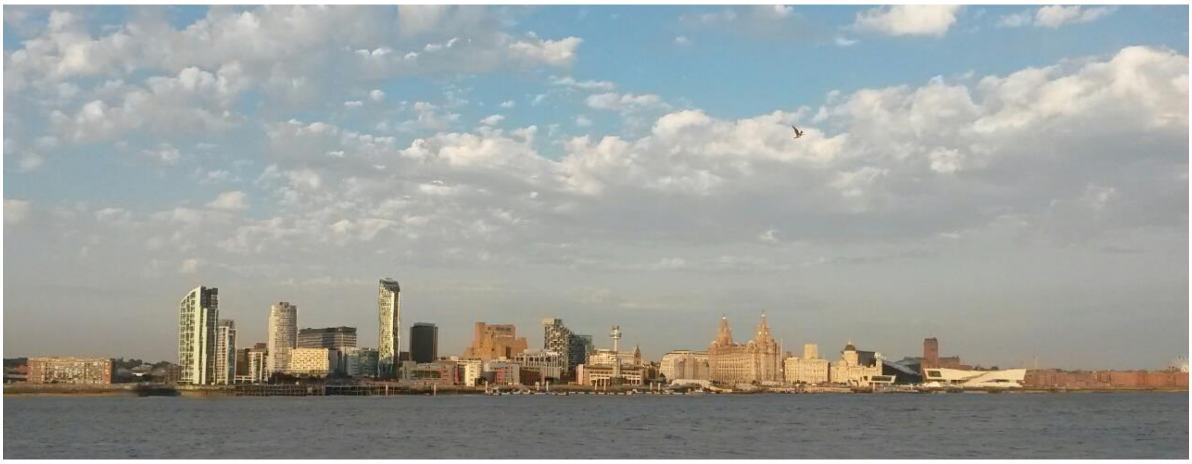
The Energy River:
Realising Energy Potential from the River Mersey



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Executive summary

This report has been commissioned by Liverpool City Council (LCC) and joint-funded through the University of Liverpool's Knowledge Exchange and Impact Voucher Scheme to explore the potential to obtain renewable energy from the River Mersey using established and emerging technologies.

The report presents an assessment of current academic literature and the latest industry reports to identify suitable technologies for generation of renewable energy from the Mersey Estuary, its surrounding docks and Liverpool Bay. It also contains a review of energy storage technologies that enable cost-effective use of renewable energy. The review is supplemented with case studies where technologies have been implemented elsewhere.

Consideration is also given to strategic planning and stakeholder involvement in taking forward renewable energy projects. These matters are broadly described, with links to the work being carried out in other UK estuaries where similar priorities are being taken forward.

Liverpool currently generates 26 GWh/yr of its annual energy (electricity and heat) from renewable sources, about 0.5% of consumption. From 2005 to 2014 the city successfully reduced its per capita CO_2 emissions by 31.63%. However, this renewable electricity production comes from a small range of technologies (solar photovoltaics (PV), onshore wind and sewage gas). The city must now find ways to maintain its success in reducing CO_2 emissions and increase its renewable energy generation.

The large tidal range of the Mersey Estuary presents an ideal opportunity to generate energy. The potential for tidal range energy has long been recognised and several studies have been carried out to assess the feasibility of a tidal barrage. The main issues in generating electricity from a tidal barrage are those of cost, navigation and the environment. Whilst the Mersey has the advantage of a narrow channel in comparison to other UK estuaries, which would reduce construction costs, locations for a tidal barrage are restricted due to access for commercial shipping and several areas having environmental designations. Previous feasibility studies have identified a preferred barrage location running between Rock Ferry and Dingle. A barrage on the Mersey could generate between 1.0 and 1.5 TWh electricity per year, representing up to two-thirds of Liverpool's current electricity requirement.

Other tidal energy technology options are tidal lagoons and tidal current turbines. Lagoons would not be suited to the confines of the estuary, but have the potential to be sited within the wider Liverpool Bay area and are predicted to generate similar amounts of electricity (between 0.4 and 4.9 TWh per year, dependent on size and location) to a barrage. It may be possible to locate tidal current turbines within the estuary, but due to the shallow water and need for shipping access these would need to be quite small and are only predicted to generate approximately 1 GWh per year from an array of 130 turbines. Tidal current turbines have the advantage that they could be deployed incrementally and costs are likely to reduce as the technology matures.

Other renewable energy options considered in the report include the deployment of additional wind turbines and solar PV. Previous reports by ARUP and ASC Renewables Ltd. have identified areas in Liverpool and Sefton, which could be suitable for deployment of additional wind turbines. There is also the potential to co-locate wind turbines with tidal energy technology by placing them on top of barrage or lagoon walls. The potential for additional solar PV generation proposes the use of an established technology in a new setting, i.e. floating them on water. Floating solar PV has recently been used on reservoirs in the UK and although it has not yet been used in saline water, quick easy deployment makes them an attractive option.

Locating water source heat pumps (WSHPs) in Liverpool's docks has the potential to provide heating and hot water. A funding bid for a feasibility study has been submitted by LCC to the Department for Business, Energy and Industrial Strategy (BEIS) Heat Network Development Unit (HNDU) to further investigate the potential of this technology for Liverpool.

As the energy generation mix moves towards more renewable technologies there is the need to consider energy storage, thus increasing flexibility, addressing intermittency of supply, and reducing costs. Energy storage can be deployed at a range of scales, enabling increased demand-side management in the home, bulk storage and frequency regulation - all of which will be required in the future. Most of the world's energy storage is currently provided by pumped hydro, which is the only mature technology. However, energy storage is a quickly developing area with many demonstration projects underway and technologies such as lithium-ion batteries and flywheels now being deployed. Any new large infrastructure, such as a barrage, should have storage installed alongside it to take advantage of the cost savings in shared grid infrastructure.

Governance and strategic planning are important in ensuring the legitimacy of any large-scale project and in guaranteeing that the various uses of the estuary are properly considered. Any future development must therefore be carried out with full regard for the environment and in consultation with stakeholders. There are several existing groups associated with the river, such as Mersey Maritime, the Healthy Rivers Trust, the Maritime Knowledge Hub and the Mersey River Task Force, which form part of the wider stakeholder community for successfully achieving energy from the Mersey.

In summary, whilst tidal range technology would provide the greatest amount of electricity from the Mersey, it would also have the greatest upfront cost. It may be possible to deploy a range of tidal technologies (barrage, lagoon and tidal stream turbines) within the estuary and out into Liverpool Bay, but this must be explored fully with respect to their interactions and effects on current velocity and the environment. There are other potential sources of energy, i.e. wind, solar and WSHPs, which could be deployed alongside exploitation of tidal energy. Due to their scale, these technologies can be deployed more quickly ahead of any larger scheme. The development of a strategic plan would be a useful step towards understanding the balance between competing interests in Mersey Estuary.

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1. Introduction

Secure, affordable energy is a prerequisite to the functioning of any city and is vital to economic growth. Energy powers the transport system, provides heating and cooling to buildings, enables production of goods and services and is essential to modern technology. Energy is fundamental to the city's infrastructure, from the supply of water and provision of healthcare to waste disposal and communications systems. Cities already account for nearly two-thirds of global energy use and the world's urban population is growing, with urban energy use increasing more quickly that the population (IRENA, 2016).

Liverpool is a city located on the River Mersey in the Northwest UK with a population of around 480,000, it forms part of the Liverpool City Region (LCR) - one of England's recently devolved combined authorities. LCR has a population of over 1.5 million and is regarded as one of the major drivers of the Northern Powerhouse concept.

The UK Climate Change Act (2008) set a target to reduce greenhouse gas emissions by 80% by 2050 from a 1990 baseline. In line with the act, LCC committed to a reduction in carbon emissions of 35% (from 1990 baseline) by 2024 (LCC, 2009). LCR also committed to a 20% reduction in carbon emissions by 2020 as part of the EU Covenant of Mayors (2017). All these targets have, to an extent, been superseded by the tougher ambitions of the Paris Agreement, negotiated by 195 countries at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) in 2015 and effective from 4th November 2016 (UNFCCC, 2017). The Paris Agreement is the world's first comprehensive climate agreement and further embeds decarbonisation into national energy policy. It was agreed that global average temperature increases should be kept below 2 ^{o}C and if possible to 1.5 ^{o}C, this will require emissions to reach zero by the second half of this century. It will be achieved by countries setting national determined contributions (NDCs), which will be progressively increased, and through a global stocktake every five years to assess progress.

The need to decarbonise the energy system has already driven changes in the energy supply market, with traditional energy sources being replaced by a divergent mix of technologies. The electricity generation sector is on trajectory to hit the UK 2020 renewable targets, but heating and transport still need to make considerable progress (National Grid, 2016). The demand for electricity is currently increasing due to the decarbonisation of the transport and heating sectors (Lehmann et al., 2016).

The River Mersey has the potential, as a source of renewable energy, to address the continued and growing need for electricity whilst meeting agreed emissions targets. This report will explore the options for generating energy from the River Mersey by reviewing the current status of a range of technologies and assessing their potential for deployment in and around the Mersey. In light of the intermittent nature of renewable energy generation, energy storage is recognised as an important concept which may allow more efficient use of energy and impart savings with the potential to reduce energy prices (Lehmann et al., 2016), therefore energy storage will also be discussed. A detailed assessment of the estimated investment and costs of energy for potentially viable technologies is beyond the scope of this report.

The report will provide: (i) a review of renewable energy generation technologies potentially suitable for estuarine and coastal locations, (ii) a range of suggestions for renewable energy installations in and around the Mersey, (iii) a discussion on the need for energy storage and review of storage technologies, and (iv) a discussion on the need for strategic planning and good governance for a sustainable estuary.

1.1 Renewable Energy in Liverpool

Liverpool City, the area of responsibility of LCC, lies on the north shore of the Mersey. Liverpool is one of the six council areas within LCR. It sits alongside Sefton, Knowsley and St. Helens on the north of the estuary, Wirral to the south, and Halton on both the north and south banks of the eastern end of the estuary (Fig 1.1). In addition to surrounding a large part of the Mersey Estuary, the larger LCR has coastline on Liverpool Bay and the Dee Estuary. The LCR boundary encompasses offshore windfarms in Liverpool Bay, which are in important source of renewable energy.

