 16.5 TWh by 1026 very-low-head (VLH) bi-directional turbines, with a capacity of 6.3 MW each [31]. The proposal claimed that the scheme could meet approximately 5% of the UK's current electricity demand.

The next sections provide an overview of the inventory data used in the LCA modeling. First, the data for the base case are presented, assuming the use of TRS solely for electricity generation. This is followed by the data for the optimized case whereby the TRS are operated for both generation and storage of electricity.

2.2.2 | Inventory Data for the TRS Used Solely for Electricity Generation (Base Case)

The LCI data used in the base case (related to the functional unit 'generation of 1 MWh electricity') are presented in turn for each life cycle stage shown in Figure 2.

2.2.2.1 | Dredging. Extensive dredging is required to establish a stable foundation for barrage or lagoon walls on the bedrock, install caissons and construct housings for turbines and sluice gates. Where applicable, dredging is also necessary to achieve the required depth for the lagoon or barrage, create navigation channels and facilitate caisson towing.

Various types of dredger may be employed depending on the material type and water depth, including trailer suction hopper, large rock cutter suction, grab and continuous flight bucket dredgers. According to a recent report [32], the average fuel consumption of dredgers in the UK is approximately 2.4 kg/t of marine sand and gravel dredged and delivered to a wharf. The estimated volume of dredged material for the three selected TRS ranges from 8.1 to 50 Mm^3, as shown in Table 3. Based on the design proposals, a significant portion of the dredged material is reused for embankment construction and caisson ballast. The remaining unsuitable or surplus material is assumed to be transported to nearby disposal sites, with an average transport distance of 20 km.

2.2.2.2 | Construction of TRS. The construction of TRS is highly capital-intensive, with material and energy requirements varying significantly depending on the type and design of the scheme. This stage comprises construction of embankments and bund/sea walls, production of turbine housing, turbines, and other electromechanical equipment. The quantities of construction materials required for the embankment and related infrastructure are presented in Table 4, based on estimates from project proposals and data from project developers.

For the SBTL, geo-tubes filled with dredged material and armor rocks are proposed for constructing embankments and bund walls. The WSL and STB will require substantial quantities of crushed and armor rock for embankments and breakwaters (Table 4). It is assumed that crushed rock will be sourced from UK quarries, while the armor stone will be imported from Scandinavia as the UK market is unlikely to meet the demand [26, 35].

The STB is designed to be constructed using prefabricated concrete caissons, which will be constructed in dry docks, then towed and floated to the barrage site. The average towing distance

TABLE 3 | Inventory data for dredging.

	Swansea Bay Tidal Lagoon [33]	West Somerset Lagoon [34]	Severn Tidal Bar [26]	Units
Volume of dredged material	8.1	11.8	52	Mm^3
Fuel use[a]	33	48	212	kt
Dredged material used in the construction	7.3	11.6	49.9	Mm^3
Surplus dredged material (for disposal)	0.8	0.2	2.1	Mm^3
Transport of surplus dredged material (for disposal)	2.7×10^7	6.8×10^6	7.1×10^7	t·km

[a]Estimated using the average fuel consumption by dredgers of 2.4 kg/t material dredged and the density of dredged material of 1.7 t/m^3 [32].

TABLE 4 | Inventory data for construction of the embankment and related TRS infrastructure.

Activities/Main inputs[a]	Swansea Bay Tidal Lagoon [33, 36]	West Somerset Lagoon [34]	Severn Tidal Bar [26, 35]	Units
Geo-tubes[b]	43	—	—	t
Rocks (armor and under layer)	2.8	20	15.5	Mt
Transport of rocks[c]	750	22 000	20 750	Mt·km
Concrete and mortar	1.0	5.2	21	Mt
Reinforcing steel	0.07	0.4	1.5	Mt
Stainless steel	3.0	48.0	200	kt
Sand and gravel	7.3	11.6	57.8	Mm^3
Fuel used in construction machinery, including transport of caissons[d]	15	52	224	kt

[a]Including embankments, bund and sea walls and turbine housings.
[b]Estimated from literature [37] based on the geo-tube design data. Considers only the mass of geo-tubes; the filling is considered separately (rocks, mentioned in this table, and dredged material shown in Table 3).
[c]Estimated based on the distance from the potential quarries for each site. For transport details, see Table S3.
[d]Transport from the caissons construction yards to the site by tugboats. Fuel use estimated based on data from literature [34].

from the caisson fabrication yards to the site is estimated at approximately 100 km [17]. Similarly, the lagoon enclosure and turbine housing for the WSL will also be constructed using pre-fabricated reinforced concrete caissons. In the case of the SBTL, temporary cofferdams will be built to facilitate the construction of the turbine and sluice gate housing [36]. Data on the materials and energy used for the WSL construction are sourced directly from the project developer [34], while data for the SBTL and STB are from published studies [26, 33, 35, 36].

The inventory data for the electromechanical equipment are summarized in Table 5. As mentioned earlier, the STB will use 1025 6.3-MW turbines, each weighing approximately 400 t [31]. Previous LCA studies on tidal turbines have primarily focused on smaller units with rated capacities between 0.5 and 2 MW [38, 39], and there are currently no publicly available LCA studies on large-scale tidal turbines. However, a study conducted by the DECC [35] as part of the STB feasibility assessment provides a detailed breakdown of the material composition of these turbines. These data have been used to estimate the inventory for the STB turbines (Table 5). In contrast, both the SBTL and WSL are designed to use bulb turbines, with installed capacities of 20 MW per unit. In the absence of specific data for these turbines, the LCI data for the SBTL and WSL turbines have been estimated by scaling up the STB turbine data using Equation (1), in accordance with standard engineering practice for scaling up the costs of industrial plants and equipment based on the capacity [40]:

$$E_2 = E_1 \left(\frac{C_2}{C_1} \right)^{0.6} \tag{1}$$

E_1 environmental impacts of constructing/manufacturing the smaller plant/equipment;

E_2 environmental impacts of constructing/manufacturing the larger plant/equipment;

C_1 capacity of the smaller plant/equipment;

C_2 capacity of the larger plant/equipment.

TABLE 5 | Inventory data for manufacturing of electromechanical equipment.

Activities/Main inputs[a]	Swansea Bay Tidal Lagoon	West Somerset Lagoon	Severn Tidal Bar	Units
Carbon steel	10.1	78.7	324.3	kt
Stainless steel	0.6	4.5	18.5	kt
Special alloys	0.4	3.5	14.4	t
Silicon steel	1.0	8.0	32.8	kt
Copper	0.5	4	16.4	kt
Mineral wool (insulation)	0.1	1	4.1	kt

[a]Estimated from literature [31, 35] based on the inventory data for the turbines and generators for the Severn Tidal Bar.

TABLE 6 | Key operation and maintenance activities over the lifetime of the TRS in the base case.

Activities/Main inputs	Swansea Bay Tidal Lagoon [33]	West Somerset Lagoon [34]	Severn Tidal Bar [16, 41]	Units
Electricity for pumping	—	130	1625[a]	GWh/y
Lube oil[b]	0.5	5.3	15.4	kt
Maintenance dredging	42	24.4	240	Mm^3
Maintenance of embankments and other structures[c]	25	25	25	% of initial construction
Replacement time of turbines and other equipment	60	60	60	years

[a]Includes 167 GWh/y of electricity needed for ancillary processes [16].
[b]Estimated from Ecoinvent [42].
[c]Assumed that the materials and energy used for the maintenance of these structures over 120 years would be equivalent to 25% of the materials and energy used in the construction stage (Table 4).

The above equation is considered a reasonable approximation, as both costs and environmental impacts of capital infrastructure are based on the costs of materials used.

It is assumed that the turbines have a service life of 60 years and will therefore be replaced once over the lifetime of each TRS.