Whilst this report has been commissioned by LCC, its focus on the River Mersey and the potential to use it as a source of energy may also have implications and present opportunities for the other council areas in the LCR, particularly Wirral and Halton, which also border the Mersey estuary, and Sefton which has a large stretch of coastline from the mouth of the estuary to the north of Liverpool Bay.

Figure 1.1. Liverpool City within Liverpool City Region (LCR)

Liverpool and the LCR have an ongoing commitment to develop a low carbon economy with sustainable economic growth decoupled from the consumption of fossil fuels. The LCR Sustainable Energy Action Plan (SEAP) (LCR, 2012) outlined the region’s plans to achieve this goal by decentralising energy generation and supply through the use of low carbon and renewable fuels and by utilising local supply chains, knowledge and skills. This work is ongoing, with the recent Carbon Baseline Management Report (Upton, 2016) providing an overview of progress in support of an update of the SEAP.

The River Mersey has been essential to the existence of Liverpool, responsible for its industrial and urban development (Ridgway et al., 2012). For the future, it could provide the city and the wider region with a renewable energy resource in support of low carbon goals. Indeed, the LCR Devolution Agreement (HM Treasury, 2015) recognised that:

"A next step in the river's recent evolution could be to harness its huge tidal range to produce power for the City Region's businesses and citizens.",

and included a government commitment to support:

"Liverpool City Region by providing guidance to support Liverpool City Region's development of a cost effective tidal power scheme proposal for the River Mersey or Liverpool Bay that could generate low carbon energy for businesses and consumers"

The Devolution Agreement (HM Treasury, 2015) also acknowledged that the River Mersey *"has undergone the greatest clean-up of any river in Europe over the last thirty years"* and committed to *"the cleanest river standard by 2030"*. This emphasizes the requirement for any energy extraction from the river to be carried out sustainably and with full regard for the environment.

1.2 Current levels of energy consumption, emissions and generation

1.2.1 Current energy consumption in Liverpool and Liverpool City Region (LCR)

The City of Liverpool consumes 1.9 TWh electricity and 3.8 TWh gas every year, whilst for the LCR these figures are 6.2 TWh and 13.8 TWh, respectively (2014 figures, Table 1.1).

The total cost to Liverpool of gas and electricity use by industrial, commercial and domestic sectors is estimated at £340 million. The figure for LCR is £1150 million (Fig. 1.2). This estimate is based on the domestic and industrial and commercial gas and electricity consumption in 2014 (Table 1.1) at the average cost of gas and electricity to the domestic and non-domestic sectors in 2016[1].

[1] Data on gas and electricity prices sourced from BEIS available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/622615/QEP_Q117_tables_annex.pdf and https://www.gov.uk/government/statistical-data-sets/gas-and-electricity-prices-in-the-non-domestic-sector. Prices for non-domestic consumers include the climate change levy. Prices for domestic consumers do not include standing charges.

Table 1.1. Energy consumption in **(a)** Liverpool and **(b)** LCR in 2014 (source: https://www.gov.uk/government/collections/total-final-energy-consumption-at-sub-national-level)

(a)

Fuel Type	**Industrial and Commercial** (GWh)	**Domestic** (GWh)	**Transport (road and rail)** (GWh)	**Total** (GWh)
Coal	0.5	7.3	-	7.8
Manufactured solid fuels	0.8	9.7	-	10.5
Petroleum products	130.0	9.3	2,022.5	2,161.8
Gas	1,529.0	2,222.3	-	3,751.3
Electicity	1,201.5	731.1	-	1,932.6
Bioenergy and wastes	-	-	-	-
All fuels	2,861.8	2,979.7	2,022.5	7,864.0

(b)

Fuel Type	**Industrial and Commercial** (GWh)	**Domestic** (GWh)	**Transport (road and rail)** (GWh)	**Total** (GWh)
Coal	36.7	56.9	-	93.6
Manufactured solid fuels	31.4	73.1	-	104.5
Petroleum products	1,394.2	59.5	7,851.5	9,305.2
Gas	5,978.0	7,841.4	-	13,819.4
Electicity	3,785.6	2,426.2	-	6,211.8
Bioenergy and wastes	-	-	-	33.1
All fuels	11,225.9	10,457.1	7,851.5	29,567.6

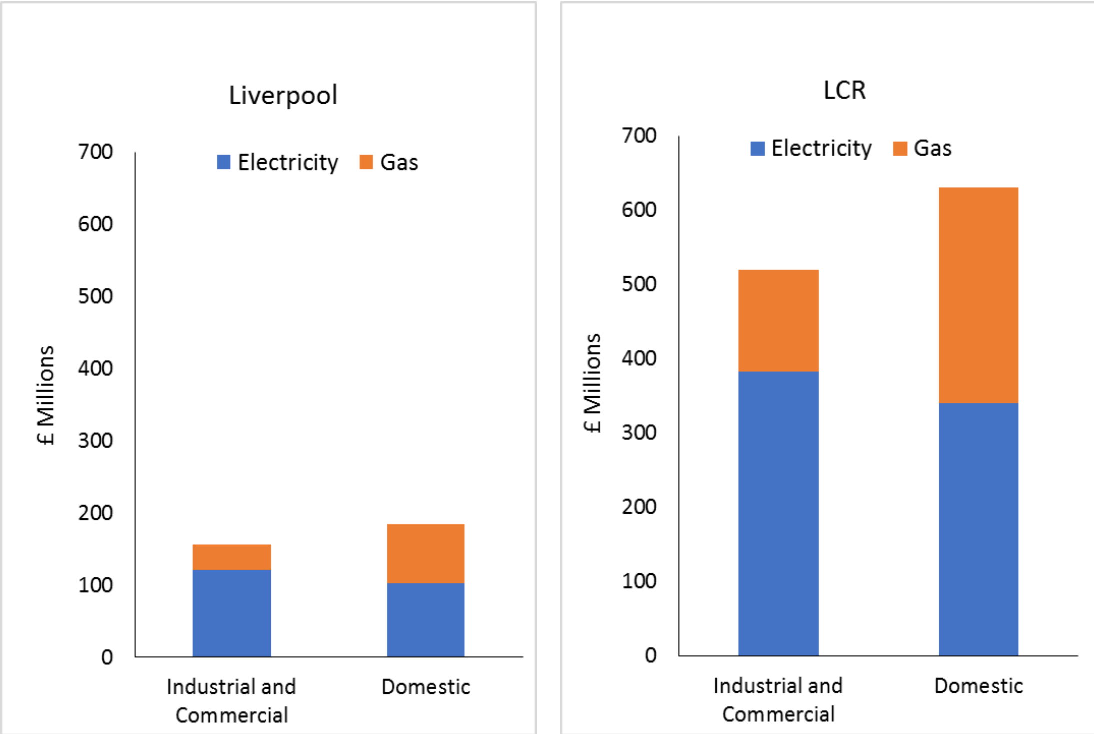


Figure 1.2. Estimated current annual cost of gas and electricity use by sector in Liverpool and the Liverpool City Region (LCR) (see text for calculation details)

1.2.1 CO_2 emissions

Emissions associated with energy use in 2014 in Liverpool were 2.06 Mt CO_2, equating to approximately 4.4 t CO_2 per capita (BEIS, 2016), whilst in the LCR they totalled 8.09 Mt CO_2, or 5.3 t CO_2 per capita. Although the per capita figures are higher for the LCR than Liverpool, over the last 10 years they have been reducing at a similar rate (Fig. 1.3). All the councils within the LCR have reduced per capita emissions of CO_2 since 2005. Sefton saw the smallest reduction, with CO_2 emissions 2014 only 12.54% less than in 2005; this may in part be due to Sefton having the lowest per capita emissions in the LCR at the 2005 baseline. Halton has seen the greatest reduction in CO_2 emissions which were 40.20% less in 2014 than 2005, this compares to a national emissions reduction of 27.83%. The difference in the trajectory of Sefton's per capita emissions compared to the rest of the LCR (Fig. 1.3) could be because trends at local authority level tend to show greater variation than at a regional level, with changes at a single industrial site having a big impact on emissions trends (DECC, 2016).

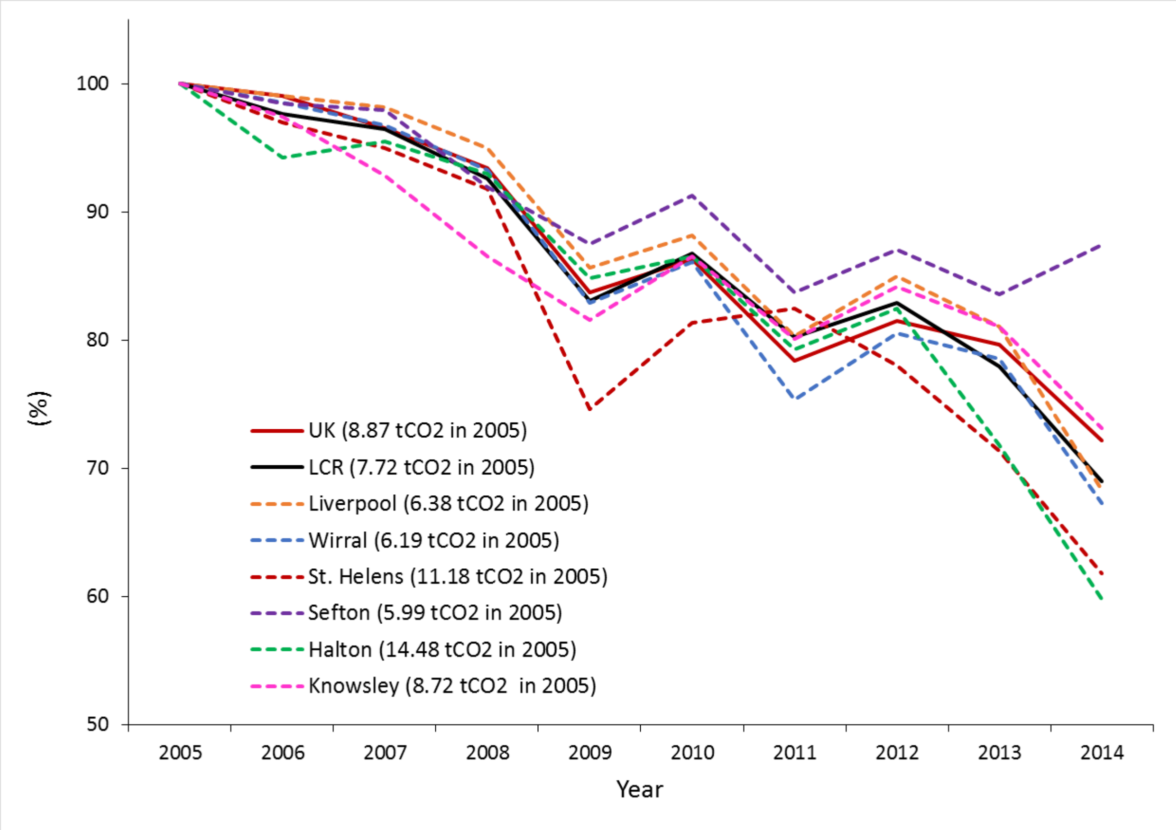


Figure 1.3. Trend in per capita CO_2 emissions expressed as a percentage of 2005 emissions. Baseline per capita emissions for 2005 shown in legend (Source: UK local authority and regional carbon dioxide emissions national statistics: 2005-2014, https://www.gov.uk/government/collections/uk-local-authority-and-regional-carbon-dioxide-emissions-national-statistics)

1.2.2 Renewable energy generation (electricity and heat)

Liverpool generates 19.2 GWh of electricity and 6.8 GWh of heat per year from renewable sources, just 0.46% of what is used in the city. The LCR as a whole does slightly better at 432.7 GWh electricity and 416.7 GWh heat per year from renewable generation, 6.97 % of its electricity and 3.02% of heat are from renewable sources (Table 1.2). A substantial proportion of this is generated by the offshore windfarm at Burbo Bank and the INEOS energy from waste (EfW) plant in Halton.