2.2.2.3 | Operation and Maintenance. During operation, some TRS may require water pumping to raise the water level within the lagoon or basin for operational reasons. For the SBTL, no pumping is anticipated. However, for the WSL, pumping may be necessary during neap tides (during which there is a small difference between high and low water) to restore lagoon levels to minimise the loss of intertidal habitat. Similarly, for the STB, limited "flood pumping" would be required to raise the basin-side water level artificially prior to generation [16]. Assuming that the operation would start in 2030, the grid electricity projected for that year grid [12] is used for all pumping operations; for the assumed 2030 electricity mix, see Table S1. Additionally, a small amount of grid electricity may be consumed for auxiliary processes when the TRS are not generating power (see Table 6).

Various maintenance activities are expected over the lifetime of each TRS, as summarized in Table 6. These include:

- Maintenance dredging, which depends on sediment concentration, geomorphology and tidal conditions. For the SBTL, maintenance dredging is expected every two years [33] and every five years for the WSL [34], to maintain the depth of the lagoon and the head difference required for efficient electricity generation. For the STB, maintenance dredging is not anticipated for power-generation purposes but may be required to maintain navigation channels for port access [41]. It is also assumed that no maintenance dredging will be required during the first 15 years of operation.
- Embankment and bund wall maintenance, for which it is assumed that the cumulative maintenance effort over the TRS lifetime will be equivalent to 25% of the initial construction effort in terms of the materials and energy used (see Table 4) due to the lack of detailed data in project proposals; this assumption has been tested through a sensitivity analysis.
- Electromechanical equipment maintenance and replacement, with turbines and associated equipment assumed to have a 60-year lifespan, requiring one replacement during the operational life of the TRS [34].

2.2.2.4 | Decommissioning. The lifespan of TRS civil structures typically extends beyond the nominal 120 years [41]. Therefore, estimating data for TRS decommissioning is challenging. According to the decommissioning plan for the SBTL, most of the structure is expected to remain in situ, with the lagoon potentially repurposed for leisure activities [36]. It is assumed that the turbines and generators will be removed and recycled, while

TABLE 7 | Electricity input and output of the selected TRS in the optimized case.

Inputs and outputs	Swansea Bay Tidal Lagoon	West Somerset Lagoon	Severn Tidal Bar	Units
Total electricity output (including storage)[a], of which:	0.688	7.19	20.85	TWh/y
Electricity generation[b]	0.534	5.78[c]	16.5	TWh/y
Electricity storage[d]	0.154	1.41	4.35	TWh/y
Electricity required for pumping[a]	0.05	0.34	2.85	TWh/y

[a]Data from [27].
[b]As in the base case (Table 2).
[c]Without pumping (see footnote "a" in Table 2).
[d]Calculated as the difference of electricity generation with pumping (in the optimized case) and electricity generation without pumping (in the base case in Table 2).

turbine housings will be protected with armor rocks. Similar assumptions are made for the WSL. For the STB, it is anticipated that the electromechanical components will be decommissioned and recycled, while the main structure will remain in place to provide flood protection against storm surges in the upstream basin [35, 43].

For the equipment recycling, it is assumed that steel and copper will be recycled, crediting the system for the avoided production of virgin materials using system expansion and the "net scrap" method. This means that the system is credited only for the amount of the recycled material that exceeds the recycled content in the original raw materials [44]. For example, if the recycling content in the original raw material is 40% and the recycling rate at the end of life is 90%, then the system is credited for the remaining 50% of the avoided production of the virgin material.

2.2.3 | Inventory Data for the TRS Used for Electricity Generation and Storage (Optimized Case)

The optimized case considered in this work is aimed at maximizing generation to enable storage of electricity. Hence, the functional unit in this case is generation and storage of 1 MWh of electricity. The inventory data are the same as in the base case for all the life cycle stages, except for the operation stage, as detailed below.

Previous work has demonstrated that the annual electricity output of various TRS in the UK could be increased by up to 35% through the use of pumping [27]. Unlike conventional hydro-pumped storage systems, where pumping typically exceeds electricity generation due to efficiency losses, TRS can offset these losses. This is achieved by utilizing the reversible turbines and operating them to pump water when the internal water level is close to the external sea level and releasing it when the external level drops during the ebb tide, thereby creating a larger head difference and improving generation efficiency [45].

The annual electricity output and the electricity required for pumping in the optimized case are presented in Table 7. It can also be inferred from the table that the storage accounts for ~20% of the total electricity output. Therefore, as mentioned in Section 2.1 when defining the second functional unit, the split between electricity generation and storage is 0.8 and 0.2 MWh, respectively. For pumping, two electricity sources are considered: 2030 grid electricity (Option 1) and wind (Option 2).

2.2.4 | Other Electricity Generation and Storage Technologies

As mentioned earlier, TRS is compared with other electricity-generating and storage technologies which are described in turn in the next sections.

2.2.4.1 | Electricity Generation. The LCA impacts of TRS are compared with the main sources of electricity generation in the UK, i.e., wind, solar PV, hydro, nuclear and natural gas [12]. The LCA data for these technologies have been sourced from Ecoinvent 3.10 [23]. In addition, a future electricity mix is expected to include carbon capture and storage (CCS) for biomass and natural gas power plants (Table S1), which are also considered here. The inventory data for CCS are sourced from the literature [46], with details provided in Table S2.

2.2.4.2 | Electricity Storage. Grid-scale electricity can be stored using a variety of technologies, including pumped hydro storage (PHS), battery energy storage (BES), compressed air energy storage (CAES), liquid air energy storage (LAES), hydrogen and ammonia-based systems [47]. The UK currently has a total installed electricity storage capacity of 6.2 GW, comprising 2.7 GW from pumped hydro and 3.5 GW from battery storage [48]. Future energy scenarios developed by the National Grid [49] anticipate the deployment of a mix of pumped hydro, batteries, advanced CAES (A-CAES) and LAES by 2050 to meet grid-scale electricity storage needs in the UK. Hydrogen and ammonia-based storage systems are excluded from these scenarios due to their low round-trip efficiencies (see Table 8) and high costs [47]. Moreover, green hydrogen is expected to be primarily used in fuel-cell vehicles or injected into the gas grid [50]. Therefore, this study compares the environmental performance of TRS with the following four electricity storage technologies: pumped hydro, BES, A-CAES and LAES. Inventory data for the last three have been sourced from literature (Tables S4–S6), while data for pumped hydro are from Ecoinvent. Further details on the data

TABLE 8 | Efficiency and technology readiness level (TRL) of large-scale electricity storage technologies [47].

Electricity storage technology	Round-trip efficiency	TRL
Pumped hydro storage	≤ 80%	9
Battery energy storage	≤ 90%	9
Advanced compressed air energy storage	≤ 70%	7–8
Liquid air energy storage	≤ 55%	7
Hydrogen (storage in caverns and conversion to electricity by 4-stroke engines)	≤ 40%	6–7
Ammonia (storage in large tanks and conversion to electricity)	≤ 35%	5

sources and assumptions used for inventory data are provided below, along with a brief description of each technology.

Pumped hydro storage: PHS is a mature and widely adopted technology for large-scale energy storage. It stores excess electricity as gravitational potential energy by pumping water from a lower reservoir to a higher one. When electricity demand increases, the stored water is released to flow back down through turbines, generating electricity. For this study, a round-trip efficiency of 80% is assumed for PHS systems [51]. The rest of the inventory data for the construction and operation of PHS facilities in the UK are sourced from Ecoinvent [23].

Battery energy storage: Several technologies are under consideration for grid-scale electricity storage, including lithium-ion, lead-acid and redox flow batteries [47]. Among these, lithium-ion batteries are the most widely deployed in the UK, accounting for over 90% of grid-scale installations [31]. They also offer high round-trip efficiencies and have reached a technology readiness level of 9, as shown in Table 8.

Several types of lithium-ion battery are currently available [47]. This study focuses on lithium nickel-manganese-cobalt (NMC) oxide batteries, which are commonly used in grid applications and are associated with lower environmental impacts and costs compared to other lithium-ion batteries [52]. The key assumptions and inventory data for the battery storage system are provided in Table S4. The foreground data are sourced from the literature [53], while the background data are from Ecoinvent [23].

Advanced compressed air energy storage: CAES is considered a promising solution for grid-scale energy storage due to its potential for long-duration operation, low operating costs, and long service life [54]. In CAES systems, energy is stored in the form of pressurised air in underground storage caverns, such as repurposed salt mines [55]. To generate electricity, the stored air is heated and expanded to drive a turbine. A-CAES systems recover and store the heat generated during the compression phase using a thermal energy storage system, which is subsequently used to heat the air [55, 56]. The inventory data for the A-CAES system considered in this study are sourced from the literature [57] and detailed in Table S5, based on a 150 MW capacity. This system is capable of stabilizing the intermittency of a 400 MW wind power plant and can increase its capacity factor from 40% to > 80% [57]. It should also be noted that, currently, there are no A-CAES systems installed anywhere in the world, but there are two CAES systems in operation: one with a capacity of 290 MW in Germany and another with 110 MW in the US [58]. Hence, the 150 MW capacity of the A-CAES system considered here is in the range of the currently operating commercial CASE plants.

Liquid air energy storage: This technology operates on a principle similar to CAES. However, in LAES systems, air is liquefied and stored in well-insulated, low-pressure vessels. A key advantage of LAES is its significantly higher energy density, approximately ten times greater than that of CAES, allowing for a much smaller system for the same storage capacity [55]. The inventory data for the LAES system considered here are presented in Table S6. They are based on literature data for a 50 MW capacity plant [57, 59]. To enable a fair comparison with the A-CAES system, these data have been scaled up to a 150 MW capacity using Equation (1).

For comparison with the TRS, assuming their dual function as both generating and storage facilities (optimized case), the above four storage options are considered, each coupled with wind electricity in turn. The latter is selected over the other electricity options due to its highest share in the UK grid (see Table S1). In congruence with the TRS, each wind-and-storage option generates 0.8 MWh and stores 0.2 MWh.

As in the optimized TRS case, two options are considered for operating the wind-and-storage systems: 2030 grid electricity (Option 1) and wind (Option 2).

2.3 | Life Cycle Impact Assessment

The life cycle environmental impacts have been estimated using the ReCiPe 2016 V1.1 impact assessment method at the midpoint level, following the hierarchist approach [60]. For transparency and comprehensiveness, all 18 impact categories included in this method are considered: climate change, fossil depletion, freshwater consumption, freshwater eutrophication, freshwater ecotoxicity, human toxicity (cancer and non-cancer), ionizing radiation, land use, marine eutrophication, marine ecotoxicity, metal depletion, ozone depletion, particulate matter formation, photochemical ozone formation (ecosystems and human health), terrestrial acidification and terrestrial ecotoxicity.

2.4 | Implications of TRS Deployment at the UK Level

2.4.1 | Environmental Implications

Aligned with the net-zero timeline, the potential role of TRS in contributing to the net-zero targets and the associated life cycle impacts are evaluated for the year 2050, considering a potential UK-wide deployment of some of the currently proposed

TABLE 9 | Annual electricity generation potential of the selective TRS in the UK [27] assumed to be operational by 2050.

TRS	Electricity generation potential (GWh/y)		Electricity storage potential (GWh/y)
	Base case	Optimized case	Optimized case
Aberthaw Lagoon	202	273	71
Cardiff Lagoon	5283	6467	1184
Mersey Tidal Barrage	1033	1280	247
Morecambe Barrage	7518	9569	2051
Newport Lagoon	2975	3658	683
North Wales Lagoon	4489	5543	1054
Severn Tidal Bar	16 500	20 850	4350
Solway Firth Barrage	5691	5941	250
Swansea Bay Tidal Lagoon	534	688	154
West Somerset Lagoon	5785[a]	7195	1410
Total	50 010	61 464	11 454

[a]Without pumping. With pumping, the electricity output is 6.5 TWh/y [25].

schemes. Taking a conservative approach and assuming that not all of the 20 TRS currently proposed will be realized, only half are included in this analysis. These are listed in Table 9, along with their estimated annual generation potential in the base and optimized cases. As can be seen in the table, these proposed schemes could generate 50 TWh/year in the base case and up to 61.46 TWh/year in the optimized case. In the latter, the TRS would also provide 11.45 TWh/year of electricity storage. The three TRS evaluated in this work could generate around half of the total electricity (22.8 TWh/y in the base and 28.7 TWh/y in the optimized case) and provide half of the total storage capacity (5.9 TWh/y; Table 9).

The National Energy System Operator (NESO) has developed three pathways—Holistic transition, Electric engagement and Hydrogen evolution—to explore how the UK could achieve a net-zero energy system by 2050 [12]. The Electric engagement pathway mainly focuses on reducing energy demand through smart technologies, while the Hydrogen evolution pathway assumes hydrogen providing 40% of energy (electricity and heat) demand. Holistic transition is midway between the other two pathways and has lower costs [61]; hence, it is more likely to be followed. In this pathway, total electricity demand in 2050 is projected to reach 820 TWh/y (see Table 10), with 8% of this expected to be met by various energy storage technologies. However, only a small contribution of tidal energy is considered (2.6 TWh or 0.3%), and the use of TRS for storage is not included. Therefore, to enable assessing the environmental implications of integrating a much higher share of TRS into the UK grid, commensurate with its estimated potential, three new scenarios have been developed as part of this study. As shown in Table 10, these scenarios incorporate 61.46 TWh/y (7.5%) of electricity from TRS, of which 11.45 TWh/y is assumed to offset the need for other storage technologies, while the remaining 50 TWh/y is assumed to displace electricity from non-renewable (natural gas and/or nuclear) generation sources. Given that TRS would store electricity for shorter times, they are more likely to offset battery storage rather than other storage technologies (pumped hydro, CAEA, and LAES) which are used for long-duration storage. Hence, battery storage is assumed to be replaced by TRS in each scenario. Regarding the replacement of non-renewable electricity sources, the first scenario assumes all electricity from natural gas is displaced by TRS, the second displaces all nuclear power, while in the third, half of electricity from natural gas and half from nuclear power is replaced by TRS. Therefore, the scenarios are defined as follows:

- S-1: TRS displaces 50 TWh/y of natural-gas electricity (with CCS) and 11.45 TWh/y of battery storage;
- S-2: TRS displaces 50 TWh/y of nuclear electricity and 11.45 TWh/y of battery storage; and
- S-3: TRS displaces 25 TWh/y of natural-gas and 25 TWh/y of nuclear electricity and 11.45 TWh/y of battery storage.

In addition, the following sensitivity analysis for S-1 is carried out:

- S-1A: only 50% of the assumed TRS potential would be realized by 2050, i.e. TRS would provide 25 TWh/y of electricity and 5.725 TWh/y of storage, displacing electricity from natural gas and battery storage as in S-1.

The life cycle inventory data for all the electricity sources shown in Table 10 are sourced from Ecoinvent, except for TRS, for which the data are based on the average of three TRS assessed in this study.

Wind electricity has been assumed for operating all the systems as it is projected to be by far the largest single source of electricity (60%) in the 2030 grid (Table S1) and hence more likely to be used for these purposes than other sources. Both offshore and

TABLE 10 | The assumed grid composition in 2050 based on the projection by the National Energy System Operator (NESO) [12].