The current mix of electricity generation in Liverpool is limited to sewage gas, solar PV and onshore wind, whilst heat is generated through biomass, heat pumps and solar. LCR electricity generation is more diverse and heat generation is dominated by EfW, as previously stated (Fig. 1.4).

Table 1.2. Energy generation in **(a)** Liverpool and **(b)** LCR in 2014 (sources: https://www.gov.uk/government/statistics/regional-renewable-statistics and https://renewablelocator.green-alliance.org.uk/)

(a)	Electricity	Heat	Total
MWh	19,237	6,807	26,356
Percentage of consumption (%)	1.00	0.18 [(a)]	0.46

(b)	Electricity	Heat	Total
MWh	432,677	416,664	891,290
Percentage of consumption (%)	6.97	3.02 [(a)]	4.24

(a) Gas consumption met from renewable heat

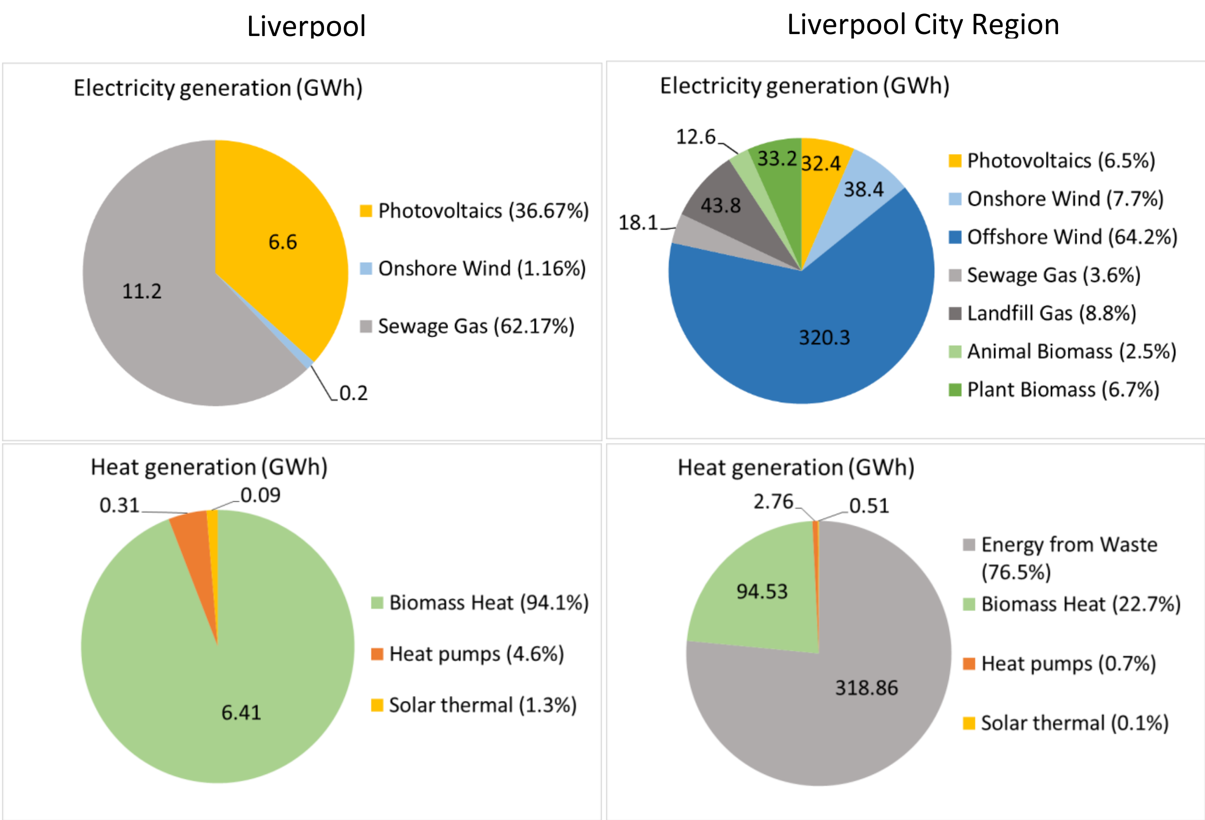


Figure 1.4. Sources of renewable electricity and heat in Liverpool and Liverpool City Region (LCR) in 2014 (sources: https://www.gov.uk/government/statistics/regional-renewable-statistics and https://renewablelocator.green-alliance.org.uk/)

At around 480,000 residents, Liverpool represents 0.73%[2] of the UK population and contributes £10.9bn[1], equivalent to 0.66%[1], to UK Gross Value Added (GVA). The city uses 0.67%[3] of the electricity and 0.77%[2] of the gas used in the UK and emits 0.51%[4] of the CO_2. It currently generates just 0.03%[5] of the UK's renewable electricity.

The LCR has over 1.5 million residents, which represents 2.34%[1] of the UK population, and contributes £29.4bn[1], equivalent to 1.78%[1], to UK GVA. The region uses 2.10%[2] of the electricity and 2.78%[2] of the gas used in the UK and emits 2.00%[3] of the CO_2. It generates just 0.67%[4] of the UK's renewable electricity.

1.3 The need for energy storage

A recent report for the Carbon Trust (Lehmann et al., 2016) set out the requirement for increased energy storage, which is driven by changes in the way that energy is being generated, transported and consumed in the UK. These trends are: the large-scale deployment of wind power; a shift to distributed generation; the closure of large conventional generating plant; and changes in demand profiles.

In order to meet renewable generation and CO_2 emission targets, energy generation by large-scale wind power is increasing. If all onshore and offshore projects (in planning, consented and under construction) were to go ahead the nationally installed capacity of wind power would see a three-fold increase to 44.6 GW (Lehmann et al., 2016). In the UK, installed solar PV saw a five-fold increase from 2011 to 2014 and the installed coal-fired capacity has decreased by 9 GW since 2011 (Lehmann et al., 2016). Additionally, in order to meet emissions targets, heat and transport are likely to be electrified, thus increasing electricity demand.

The impacts of these trends are: issues of balancing supply and demand; problems in maintaining the capacity margin (required to insure peak demands are met); a greater need for flexible generation; a reduction in the efficiency of conventional plant (due to more start-ups because of the need to balance renewable generation); and impacts on the local distribution networks, which were not designed to cope with distributed generation. The final point is particularly pertinent in that a recent report (Jackson et al., 2016) attested that, within the Liverpool area and across the LCR, electricity network capacity is likely to constrain economic growth. It also noted that issues of

[2] calculated using 2015 figures for population and GVA available from https://liverpool.gov.uk/council/key-statistics-and-data/data/

[3] calculated using 2014 data on sub-national energy consumption in the UK available from https://www.gov.uk/government/collections/total-final-energy-consumption-at-sub-national-level

[4] calculated using 2014 data for CO_2 emissions available from https://www.gov.uk/government/collections/uk-local-authority-and-regional-carbon-dioxide-emissions-national-statistics

[5] calculated using 2015 renewable electricity statistics available from https://www.gov.uk/government/statistics/regional-renewable-statistics

security of supply and system resilience could impact business confidence, and highlighted the issue that the ability to generate electricity is also likely to be constrained by grid capacity.

The Carbon Trust report (Lehmann et al., 2016) concluded that, under the National Grid's "Gone Green" scenario (Fig. 1.5) annual savings of up to £2.4 billion could be achieved by 2030 and under a "Market-driven Approach" scenario (Fig. 1.5) savings of £7 billion could be achieved through a combination of storage deployment, improved utilisation of existing generation assets and reduced investment in new generation assets. The majority of savings (~ 90%) are achieved through avoidance of fuel costs, i.e. by better utilisation of renewable assets, less energy is wasted, and there is less requirement for back-up generation by gas plant, which saves money by reducing the need for carbon capture and storage (CCS). Additional savings are due to the avoidance/delay of investment in the distribution network, which is made possible by storage.

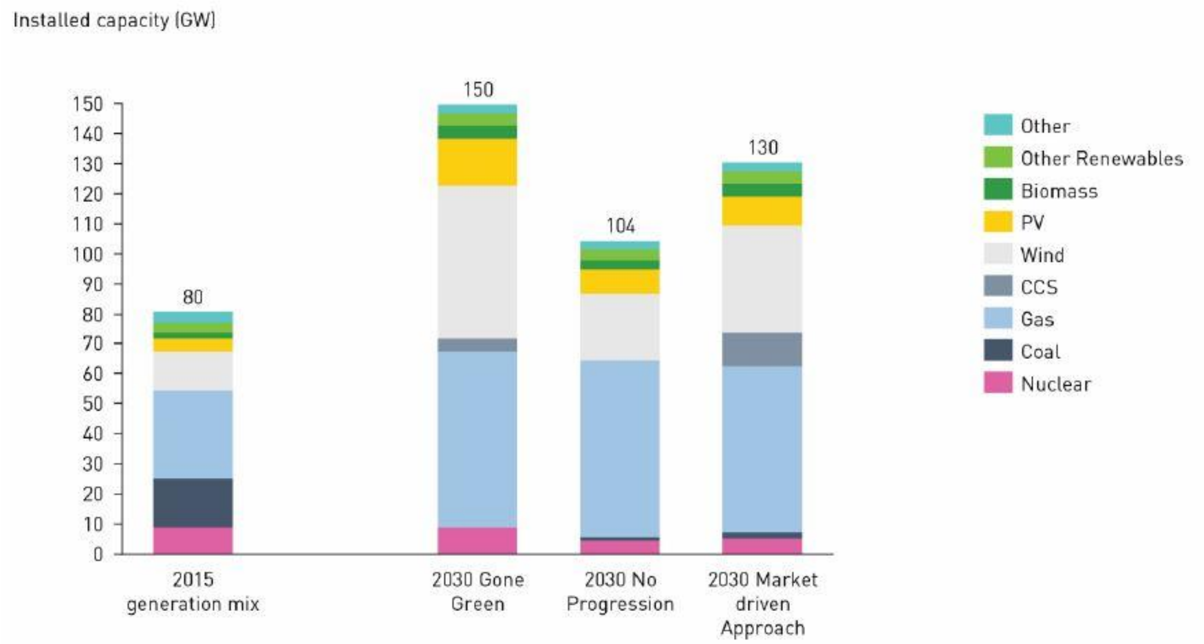


Figure 1.5. The nationally installed generation capacity mix by 2030 under a range of scenarios (Lehmann et al., 2016)

1.4 The Mersey Estuary

The Mersey catchment covers some 5000 km^2 of Merseyside, Greater Manchester, Cheshire, Derbyshire and Lancashire (Ridgway et al., 2012) with the river running from the confluence of the rivers Goyt and Tame at Stockport to the Irish Sea at Liverpool Bay. The area seaward of Perch Rock is dominated by estuarine processes and may therefore also be considered as the outer estuary (Sefton Council, 2013). The estuary can be divided into four main sections: Upper, Inner, Narrows and Outer (Fig. 1.6).

The Mersey Estuary has an unusual “banana” shaped profile which reflects the influence of the bedrock geology and Pleistocene deposits (Ridgway et al., 2012). The depth of the estuary reduces dramatically where it widens upstream of the narrows (Fig. 1.7).

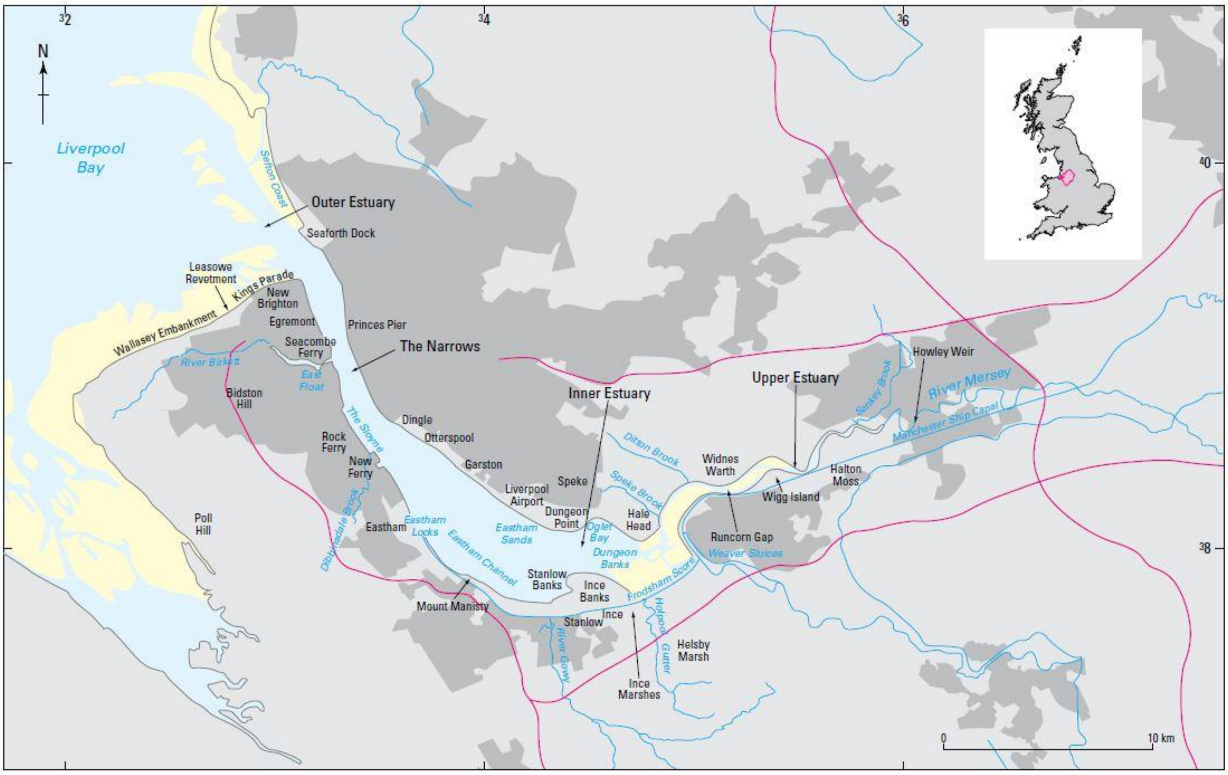


Figure 1.6. The Mersey estuary (Ridgway et al., 2012)

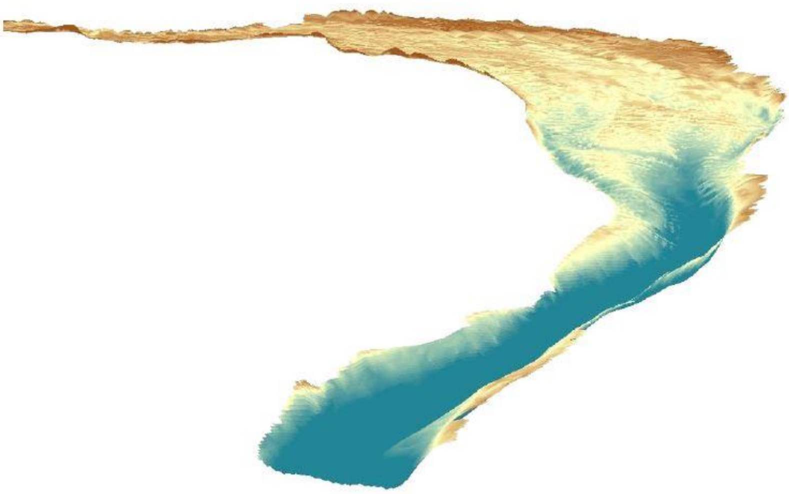


Figure 1.7. Depth colour-scaled image of estuary morphology, viewed from the north (Aggidis and Benzon, 2013)

The Mersey occupies a highly urbanised and industrialised drainage basin and was once regarded as one of the most polluted estuaries in Europe. This was addressed by the Mersey Basin Campaign (MBC) which ran from 1985 to 2010 and transformed the Mersey by improving the water quality and regenerating the waterside. The estuary, in common with most other UK estuaries, has several environmental designations (Fig. 1.8)

Although it must be recognised that the River Mersey is influenced by its entire catchment and that developments in the estuary are likely to have upstream effects, for the purposes of this report, the area of interest encompasses the length of the Mersey Estuary from Liverpool Bay, as far inland as Widnes and Runcorn, i.e. the Outer and Inner Estuaries and the Narrows.

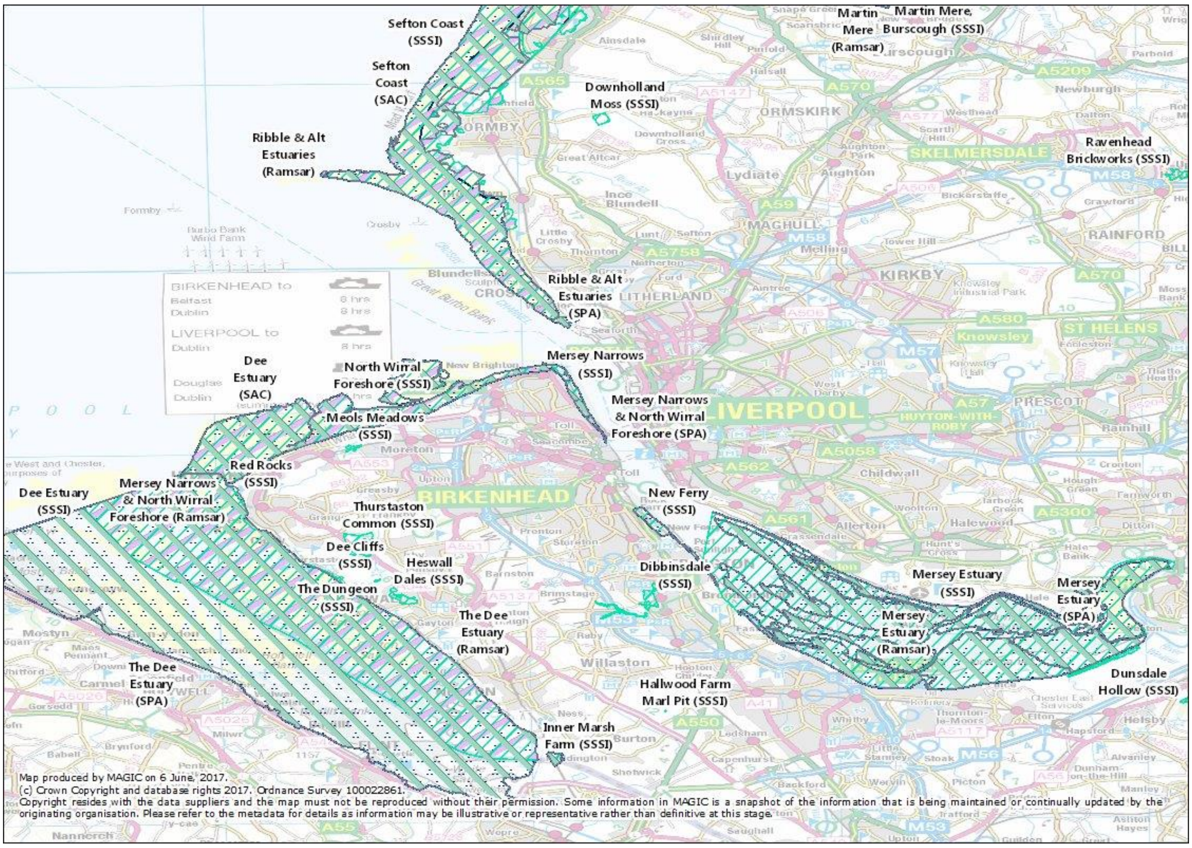


Figure 1.8. Environmental designations of the Mersey Estuary and Liverpool Bay

2. Tidal Energy options

Unlike other sources of renewable energy, tides are an extremely reliable and predictable power source. Tidal power can be harnessed in two ways, through tidal range (in which potential energy from the difference in head height is harnessed as water passes through turbines) or tidal stream (which relies on the kinetic energy of the tidal current).