Electricity source	NESO (Holistic transition pathway)	This study (modified to include higher contribution of TRS for both generation and storage)			
	Generation (TWh/y)	S-1 (TWh/y)	S-2 (TWh/y)	S-3 (TWh/y)	S-1A (TWh/y)
Generation					
Wind (offshore)	397	397	397	397	397
Wind (onshore)	95	95	95	95	95
Nuclear	94	94	46	70	94
Solar PV	83	83	83	83	83
Natural gas with CCS	52	5	52	28	30
Biomass	0.4	0.4	0.4	0.4	0.4
Biomass with CCS	21	21	21	21	21
Hydro	4	4	4	4	4
TRS	2.6	50	50	50	25
Others	9	9	9	9	9
Storage					
Battery storage	36.9	25.5	25.5	25.5	31.2
Pumped hydro storage	13	13	13	13	13
Compressed air energy storage	6.8	6.8	6.8	6.8	6.8
Liquid air energy storage	5.5	5.5	5.5	5.5	5.5
TRS storage	—	11.45	11.45	11.45	5.725
Total	820	820	820	820	820

[a]The total may be different from the values shown in the table due to the rounding off.

onshore wind electricity are considered, assuming an average of their respective impacts.

2.4.2 | Socio-Economic Implications

As mentioned in the goal and scope section, carrying out primary research on the socio-economic implications is not one of the aims of this paper as these aspects have been covered extensively in the literature. Instead, the paper relies on that literature to consider pertinent socio-economic issues surrounding TRS, to provide a more complete picture of the sustainability of tidal power and understand better any trade-offs with the life cycle environmental impacts. The socio-economic indicators considered include construction costs and LCOE, value added, provision (and loss) of jobs, community well-being and public acceptability of TRS.

3 | Results and Discussion

The LCA results are first discussed for the base case, i.e. when TRS is operated solely to generate electricity, with the functional unit defined as 'generation of 1 MWh of electricity'. This is followed in Section 3.2 by the impacts of TRS serving the dual function, for the functional unit of 1 MWh of generation and storage (0.8 and 0.2 MWh, respectively). Finally, the implications of TRS deployment at the UK level by 2050 are discussed in Section 3.3.

3.1 | Environmental Impacts of TRS Used for Electricity Generation (Base Case)

Table 11 presents the environmental impacts and rankings of electricity generation by TRS in comparison with the other electricity technologies in the UK. Overall, hydropower is the best option in most impacts, followed by the West Somerset Lagoon (WSL), with the exception of freshwater consumption for which the WSL is the best and hydro the worst option. The remaining two TRS are generally middle-ranking.

In addition to freshwater consumption, the WSL also ranks as the best option for climate change, along with nuclear power. All three TRS offer a 96%–98% reduction in this impact relative to natural gas and a 79%–91% reduction on solar PV electricity. Electricity from the WSL also demonstrates a 57% reduction in this category relative to wind and 15% relative to hydro power. On the other hand, the climate change values for Swansea Bay Tidal Lagoon (SBTL) and Severn Tidal Bar (STB) electricity are significantly higher (82%–140%) than those of both hydro and nuclear power. The STB and wind electricity have almost

TABLE 11 | A heatmap showing the life cycle impacts and ranking of the TRS (base case) in comparison with other electricity sources.

Impacts	SBTL[a]	WSL[a]	STB[a]	Hydro[b]	Solar PV	Wind[c]	Nuclear[d]	Natural gas[e]
Climate change (kg CO_2 eq./MWh)	15.90	7.48	17.78	8.76	85.06	17.52	7.43	465.68
Fossil depletion (kg oil eq./MWh)	4.62	2.66	7.67	1.22	27.56	5.35	298.20	180.83
Freshwater consumption (m^3/MWh)	0.10	0.07	0.19	14.67	2.79	0.20	3.08	0.81
Freshwater eutrophication (g P eq./MWh)	3.29	2.38	5.04	1.216	39.05	9.71	4.12	4.53
Freshwater ecotoxicity (kg DCB eq./MWh)	0.31	0.23	0.51	0.12	1.06	0.74	0.58	0.28
Human toxicity, cancer (kg DCB eq./MWh)	21.41	15.89	34.31	8.48	50.87	50.58	11.18	16.98
Human toxicity, non-cancer (kg DCB eq./MWh)	9.14	7.39	18.51	1.72	105.86	36.72	155.85	8.35
Ionizing radiation (kBq Co-60 eq./MWh)	0.53	1.58	6.91	0.31	5.47	0.64	739.75	1.28
Land use (crop eq./MWh y)	0.39	0.65	2.21	0.15	28.87	0.94	0.30	0.41
Metal depletion (kg Cu eq./MWh)	0.21	0.16	0.35	0.09	1.09	0.64	0.11	0.23
Marine eutrophication (g N eq./MWh)	0.39	0.32	0.87	0.14	6.38	1.31	13.69	12.30
Marine ecotoxicity (kg DCB eq./MWh)	1.12	0.72	1.42	0.39	4.05	2.39	1.06	1.29
Ozone depletion (mg CFC eq./MWh)	3.17	3.81	14.17	1.28	29.17	5.89	4.32	113.90
Particulate matter formation (g PM2.5 eq./MWh)	53.66	16.54	32.61	8.17	166.86	41.13	18.23	86.34
Photochemical ozone formation-ecosystem (g NOx eq./MWh)	141.43	34.53	67.02	17.05	232.36	51.04	41.15	499.51
Photochemical ozone formation-human health (g NOx eq./MWh)	138.82	33.70	65.28	16.51	220.42	49.11	38.95	475.04
Terrestrial acidification (g SO_2 eq./MWh)	136.04	37.37	74.41	12.50	355.07	92.42	35.62	233.42
Terrestrial ecotoxicity (t DCB eq./MWh)	0.78	0.46	0.82	0.23	3.56	1.39	0.41	0.85
Legend for the color coding and ranking of options	Best	2nd	3rd	4th	5th	6th	7th	Worst

[a]SBTL: Swansea Bay Tidal Lagoon; WSL: West Somerset Lagoon; STB: Severn Tidal Bar.
[b]Average of reservoir and run-of-river hydroelectricity.
[c]Average of offshore and onshore wind electricity.
[d]Average of pressure water and boiling water nuclear electricity.
[e]Average of conventional and combined cycle natural gas electricity.

the same climate change impact, while the SBTL shows a 9% reduction relative to wind.

Considering the other impacts, electricity from the WSL shows 1.5 times higher ionizing radiation than wind power, but 33%–80% lower values across all other categories. The SBTL electricity also has lower impacts than wind in 13 other categories, including freshwater eutrophication (66%), human toxicity (58% cancer and 75% non-cancer), metal depletion (67%) and marine eutrophication (70%). However, for particulate matter, photochemical ozone formation and terrestrial acidification, the SBTL shows 30%–183% higher values compared with wind power. Electricity from the STB performs better in 11 other categories but has higher fossil depletion (43%), ionizing radiation (10 times), land use (135%), ozone depletion (141%) and photochemical ozone (31%–33%). Compared with hydro, all three schemes show > 70% higher impacts across all other categories, except freshwater consumption, which is reduced by 99%.

Electricity from the TRS also exhibits a 33%–99% reduction across all other impact categories relative to solar PV. The exception is the STB, which shows a 26% higher ionizing radiation—largely attributed to the nuclear power in the grid electricity used for flood pumping. Against nuclear power, the WSL electricity has significantly (> 15%) lower values in nine other categories, with the highest reductions found (95%–99%) for fossil depletion, freshwater consumption, non-cancer human toxicity, ionizing radiation, and marine eutrophication. However, it shows higher impacts for cancer toxicity (42%) and metal depletion (44%). In contrast, the SBTL and STB exhibit higher values than nuclear in nine and 11 other categories, respectively. Finally, compared to natural gas, electricity from the WSL shows 6%–99% lower impacts in all other categories, except ionizing radiation and land use. The SBTL and STB also have significantly (> 15%) lower impacts than natural gas in 10 and nine other categories, respectively.