2.1 Tidal Range

Technologies that harness tidal range energy include barrages, lagoons and tidal reefs. Good resources exist where large water masses flow into bays or estuaries in macrotidal (defined as tidal ranges of 4 m or more) areas. Worldwide, locations with the greatest tidal ranges are in Canada, the UK, Korea, China, etc. (Fig. 2.1). It is estimated that approximately 500 to 1000 TWh per year could be generated from tidal range resources worldwide (Baker, 1991). The resource in the UK is estimated at 50 TWh annually (Hammons, 1993), mainly on the west coast where tidal range is high, with potential outputs from some of the major estuaries shown in Table 2.1. Tidal range energy potential is proportional to the tidal range squared, multiplied by the area of the water mass involved (Burrows et al., 2009b).

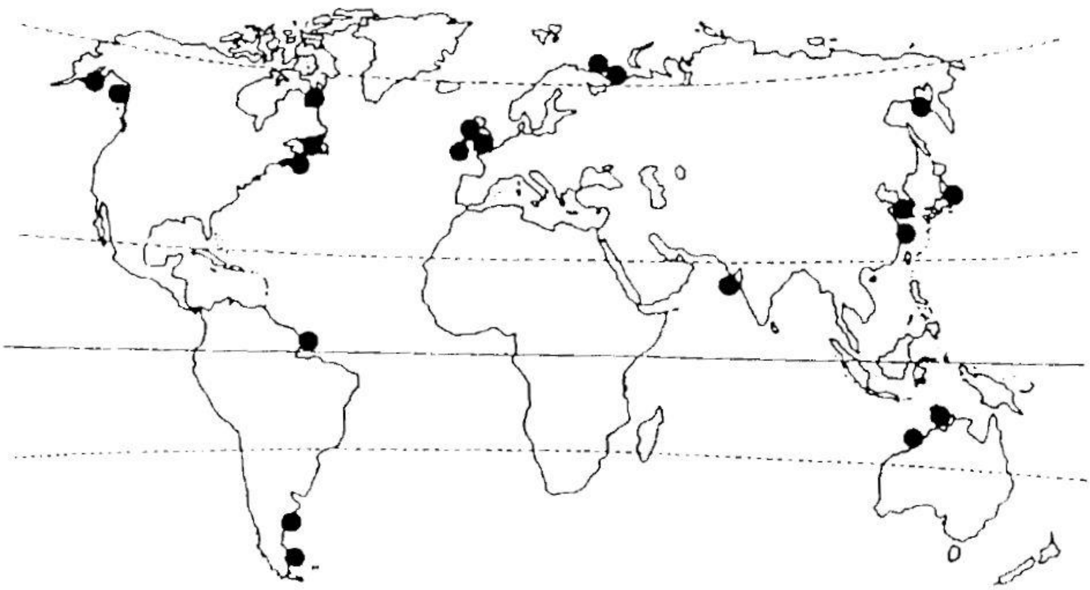


Figure 2.1. Locations with the potential to generate energy using tidal range (Hammons, 1993)

Table 2.1. Potential annual energy output from tidal barrages in the UK

Location	Resource (TWh/y)
Severn	17[a]
Mersey	1.4[a], 1.38[b]
Duddon	0.212[a]
Wyre	0.131[a]
Conwy	0.06[a]
Dee	1.10[b]
Solway Firth	13.10[b]
Morecambe Bay	6.62[b]
Ribble	0.53[b]

[a] (Sustainable Development Commission, 2007), [b] (Burrows et al., 2009a)

2.1.1 Tidal Barrage

Tidal barrages operate in a similar way to traditional large-scale hydroelectric power in that they use a dam to create a difference in head between the two bodies of water on either side of a dam wall. As water flows either in or out of the estuary at flood and ebb tide, the dam blocks the flow creating a head difference. When the desired difference in head is reached, the water is released through the turbines in the dam wall generating electricity. In contrast to hydroelectric dams, tidal barrages can be bi-directional, making them capable of producing power four times a day, with a head difference created twice over each tidal cycle (as the tide comes in and as it goes out), which occurs twice a day where tides are semi-diurnal (as in Liverpool).

Although the technology to harness energy from tidal range has long been understood, there are currently very few tidal barrages in operation worldwide although there are several proposals to develop more, for example in South Korea and the UK.

There are several generation options for power generation with a tidal barrage, these include: one way generation at ebb tide; one way generation at flood tide; two-way generation (on flood and ebb tides); the incorporation of additional pumping; and double-basin barrages.

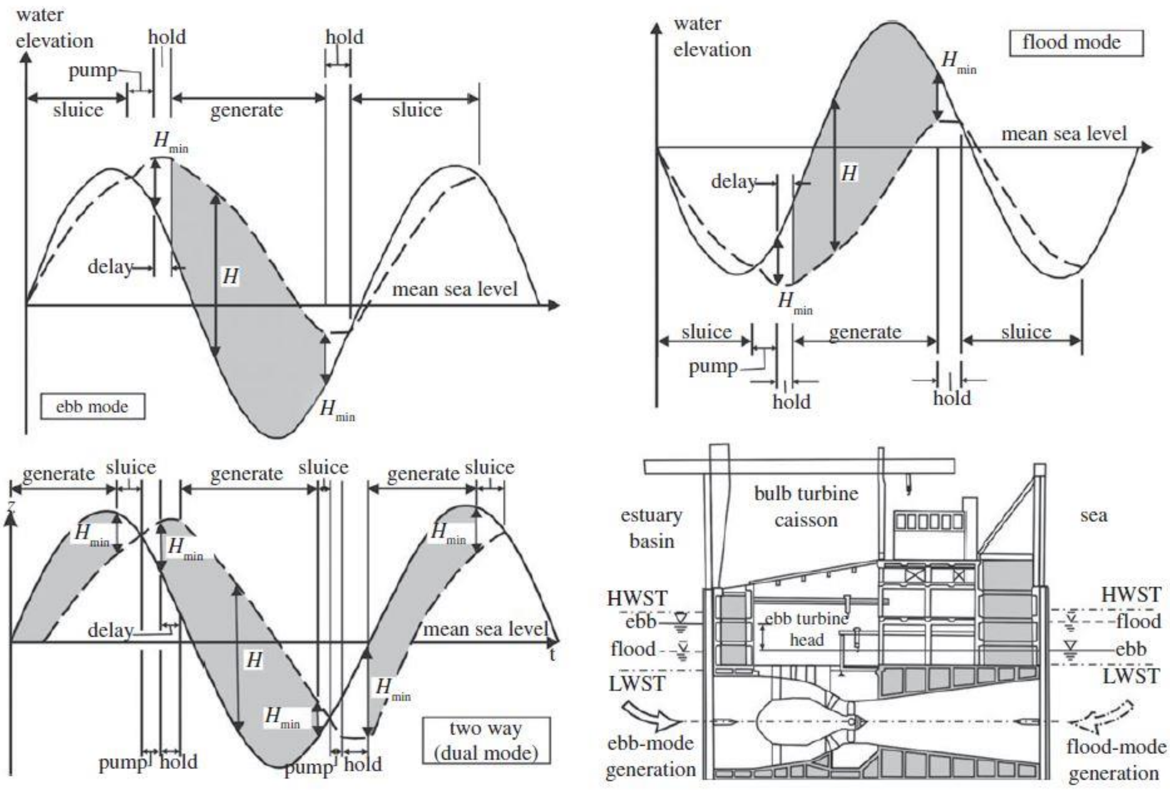


Figure 2.2. The modes of operation of a tidal barrage or lagoon and an illustration of a turbine caisson. Dashed lines are basin water level and solid lines are sea water level. HWST, high water spring tide: LWST, low water, spring tide. (Burrows et al., 2009a, Yates et al., 2013)

In ebb generation, the estuary basin fills with water through the sluice gates over the flood tide. At high tide the sluices are closed, trapping the water behind the barrage (at this point additional water may be pumped into the basin, further increasing the difference in head). When the tide has ebbed sufficiently on the seaward side of the barrage to create a hydrostatic head the water is allowed to flow through the turbines, generating electricity. This continues until the hydrostatic head has dropped to the lowest level at which the turbines can operate.

In flood generation, the sluice gates are kept closed as the tide rises until a sufficient hydrostatic head develops. The turbines are then opened and electricity generated as the basin fills. This is usually less efficient than either ebb or two-way generation as the basin is never either fully emptied or filled (Fig. 2.2) (Waters and Aggidis, 2016).

In two-way or dual mode generation, both the flood and ebb tide are used. The sluice gates are closed until near the end of the flood cycle. The turbines are opened to allow generation until the difference in head becomes too small for generation to continue the sluice gates are opened so that the basin fills to the high tide level. At high tide the gates are closed until the tide has ebbed sufficiently for the difference in head to allow generation. At this point the turbines are opened for ebb generation.

In two-way generation, the difference in head height before generation begins is reduced (Fig. 2.2) and the turbines operate less efficiently in flood mode (Waters and Aggidis, 2016), therefore there may be less electricity generated from two-way generation than from ebb only. However, two-way generation reduces the period of non-generation, giving a more consistent supply of electricity, although there are still periods when generation must stop because of reduced difference in head.

To incorporate additional pumping, the turbines used are powered to operate in reverse, moving water through the barrage and increasing the difference in head. Although this uses some energy, it can significantly increase generation (Waters and Aggidis, 2016).

Double-basin generation is achieved through the adaptation of the barrage design to create a main and secondary basin. The main basin is operated as for ebb generation with water pumped and stored in the second basin. This allows generation to be staggered or delayed for peak periods in the same way as traditional pumped hydro (See section 5.1.1).