The system boundary for the TRS includes the decommissioning stage, whereas the Ecoinvent data for the other technologies exclude this stage. However, for some, particularly wind and solar PV, decommissioning would reduce their impacts due to the recycling credits for recovered materials, as observed in a cradle-to-grave LCA study on wind electricity [62]. The authors reported that the decommissioning stage lowered the climate change and several other impacts of wind electricity by 7%–25%, while increasing some ecotoxicity impacts by around 20%. Applying similar assumptions to solar PV (as studies on its decommissioning are not readily available in the literature, as far as the authors are aware) and assuming that decommissioning reduces the impacts of both wind and solar PV electricity by an average of 15%, the ranking of wind electricity improves relative to the SBTL in only two categories (climate change and fossil depletion), with no change in the ranking for any other impact categories for either solar PV or wind when compared with any of the TRS considered. This indicates that the inconsistency in the system boundaries is likely to have a minimal effect on the overall ranking of the TRS relative to the other technologies.

Among the three TRS, the WSL has the lowest impacts in all categories except for ionizing radiation, land use and ozone depletion, where the SBTL performs better. Compared to the SBTL, the WSL shows 17%–76% lower impacts in 15 categories. This is primarily due to two reasons: (i) the economies of scale, as the WSL is a larger lagoon; and (ii) favorable site conditions, including lower dredging requirements due to less silt in the water and tide levels. On the other hand, despite being the largest scheme and the expected economies-of-scale benefits, the STB exhibits the highest impacts in 14 categories, including climate change. This is largely attributed to the high electricity demand for flood pumping (see Table 6). Therefore, larger installations may not offer the environmental benefits that may be expected with the economies of scale, as the impacts will also depend on the type of the scheme, its design, tidal levels, and the amount of silt in the water affecting the dredging requirements. The contribution of different life cycle stages to the overall impacts is discussed below for each TRS in turn.

3.1.1 | Swansea Bay Tidal Lagoon

The contribution analysis for the SBTL, shown in Figure S1, indicates that the construction stage is the main hotspot for climate change and fossil depletion, contributing 39%–42% to these impacts. This stage also accounts for the majority of 12 other categories, including metal depletion (64%) and marine and terrestrial ecotoxicity (65% each). The impacts in the construction stage are largely driven by the concrete and reinforcing steel used in the construction. The operation and maintenance phase is the major contributor to the remaining six impact categories, also contributing significantly to climate change and fossil depletion (35% each). The impacts in the operation and maintenance stage are mainly due to maintenance dredging.

The turbines and other electromechanical equipment contribute > 15% to six categories: freshwater and marine eutrophication, human toxicity-non-cancer, metal depletion and marine and terrestrial ecotoxicity. Transport accounts for > 10% of climate change, land use and fossil and ozone depletion. Decommissioning is significant (> 15%) only for human toxicity-cancer and freshwater ecotoxicity due to the impacts of metals recycling. For most other categories, due to the credits from recycling of turbines and other equipment, the net impacts of decommissioning are negligible or even net-negative (savings).

3.1.2 | West Somerset Lagoon

As illustrated in Figure S2, operation and maintenance of the WSL is the major contributor to 13 impact categories, including climate change and fossil depletion, to which it contributes 43% and 55%, respectively. This is largely attributed to the use of grid electricity for operational pumping and to the replacement of turbines and other electromechanical equipment. This is followed by the construction stage, which is the main hotspot for the remaining five categories. The construction stage also contributes > 30% to climate change, freshwater and marine eutrophication, particulate matter, photochemical ozone and terrestrial acidification. Similar to the SBTL, the contribution of turbines and equipment is significant (> 15%) for freshwater and marine eutrophication, human toxicity-non-cancer, metal depletion and terrestrial ecotoxicity. Transport contributes > 15% to photochemical ozone and terrestrial acidification and 6% to climate change and fossil depletion. The decommissioning stage shows a similar contribution profile to that of the SBTL, with notable contributions only in a few categories. However, unlike the SBTL, dredging has a negligible contribution (~1%) to climate change and fossil depletion due to the lower dredging requirements per unit of electricity generated (see Table 6).

3.1.3 | Severn Tidal Bar

Similar to the WSL, the operation and maintenance stage is also the main hotspot for the STB (Figure S3) across all impact categories. Its contribution ranges from 44% (terrestrial ecotoxicity) to 97% (ionizing radiation). This is primarily due to the use of

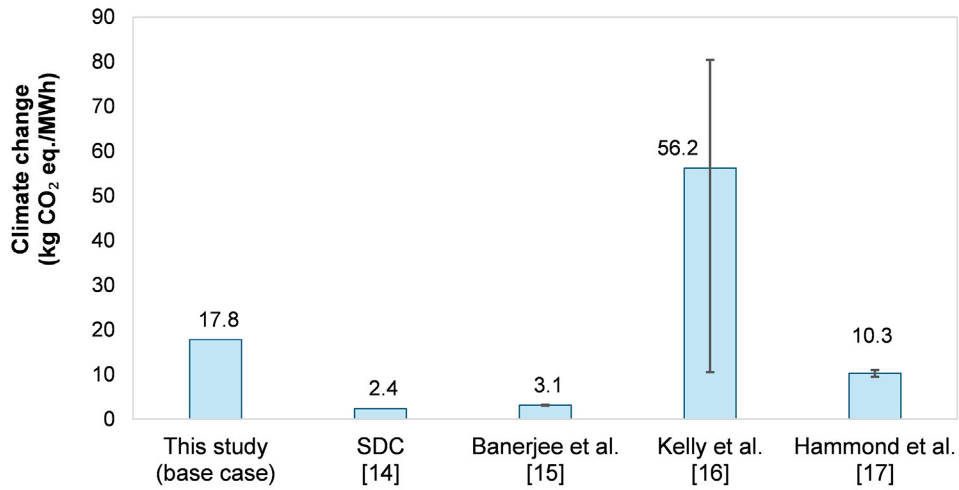

FIGURE 3 | Comparison with literature of the climate change impact of electricity generated by the Severn Tidal Bar estimated in this study in the base case.

grid electricity for flood pumping (Table 6). The contributions of the barrage construction and the manufacture of the electromechanical equipment are also significant (> 15%) for several impact categories. The dredging, transport and decommissioning stages follow a similar trend to that observed for the WSL, with relatively minor contributions to the overall environmental impacts.

Finally, across the three TRS, the results show that the contribution of bund and embankment maintenance to the overall impacts is 0.5%–3%. This is based on the assumption that the cumulative maintenance effort for all three TRS over their lifetime is equivalent to 25% of the initial construction effort (Section 2.2.2.3). However, the sensitivity analysis shows that, even if the maintenance efforts were increased to 50% of the initial construction effort, the total impacts would rise by less than 3%. This indicates that the results are not sensitive to this assumption.

3.1.4 | Comparison of Results with Other Studies

As discussed in the introduction, several previous UK-based studies estimated the climate change impact of tidal electricity, most of which focused on the STB (Table 1). Therefore, the impact of this TRS estimated in this study is compared with the values reported in those earlier studies. As no previous LCA studies considered any other environmental impacts of electricity generation from TRS, comparison of the other impact categories is not possible.

As indicated in Figure 3, the values for the climate change impact vary widely in the literature, spanning a range of 2.4–80.4 kg CO_2 eq./MWh due to different system boundaries and assumptions. This wide range is in particular due to the study by Kelly et al. [16], who considered multiple scenarios for electricity used for flood pumping, reporting the impact in the range of 10.5–80.4 kg CO_2 eq./MWh. The value determined in the current study (17.8 kg CO_2 eq./MWh) falls within this range. However, it is higher than the 2.4 kg CO_2 eq./MWh projected by the Sustainable Development Commission (SDC) [14], 3.1 kg CO_2 eq./MWh estimated by Banerjee et al. [15], and the 10.3 kg CO_2 eq./MWh reported by Hammond et al. [17]. This is mainly due to the differences in the system boundaries, with the SDC and Banerjee et al. focusing solely on the construction stage and Hammond et al. excluding some activities in the operation stage, such as electricity consumption for flood pumping and ancillary services, all of which are shown in the current study to influence the results.

3.2 | Environmental Impacts of TRS Used for Electricity Generation and Storage (Optimized Case)

As shown in Figure 4, when grid electricity is used for storage pumping (Option 1), the climate change impact of electricity from the SBTL, WSL and STB is estimated at 18, 9 and 19 kg CO_2 eq./MWh, respectively. These values represent a 10%–25% increase relative to their respective base-case values (Table 11) due to the additional pumping for electricity storage. In addition to climate change, several other impacts also show notable increases relative to the base case, including fossil depletion (20%–56%), ionizing radiation (38%–864%), marine eutrophication (16%–71%) and ozone depletion (32%–253%), with the lowest increase in the ranges corresponding to the STB and the highest to the SBTL.

Using wind electricity for storage pumping instead of grid electricity (Option 2; Figure 5) decreases the climate change impact by 14%–44% relative to the base case. Most of the other impacts are also reduced (by 1%–84%). It can also be inferred from Figures 4 and 5 that TRS electricity in Option 2 has a 26%–49% lower climate change impact compared to Option 1. The TRS in Option 2 also outperforms Option 1 across all other environmental categories with 3%–88% lower values. The reason for this is that wind electricity has significantly lower impacts than the 2030 grid as shown in Table S7. These findings highlight that the source of electricity used for storage pumping plays a critical role in the environmental sustainability of tidal power.

Comparing TRS with the wind coupled with other storage systems when grid electricity is used for storage and/or pumping

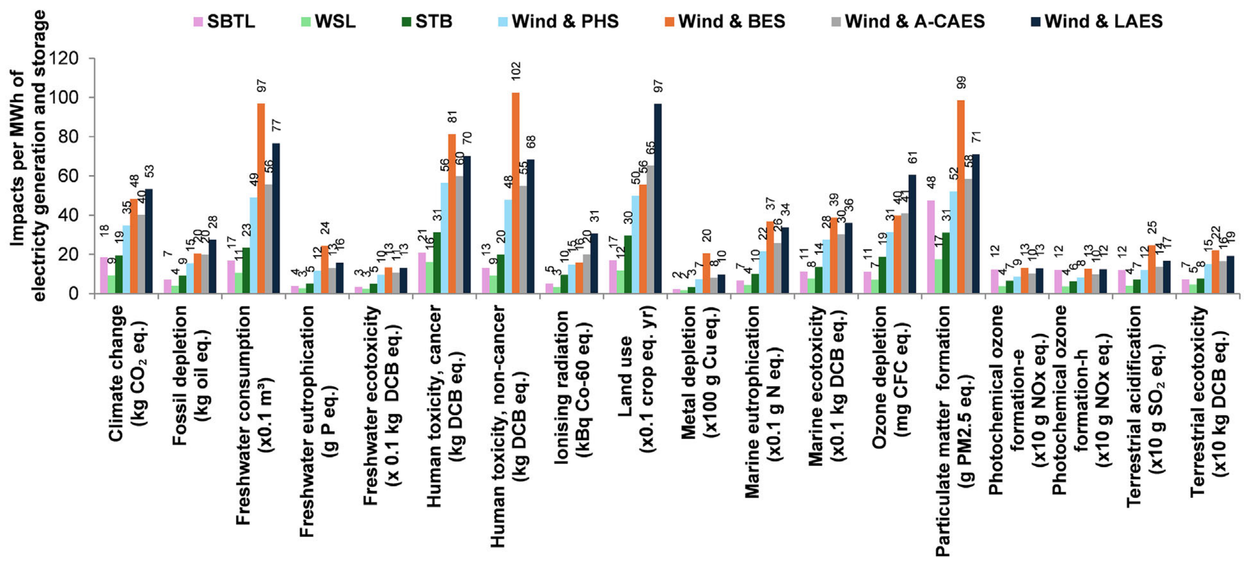

FIGURE 4 | Life cycle environmental impacts of electricity generation and storage by TRS (optimized case) in comparison with wind electricity generation combined with other storage options, assuming 2030 UK grid for operating all systems (Option 1). [SBTL: Swansea Bay Tidal Lagoon; WSL: West Somerset Lagoon; STB: Severn Tidal Bar; PHS: Pumped hydroelectric storage; BES: Battery energy storage; A-CAES: Advanced compressed air energy storage; and LAES: Liquid air energy storage. Some impacts have been scaled to fit—to obtain the original values, multiply by the factors shown on the x-axis for relevant impacts].

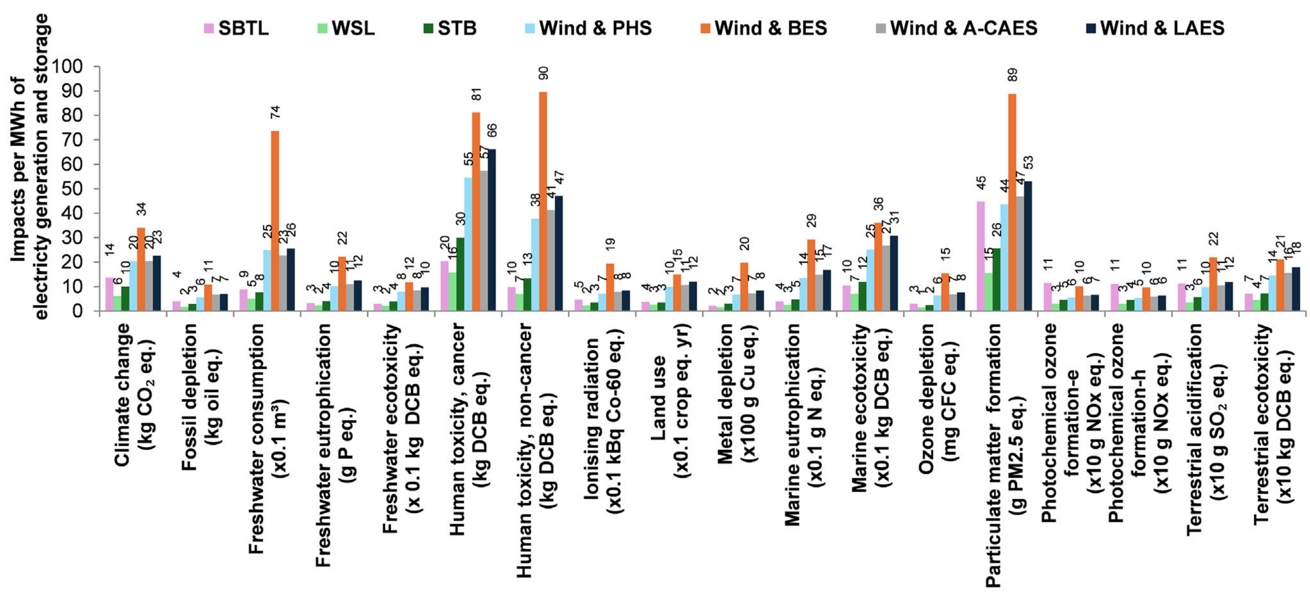

FIGURE 5 | Life cycle environmental impacts of electricity generation and storage by TRS (optimized case) in comparison with wind electricity generation combined with other storage options, assuming wind electricity for operating all systems (Option 2). [SBTL: Swansea Bay Tidal Lagoon; WSL: West Somerset Lagoon; STB: Severn Tidal Bar; PHS: Pumped hydroelectric storage; BES: Battery energy storage; A-CAES: Advanced compressed air energy storage; and LAES: Liquid air energy storage. Some impacts have been scaled to fit—to obtain the original values, multiply by the factors shown on the x-axis for relevant impacts].

(Option 1) shows that TRS electricity has 44%–82% lower climate change impact than the four other energy storage technologies. TRS also outperforms these technologies across at least 14 other environmental categories with 10%–92% lower values (Figure 4). In Option 2, the WSL and STB have 17%–93% lower impacts than the wind-other storage systems across all categories. The SBTL shows lower values for 14–16 categories, but 3%–108% higher particulate matter, photochemical ozone, and acidification.