In addition to options in generating strategies, there are various different turbine types. The current options are either bulb or Straflo turbines, created in 1913 and 1919 respectively. Straflo turbines have lower construction costs, but do not have as high peak efficiency as bulb turbines, and only operate in ebb generating mode. Future tidal range turbines may include a modified bulb turbine (designed to improve the low efficiencies when operating in reverse); Archimedes screw (currently used in freshwater hydroelectric schemes); Gyro (currently used for tidal stream generation); and a counter rotating device (Waters and Aggidis, 2016).

Despite the proven technology of barrage construction, operation and maintenance and the fact that tidal range power plants have the potential to produce more electricity than any other form of renewable energy (Waters and Aggidis, 2016) very few have been constructed. This is thought to be due to high capital costs with little short-term financial gain and the potential negative environmental impacts (O'Rourke et al., 2010).

The environmental implications of a tidal barrage are difficult to predict partly because, although there are examples in operation, there have been no measurements of impact. At La Rance (Fig. 2.3) there was no assessment of environmental conditions prior to construction (Waters and Aggidis, 2016) and at Lake Sihwa the power generation was initiated in an attempt to remedy environmental degradation (Lee et al., 2014). There are some indications from La Rance that there were impacts to the environment due to modification of the tidal regime causing changes in water depth, intertidal area, salinity and sediment which have resulted in, for example, the loss of sand-eels and other marine fauna during the three year construction phase (British Hydro, 2009; Waters and Aggidis, 2016). However, by 1976 (10 years after completion) the estuary was considered to be richly diverse as a new biological equilibrium was reached (British Hydro, 2009).

There are likely to be physical changes to the estuary channel and basin due to impoundment of the water by a barrage. Modification of flows may cause scouring around the structure and silting of the basin behind the barrage (Wolf et al., 2009). Where there is scouring there may be increased sediment suspension and a decrease in water quality (Burrows et al., 2009a). Where there is siltation (settling in the lower-energy environment), levels of suspended particles in the water are likely to decrease, due to causing greater penetration of light into the water column (Hooper and Austen, 2013). There may be an increase in contamination due to reduced flushing and a decrease in salinity upstream of the barrage (Kadiri et al., 2012). If there is a build-up in nitrate concentration, primary production may increase and eutrophication could occur (Kadiri et al., 2012; Hooper and Austen, 2013).

Physical effects are dependent on the design of the barrage and its operation, and will be specific to the estuary. Some effects could be mitigated against through increased dredging and rigorous discharge controls.

The main environmental impact cited in objections to tidal barrages is the loss of intertidal area and the loss of their associated habitats, mudflats and saltmarshes (Burrows et al., 2009a). These areas are important to bird life, providing essential feeding habitat and are often national and internationally protected. Other impacts may be the impediment of migratory fish, although fish passes could be constructed, and the potential for injury to fish and marine mammals through collision with the barrage and its turbines (Wolf et al., 2009; Roche et al., 2016). Changes to the estuary may mean that areas that were previously useful nursery habitat are no longer suitable. On the other hand, any increase in primary production could be beneficial to filter feeders (Wolf et al., 2009). Importantly, the operation of a tidal barrage in generating energy reduces carbon emissions across the energy mix and thus has environment benefits at both local and global scales.

A major potential impact of tidal barrages is to channel navigation (Mersey Tidal Power, 2011b). This would need to be addressed at the design stage with consideration of the position of a barrage and inclusion of locks, however the greatest disruption would probably occur (albeit temporarily) during the construction phase.

A recent review of tidal range technologies (Waters and Aggidis, 2016) concludes that, due to technological advances, the time of objections to tidal range technology on environmental and cost grounds is coming to an end.

Although tidal range is a highly predictable renewable resource, giving this form of generation an advantage over other renewable resources, it does not produce a constant source of energy. There is a large variation in the electricity generated due to the spring-neap cycle of the tide. The maximum power output during neap tide is about 48% of that on a spring tide, with the total energy output for the neap tide being roughly 26% of that for the spring tide (Burrows et al., 2009). Similarly, due to the phase of the tides, they do not occur at the same time every day. Half the generating potential is likely to occur when demand is very low (e.g. in the very early morning). Maximum electricity demand occurs in the evening, with a peak when people come home from work at about 6:30pm. Additionally, although highly predictable, generation is intermittent, with two (or four) peaks a day coinciding with the ebb (and flood) tide. It has been proposed that this might be overcome through conjunctive operation of multiple barrages (Burrows et al., 2009a). It was found that if eight barrages around the UK operated for the maximum time per day, electricity could be generated for about 20 hours with two peak generating periods. If barrages were operated only to achieve maximum power output, the generating window is reduced.

La Rance Case Study

The world's first tidal barrage, at La Rance in France (Fig. 2.3), was completed in 1966 (Charlier, 2007). A 720 m barrage across the river Rance enclosed 22 km^2 surface area of water. It uses a combination of two-way generation through 24 10 MW bulb turbines and pumped storage which enhances the power generated on the ebb tide to produce a net output of approximately 480 GWh annually (O'Rourke et al., 2010). This barrage has now been operating successfully for over 50 years.

Figure 2.3. La Rance tidal barrage at St. Malo, France (DOE Global Energy Storage Database, 2016)

Lake Sihwa Case Study

The most recently built and largest tidal barrage is at Lake Sihwa, South Korea. It started operation in 2012, generating an estimated 550 GWh annually from 10 bulb turbines operating in the flood direction only (Waters and Aggidis, 2016, Borthwick, 2016). The barrage was initially constructed as a dam to convert an intertidal area into a freshwater lake, this was completed in 1994. However, the project failed due to water quality deterioration (Lee et al., 2014) and the decision was made to reintroduce seawater circulation to the lake in an attempt to improve water quality. The dam was converted to a tidal barrage through the installation of turbines, enabling electricity generation in addition to water exchange (Waters and Aggidis, 2016). Because the turbines were installed post-construction, primarily for water exchange, the barrage only generates electricity on the flood tide, which means it is less efficient for energy generation than it would be if it operated on both the flood and ebb tides.

Other Schemes

Other barrages have been constructed in Annapolis, Canada (1984); Jiangxia, China (1985); and Kislaya Guba, Russia (1968). In addition to power generation, the La Rance, Annapolis and Lake Sihwa barrages all also double up as transport links.

Tidal barrages were first proposed as an energy generating option for the UK in the 1970s (Lawn, 2009), however, despite repeated proposals for a range of sites, none have yet passed the feasibility stage. An ambitious project currently being put forward for North West England proposes the construction of six barrages across the Dee, Mersey, Ribble and Duddon Estuaries, Morecambe Bay and the Solway Firth. In addition to tidal energy, the project proposes to improve transport links across the North West region by creating dual carriageway road links on top of the barrages (NWE2, 2015). A more modest scheme in Lancashire proposed a barrage over the Wyre Estuary from Fleetwood to Knott End. This has a predicted annual energy output of 287 GWh at an estimated construction cost of £400 million (NEW, 2017).

2.1.2 Suitability of the Mersey for energy generation by tidal barrage

With a maximum tidal range of 8.9 m, a current speed of up to 2 ms^{-1}, its narrow mouth and close proximity to population centres, the Mersey has often been identified as highly suitable for tidal range generation (Hammons, 1993; Mersey Tidal Power, 2011c). Indeed, the potential for tidal range energy generation from the Mersey has been under discussion for over 35 years, with a range of proposals and feasibility studies having been carried out over that time.

The first proposal for a barrage was made by the Merseyside County Council in 1981, with studies undertaken by Marinetech North West published in 1983 and 1985 (Hammond and Wood, 1990). These studies prompted the formation of the Mersey Barrage Company, a consortium of construction companies and local interests, to promote the scheme. Three possible locations (Fig. 2.4) were considered in the 1983 study (Reilly and Jones, 1990), New Brighton to Langton Lock (Line 1); Seacombe Promenade to Trafalgar Dock (Line 2); and Rock Ferry to what was Herculaneum Dock (now filled in, Line 3). The line from Seacombe to Trafalgar Dock was immediately abandoned, whilst the most downstream option, Line 1, was moved 800 m upstream (Line 1A) to a location identified as more suitable with consideration to shipping. Although Line 1A was considered the better choice geologically and would require a shorter dam to be constructed, providing cheaper electricity, Line 3 was selected as the most economic overall as Line 1A required a larger ship lock to allow tankers to access Tranmere Oil Terminal (Sustainable Development Commission, 2007).

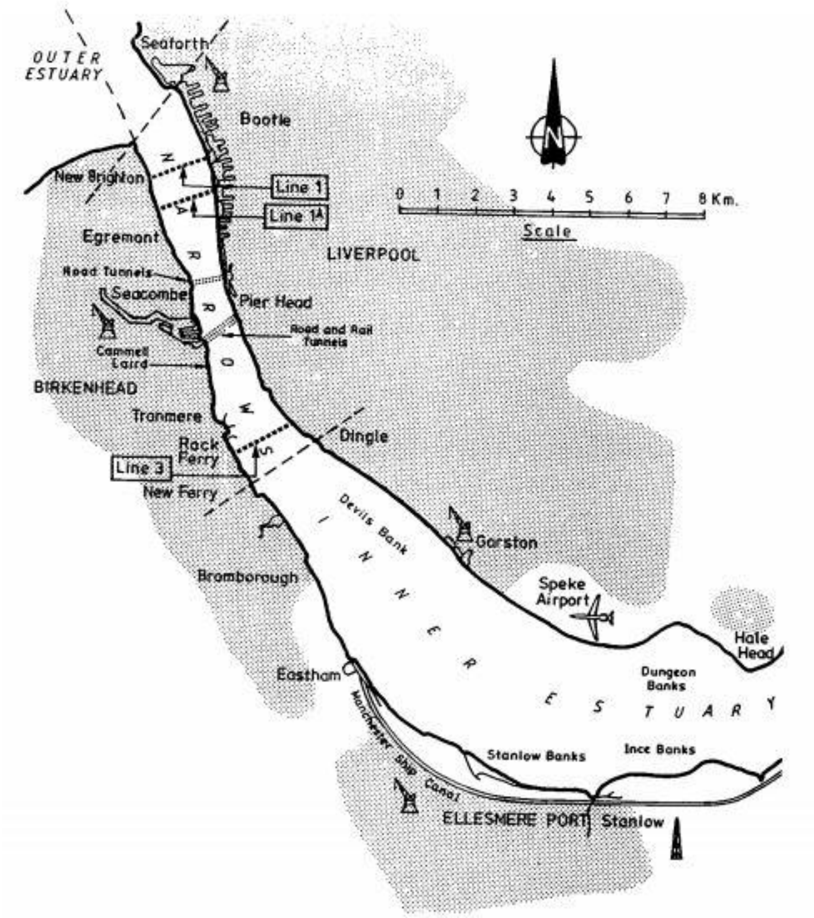


Figure 2.4. Lines for a Mersey Barrage proposed by the Marinetech North West (1983, 1985) (Reilly and Jones, 1990)

A further study, termed a "pre-feasibility study" was commissioned by Peel in partnership with the North West Development Agency (NWDA) in 2006. This was followed up with a three-stage feasibility study which ran from 2009 to 2011 under the banner of Mersey Tidal Power (MTP) project (Mersey Tidal Power, 2011c).

The MTP report identified three broad locations (Bands A, B and C, see Fig. 2.5) and a range of potential technologies, described as an impounding barrage; a very low head barrage; a tidal fence; and a Spectral Marine Energy Converter (SMEC), which led to a shortlist of five location/technology options. It was found that the current velocity was too low for a tidal fence and that the SMEC required further development. The B and C locations were discounted due to navigation issues, with the location being required for manoeuvring in and out of the docks and the channel at this point being too narrow for accommodation of both the lock and tidal power plant. The shortlist was further reduced to three possible schemes, an impounding barrage at Band A, or a very low head barrage at either Band A or B (Mersey Tidal Power, 2010b). The final selected scheme was aligned between New Ferry and Dingle, a similar location to that identified as optimal in the 1983 study (Mersey Tidal Power, 2011a).

Figure 2.5. Locations for Mersey Tidal Power project feasibility study (Mersey Tidal Power, 2010b)

The amount of power it is possible to produce from any barrage scheme is dependent on a range of factors including the location of the barrage; the type, size and number of turbines installed; whether energy is generated on the ebb tide only, or both ebb and flood; and whether additional pumping (to increase the difference in head) is used. These output calculations can only be made once design decisions have been made. However, although there are very few tidal barrages worldwide, they are an established and well-understood technology, it is therefore expected that calculations made for previous reports and feasibility studies should provide a reasonable guide as to what could be achieved. These figures are presented in Table 2.2, below.

A recent study (Aggidis and Benzon, 2013) undertook to review the predicted energy outputs of the studies described in Table 2.2 using new double regulated turbine technology from Andritz Hydro (Aggidis and Feather, 2012) and improved bathymetric data (Fig. 1.6). Results showed that, for operating modes of ebb generation with and without additional pumping, these turbines increased predicted annual energy output by around 20 %.

Whilst the Mersey estuary is a strong candidate for a future tidal barrage there are various issues which must be addressed. These include environmental, navigational and cost issues, which may prove a barrier to construction (O'Rourke et al., 2010). A barrage would cause disruption to the natural tidal cycle within the estuary with a decrease in exposed intertidal mudflat area. Mudflats are an important zone for primary production within the estuarine system and represent an important feeding habitat, particularly for migratory birds (Wolf et al., 2009). This is recognised in the environmental designations with which large areas of the estuary and Liverpool Bay have been awarded (Fig. 1.7). Effects to the intertidal zone could be reduced by implementation of dual (ebb and flood) generation, which could maintain the size of the Mersey intertidal area close to that without a barrage (Fig. 2.6) (Wolf et al., 2009).

Table 2.2. Comparison of configuration and predicted energy outputs of previous Mersey barrage studies

Study	Year	Capacity (MW)	Output (TWh/y)	Physical and operational parameters (ø = diameter)	Source
Department of Energy	1984	621	1.32	27 x 7.6 m ⌀, 23 MW turbines, with 18 sluice gates. Ebb generation	(Mersey Tidal Power, 2011a)
Mersey Barrage Company	1991	700	1.45	28 x 8 m ⌀, 25 MW turbines, with 47 channel sluices. Ebb generation	(Sustainable Development Commission, 2007)
University of Liverpool, Joule project	2009	621	1.07	27 x 7.6 m ⌀, 23 MW turbines, with 18 sluice gates. Ebb generation	(Burrows et al., 2009a)
University of Liverpool, Joule project	2009	621	0.98	27 x 7.6 m ⌀, 23 MW turbines, with 18 sluice gates. Ebb and flood generation	(Burrows et al., 2009a)
University of Liverpool, Joule project	2009	1863	1.72	81 x 7.6 m ⌀, 23 MW turbines, without sluice gates. Ebb and flood generation	(Burrows et al., 2009a)
Mersey Tidal Power	2010	700	0.90	28 x 8 m ⌀, 25 MW turbines, with 18 sluice gates. Ebb generation with fixed starting head of 3.9 m	(Aggidis and Benzon, 2013)
Mersey Tidal Power*	2011	700	0.92	28 x 8 m ⌀, 25 MW turbines, with 18 sluice gates. Flexible ebb generation with starting head optimised for maximum energy for 8 months and head limited to 3 m for 4 months of every year	(Mersey Tidal Power, 2011a)

*In this study the barrage location was moved 300 m downstream compared to previous studies to avoid Devil's Bank

A barrage would also represent a barrier to shipping within the estuary. The Mersey is a commercial waterway, with about 8,500 vessel calls each year. Of these, around 4,100 enter Liverpool Docks, 1,800 go to Garston or Eastham (for the Manchester Ship Canal or QEII Dock) with the remaining 2,600 berthing at intermediate points (Mersey Tidal Power, 2011b). Whilst the barrage location can be selected to minimise disruption, and lock gates would be included in the design, navigation times are likely to be increased which could have economic implications to LCR and the wider North West region. The Mersey Tidal Power report (2011b) concluded that whilst a barrage at Band B (Fig. 2.5) offered the best navigation solution, impacts to navigation caused by a barrage at Band A (Fig. 2.5) could be overcome. It has been suggested (Mersey Tidal Power, 2011b) that access to leisure craft through locks may be restricted, with access permitted to commercial shipping only, although there was some indication that alternate means could be provided.

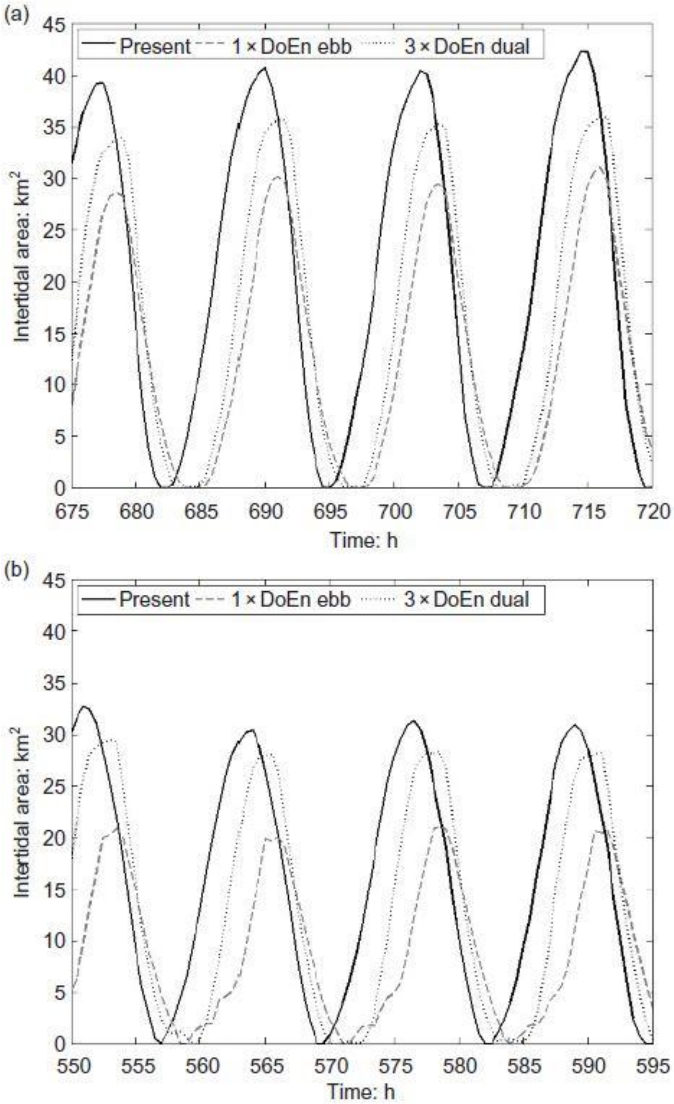


Figure 2.6. Effect of different generating regimes on the intertidal area of the Mersey during a typical (a) spring tide and (b) neap tide (Wolf et al., 2009)

Finally, whilst the concept of a barrage has been explored on several occasions it has never gone beyond the feasibility stage; a major reason for this is the cost of construction. Following the most recent feasibility study, completed in 2011, Anthony Hatton, Peel Energy's Development Director, stated that "the preferred scheme is unlikely to attract the necessary investment while the emphasis in the financial sector and renewable energy incentives is on technologies that provide short to medium term returns". A barrage would be expected to have a lifespan of 120 years and cost around £3.5 billion (2011 prices) to construct (Mersey Tidal Power, 2011c).

A barrage on the Mersey could present opportunities in addition to electrical generation. These include cultural and transport benefits such as a visitor centre and a pedestrian crossing and cycleway over the river. It has also been proposed that, in light of predicted future sea-level rise, a tidal barrage could offer improved flood protection. A recent study by Hinkel et al. (2015), conducted as part of the EU funded RISES-AM project, found that although a barrage in the proposed location at Band A (Fig. 2.5) would reduce the number of people affected by flooding, the depth of flood water would be increased at other locations and therefore the costs would be increased. However, it was acknowledged that the study treated the barrage as a solid wall and did not simulate active management of the barrage or the potential for alleviation of flooding caused by a combination of storm tides and high river flows (Hinkel et al., 2015). It would be recommended, therefore, that the potential for flood alleviation by a Mersey barrage be investigated further.

2.1.3 Tidal Lagoon

A tidal lagoon operates in a similar way to a barrage in that it relies on a difference in head height, created by the incoming and outgoing tide on either side of a dam structure. Lagoons, however, do not depend on the complete separation of an estuary or bay from the sea. Instead, either a semi-circular barrier is built along a section of coast, creating an impoundment with the coast making up one edge, or a fully self-enclosed barrier is built to encircle an area of water offshore, entirely disconnected from the land.