Among the wind-based systems with the other storage technologies, wind & BES exhibits the highest impacts in 11 out of 18 categories in Option 1 and in all categories in Option 2, primarily due to the environmental burdens associated with

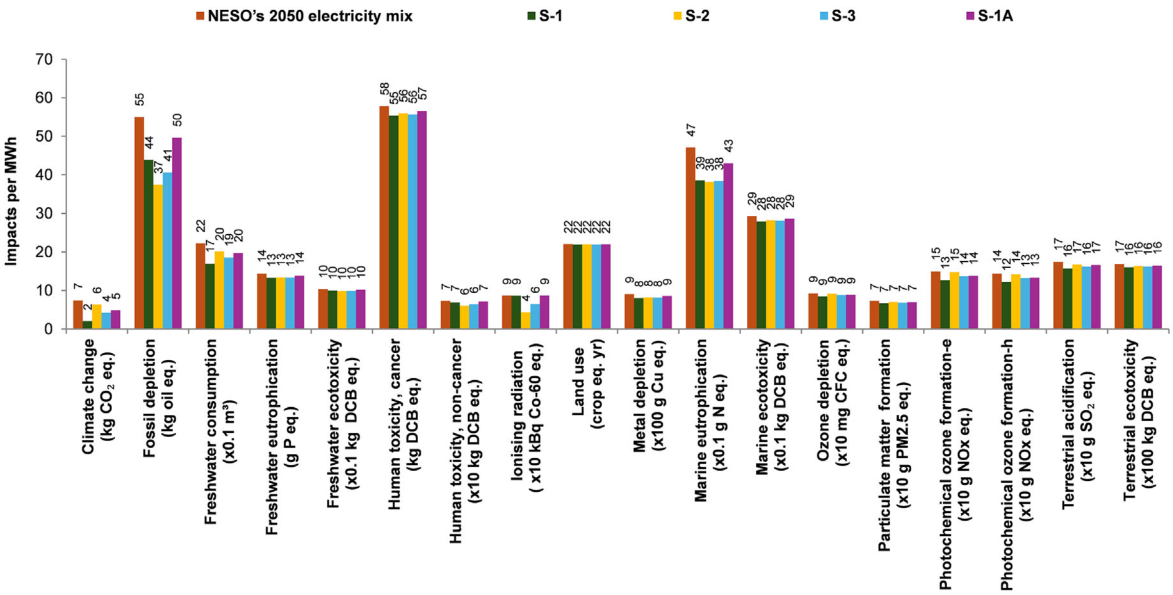

FIGURE 6 | Environmental impacts of different grid scenarios. [NESO: National Energy System Operator. For the grid compositions, see Table 10. S-1: modification of the NESO's 2050 grid with TRS displacing 50 TWh of electricity from natural gas and 11.45 TWh of battery storage; S-2: modification of the NESO's 2050 grid with TRS displacing 50 TWh of nuclear electricity and 11.45 TWh of battery storage; S-3: modification of the NESO's 2050 grid with TRS displacing 25 TWh of electricity from natural gas, 25 TWh of nuclear electricity and 11.45 TWh of battery storage; S-1A: As S-1 but with TRS providing only half the electricity and storage (25 and 5.725 TWh/y, respectively)].

battery production. In Option 1, the wind- LAES system has the highest values in seven categories, including climate change. This is largely due to the lower round-trip efficiency of LAES (see Table 8), which results in higher electricity consumption (Table S6). Round-trip efficiency is also a key differentiator between pumped hydro storage and the TRS. While the former typically achieves an efficiency of around 80%, TRS benefit from the natural tidal cycle. In TRS, electricity generation takes advantage of the large head differences created by ebbing tides, reducing the need for pumping and avoiding efficiency losses. Furthermore, in the optimized TRS options considered in this study, the majority of the stored energy is derived from tidal energy, with only a small proportion requiring pumping (see Table 7). In contrast, all other storage technologies rely entirely on electrical input for energy storage, which increases their environmental impacts significantly.

3.3 | Implications of TRS Deployment at the UK Level

This section first explores the potential role of TRS in achieving the 2050 net-zero targets and their environmental implications for the UK electricity grid, followed by a discussion of some of the key socio-economic factors that may affect their future deployment.

3.3.1 | Environmental Implications

The life cycle impacts of different scenarios for integrating all the assumed TRS capacity (Table 10), with a total share in the 2050 grid of 7.5% (generation and storage), are compared in Figure 6 with the impacts of the 2050 grid projected by the NESO (Table 10), the latter of which includes only 0.3% of TRS (generation only). As can be seen in the figure, the climate change impact of the NESO's grid electricity is estimated at 7 kg CO_2 eq./MWh. Including the assumed potential of the TRS to replace natural gas electricity and battery storage (Scenario S-1) would reduce the impact by 71%, to 2 kg CO_2 eq./MWh. However, the reduction would be only 14% if TRS electricity displaces nuclear power and battery storage (Scenario S-2). In Scenario S-3, where TRS displaces both natural gas (with CCS) and nuclear electricity, along with batteries, the climate change impact of the grid is reduced by 43%, to 4 kg CO_2 eq./MWh. Even if only half of the assumed TRS are realized (3.75% in the grid), the climate change impact of the grid electricity would still fall by 35%, to 5 kg CO_2 eq./MWh (S-1A in Figure 6). Although none of the scenarios achieves a fully net-zero grid, the assumed inclusion of TRS could result in annual emissions savings of 0.9–4.4 Mt CO_2 eq. on a life cycle basis compared to the NESO's scenario.

In addition to climate change, most other environmental impacts are also lower across the scenarios relative to the NESO's projected grid. In S-1, 16 other categories are reduced, ranging from 4% (human toxicity-cancer) to 24% (freshwater consumption), while land use and ionizing radiation remain the same as the NESO's. A similar trend can be observed for the remaining scenarios, although significant (> 15%) reductions occur only in fossil depletion, ionizing radiation and marine eutrophication.

3.3.2 | Socio-Economic Implications and Public Acceptability

Although there are no definitive estimates of costs and they vary widely with source and year of estimation, the LCOE of TRS in the UK is still considered high. According to some estimates, the LCOE falls in the range of £108–286/MWh [11]. For the three TRS considered in this work, the cost of electricity from the SBTL is predicted at £156/MWh, £117/MWh for the WSL, and £164/MWh for the STB. However, some other sources report significantly higher costs; for instance, £233/MWh for the SBTL [63]. The Tidal Range Alliance (TRA) and the British Hydropower Association (BHA) put the costs of the SBTL still higher, in the range of £244–457/MWh, with the lowest value in the range excluding storage and the highest considering both pumping and storage [64]. According to the same source, the LCOE of the STB is £112 and £184/MWh, respectively. All these values refer to the year 2025 and have been updated from the original values reported in the above-mentioned sources using the Consumer Price Index for the respective original years.

Nevertheless, regardless of the source, the LCOE of TRS compares unfavorably with other renewables, such as onshore wind (£58/MWh) and large-scale solar (£60/MWh) [65], both corresponding to 2025 values. On the other hand, comparison with nuclear power (£114–119/MWh in 2025) [65] is slightly more favorable, assuming the above-mentioned lower cost range.

The LCOE is influenced largely by the high capital costs of TRS, which range from £1.8 bn for small-scale projects, such as the SBTL, to £33 bn for large-scale installations, such as the STB [9]. Typically, 70% of the capital costs are for the civil works and 30% for the electromechanical equipment. Compared to other power installations, including natural gas plants and wind farms, the construction time of TRS is much longer, ranging from five to nine years. Hence, capitalizing interest on debt finance over this timespan represents a high percentage of total project costs relative to shorter-duration projects [9].

Development costs may also be high, including project design, obtaining planning permissions and arranging finance. Additional costs may be incurred due to environmental habitat compensation. According to the Severn Estuary Commission [9], development costs for the TRS proposed in the region are projected between £30 m and > £200 m. By comparison, annual operating costs are low, representing ~1% of the total construction cost, including the replacement of components and decommissioning [9].

Despite the high costs, job creation is often reported as a major positive socio-economic impact of the tidal energy schemes, in the construction, maintenance and operation stages [9, 14, 30, 66, 67]. Several feasibility studies of TRS in the UK highlighted their potential for employment creation. For instance, the DECC's study on the feasibility of different TRS in the Severn Estuary, including the STB, projected that one of the major economic benefits from the scheme would be several thousand jobs created in construction and support services, of which up to 40 % would be in the region [30]. The study also estimated that the scheme would further increase regional employment opportunities by creating between 1000 and 2000 jobs for maintenance and operation of the scheme.

Similarly, it has been estimated for the WSL that around 6000 construction and more than 300 operation jobs would be created [68], while the creation of 1850 construction jobs for the SBTL is quoted as a "major beneficial" socio-economic impact of the project [69].

More recently, the Severn Estuary Commission's assessment of a range of tidal lagoon projects, including the SBTL and WSL, estimated that they could provide 30 000–220 000 job-years and £1.6–12 billion in gross value added during the development and construction stages, assuming their duration of five–nine years [9]. Operational annual jobs expected for each year range from 190 for a small TRS to 3500 for a large barrage. For example, the SBTL was estimated to be able to generate around 6000 jobs annually throughout the development and construction phases and 190 jobs in the operation stage. The WSL, on the other hand, as a medium-sized lagoon, was estimated to create 30 000 jobs annually during the development and construction stages and 240 operation jobs annually. The potential for employment creation was the highest for the largest project considered by the Commission (and in this paper), i.e. the STB. The Commission estimated that this "mega project" could support almost 600 000 direct, indirect and induced job-years.

TRS may generate further regional employment through tourism. As evidenced by the La Rance tidal barrage in France, one of the first major tidal power schemes in the world constructed in 1967, TRS may become tourist attractions. La Rance itself attracts over 70 000 visitors every year [70]. Proposals for all of the TRS in the UK have implied that they would result in further employment opportunities through tourism and associated development. The WSL, for example, could lead to more than 200 local jobs to support the lagoon as "a new destination for tourism and leisure" [68].

However, as pointed out in an early SDC's report on tidal power in the UK [14], TRS are bound to come into conflict with other business users of the marine environment, such as ports, commercial fisheries, shipping and navigation, as well as the marine aggregates industry. The report argues that the construction and operation of TRS may have adverse impacts on these business activities which could result in job losses.

The above-mentioned study of the feasibility of the Severn tidal schemes [30] specifies that, for instance, in a scenario where a TRS displaces 60% of port activity, job losses at the ports in the Severn Estuary could reach almost 4000 during the nine-year construction period. Smaller yet significant job losses could be expected in the marine aggregates industry, which would be affected by the impact of TRS on water levels and associated sediment issues, as well as in commercial fishing and angling in the estuary, due to the disruption of both nursery areas and the passage of fish up the estuary [30].

In addition to these socio-economic impacts, TRS could further affect the well-being of local communities; for instance, through visual and seascape changes, noise disturbances during construction and operation, loss of cultural heritage, or their general impact on the amenity value of the local area [14, 71]. On the other hand, they could also bring additional benefits to local communities, such as coastal and flood protection, providing transport links across barrages, as well as improved recreational opportunities [71, 72].

However, despite all the potential environmental and socio-economic benefits of TRS, one of the critical factors that is vital for successful implementation of TRS (like any other new technology) is public acceptance. As it has been well documented, people not only need to be convinced of the advantages of a novel technology but also have to accept the perceived implications for their everyday lives [73].

Recent public-attitude surveys show that public acceptance of tidal energy in the UK is high, with levels of 83% of overall support and 49% of strong support [74]. However, although people have broadly positive opinions about the technology in general, they commonly report that they do not feel well informed about tidal energy [75]. It is important to note that unfamiliar technologies often raise considerable social concerns, usually expressed as worries and anxieties about their safety or environmental impacts, which may ultimately hinder their future deployment [73]. Furthermore, as pointed out by Hooper et al. [75], general expressions of public support (as reported in national-attitude surveys) do not always translate into approval for local developments. Research also shows that balancing national needs with local requirements and preferences through early public engagement is critical in facilitating public support [75–78].

However, as much as the socio-economic costs and benefits of tidal energy developments are principal public concerns, it is worth noting that public acceptability often hinges on their perceived environmental impacts. Studies of public acceptance and attitudes toward such developments show that, while energy costs and economic benefits indeed matter to the public, it appears that local people are also very much concerned about the environmental consequences of such developments [75]. The Severn Estuary Commission [9], for instance, noted in their consultations with a number of stakeholders that there was more support for tidal lagoons due to their lower environmental impacts. By contrast, there was clear feedback from stakeholders voicing opposition to the development of large tidal barrages due to their much higher environmental impacts. Based on this feedback, and taking into account various socio-economic and environmental concerns, the Commission concluded that development of the barrage-based TRS should not be considered at this stage. Instead, they recommended that lagoons should be evaluated further. This recommendation concurs with the findings of this work, which shows that the lagoons have lower life cycle environmental impacts than the barrage TRS.

4 | Conclusions

This study has assessed the life cycle environmental sustainability of TRS in the UK for their dual roles in renewable electricity generation and storage. It has also discussed their potential socio-economic implications and public acceptability.

Considering the operation of TRS solely for electricity generation (base case), out of the three TRS considered, the medium-size West Somerset Lagoon (WSL) is the best option with the lowest impacts in 16 out of 18 categories, while the large-scale Severn Tidal Bar (STB) shows the highest impacts in 13 categories. These differences are primarily attributed to differing maintenance dredging requirements and electricity consumption for flood pumping.

In comparison with the other electricity sources, the WSL emerges as the second best option behind the first-ranked hydropower. For climate change and freshwater consumption, it is ranked the best electricity source overall. The remaining two TRS are generally middle-ranking.

All three TRS reduce the climate change impact by 79%–98% relative to electricity from natural gas and solar PV. Tidal electricity also shows significantly lower impacts in at least nine other categories compared to these two options, including fossil depletion, human toxicity-cancer, freshwater eutrophication, ionizing radiation and ozone depletion. It also has significantly lower values in 12 impacts than wind electricity. However, compared with hydro and nuclear power, tidal electricity has higher impacts across several categories.

Compared to the base case, using TRS for both electricity generation and storage (optimized case) increases the climate change impact by 10%–25% and between six and 17 other impacts by 2%–864%, depending on the scheme, due to the use of grid electricity for storage pumping. If wind electricity is used instead, the impacts decrease by 1%–84% on the base case. The impacts of TRS in the optimized case with wind electricity used for storage pumping are 3%–88% lower than when using grid electricity, including a 26%–49% lower climate change impact. These findings highlight that the source of electricity used for storage pumping plays a critical role in the environmental sustainability of tidal power.

Comparing the TRS in the optimized case with wind electricity coupled with alternative storage technologies shows that 15 out of 18 impacts of TRS are 10%–92% lower if grid electricity is used for storage and/or pumping (Option 1). If wind electricity is used to operate the TRS systems instead (Option 2), they have significantly lower impacts in most impact categories than the wind & other storage systems. The exception is the Swansea Bay Tidal Lagoon (SBTL), which has 3%–108% higher particulate matter, photochemical ozone, and acidification.

If half of the proposed TRS are developed by 2050 and they displace natural gas (with CCS) and battery storage, they could lower the environmental impacts of the grid by 14%–71%. This includes the climate change impact, which would be reduced from 7 to 2 kg CO_2 eq./MWh. Although not net-zero, this still represents an annual saving of up to 4.4 Mt CO_2 eq. However, these environmental benefits should also be considered in the context of various socio-economic implications of TRS, all of which will influence public acceptance and therefore the success of a future deployment of tidal power.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data are included in the paper and supplementary information.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: adsu70521-sup-0001-SuppMat.pdf.