The advantage of the tidal lagoon over a barrage is that the estuary is not cut off from the sea and is therefore still navigable by shipping. There is also likely to be lower environmental impact as a smaller area is affected by a changed tidal regime. Although the total amount of energy produced is likely to be lower with a lagoon than a barrage, the energy produced per unit of enclosed area is higher (Waters and Aggidis, 2016). At some locations, for example in the Severn Estuary, it may be possible to build a series of lagoons which would then be capable of producing more energy than a single barrage and would perhaps resolve the issue of intermittent energy production (Angeloudis et al., 2016).

Lagoon structures, where attached to the coast, could also provide a flood prevention function in that they would act as a barrier to waves, surges and high tides (Lyddon et al., 2015; Angeloudis et al., 2016). However, there are also indications that the presence of lagoons could increase water levels downstream of the structure and therefore potentially increase the likelihood of flooding away from the lagoon structure (Angeloudis et al., 2016). The effects of lagoon structures on coastal flooding were investigated in relation to the North Wirral and Colwyn Bay lagoons (Lyddon et al., 2015). Whilst modelling showed the North Wirral lagoon reduced flooding at Stanlow and Connah's

Quay, the lagoon at Colwyn Bay increased the extent and depth of inundation at Llandudno, Rhyl and Prestatyn, highlighting the need for consideration of near- and far-field impacts during feasibility studies. Any benefits in terms of flood protection have the potential to make a lagoon or barrage scheme more financially attractive.

Tidal lagoons are a currently untested technology with no examples worldwide (Roche et al., 2016), however, there is a proposal for a tidal lagoon in Swansea Bay. This was given development consent in June 2015 (Roche et al., 2016) with construction due to begin in 2018, however, it is still awaiting a Marine License. There are also several other UK projects are in the pipeline and interest in the concept from around the world (Tidal Lagoon Power, 2017). Construction of these initial developments would provide valuable information on impacts for future installations. A recent study recommended that improvements should be made to turbine design to improve two-way generation and minimise effects on sedimentation and water quality up and downstream of the lagoon (Angeloudis et al., 2016).

2.1.4 Suitability of Tidal Lagoons

Tidal lagoon schemes are not likely to be feasible within the confines of the Mersey estuary due to the limited available space, however there have been studies to investigate the possibility of siting this technology within the wider Liverpool Bay area on the North Wirral and Colwyn Bay coastlines (Sustainable Development Commission, 2007; Burrows et al., 2009a; Lyddon et al., 2015). Another recent investigation into the optimisation of lagoon schemes used the example of a series of coastally attached lagoons from the Wirral along the North Wales coast (Angeloudis et al., 2016), a scheme initially suggested to provide dual energy supply and flood protection (Anderson, 2012).

Although it is expected that the total amount of energy produced by a lagoon would be lower than that produced by a barrage, this would be dependent on the area impounded (Table 2.3 and Fig. 2.7). It should be noted that with an increase in impounded area there is an increase in length of sea wall and therefore the costs are also greater (Lyddon et al., 2015). One issue with offshore lagoons (those not attached to the coastline) is that, because of the greater length of wall required to enclose the area, the cost per unit energy is increased (Burrows et al., 2009a).

Table 2.3. Comparison of configuration and predicted energy outputs of previous lagoon studies, locations shown in Figure 2.7.

Location (colours relate to Fig. 4.)	**Enclosed area (km^2)**	**Seawall length (km)**	**Output (TWh/y)**	**Source**
North Wirral	139.1	34.92	1.44	(Lyddon et al., 2015)
Colwyn Bay	39.3	15.8	0.41	(Lyddon et al., 2015)
Liverpool Bay (offshore)	60	34	0.94	(Sustainable Development Commission, 2007)
Dee-Wirral	N/A	30	4.60	(Burrows et al., 2009a)
Dee (offshore)	N/A	54.1	4.60	(Burrows et al., 2009a)
Dee	321	N/A	4.95	(Angeloudis et al., 2016)

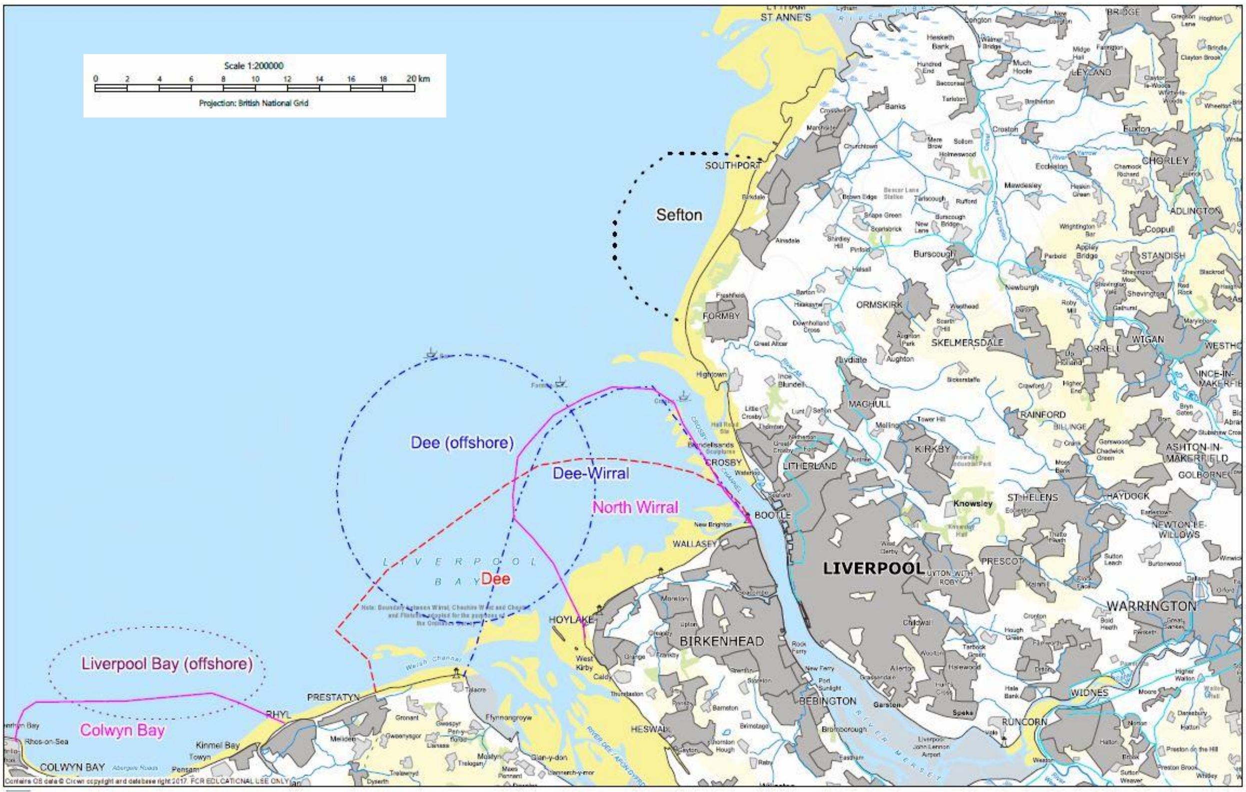


Figure 2.7 Location of lagoons in Table 2.3 with an additional lagoon located on the Sefton coast

2.1.5 Tidal Reef

The tidal reef is a design initially proposed by Evans Engineering which is essentially a low-level barrage working at a head difference of 2 m on both the flood and ebb tides, which allows the safe passage of fish and minimises the alteration of tides and currents either side of the structure (Armstrong Evans, 2011). The design consists of concrete caissons topped by steel modules which act as a siphon and contain four low-head vertical axis turbines (Fig. 2.8). This design offers minimal environmental impact and is expected to have similar power generation potential (over a longer time period) to a conventional barrage.

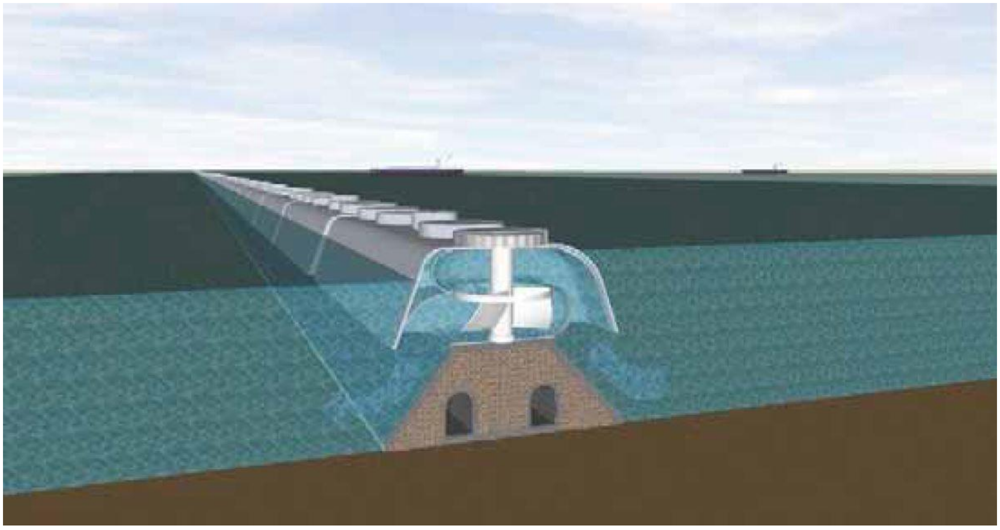


Figure 2.8. A low-head tidal reef design (Atkins Ltd., 2008)

A longer generating time would result in fewer peaks and troughs in generation, making it a more consistent energy source than a conventional barrage design, which would give up to four energy peaks over 24 hours (Armstrong Evans, 2011). The system is modular so that energy generation could start before the structure is complete.

Navigation structures for shipping would still be necessary but, because of the low head design, these would not need to withstand as much hydrostatic pressure as (and would therefore be cheaper than) those for a conventional barrage. Delays to shipping were predicted to be about 10 minutes or less, and at high tide slack water ships would be able to pass through unimpeded (Armstrong Evans, 2011).

The design concept was reviewed by Atkins on behalf of the RSPB (Atkins Ltd., 2008). There were some issues assessing the novel steel syphoning modules, which were replaced in the study by conventional turbine ducts. Although the concept was seen to be feasible, there was a lot of economic uncertainty concerning: the turbine cost; the weight of concrete required; and the annual energy capture, which they recommended should be addressed.

A very similar design, described as the very low-head turbine (or tidal bar) scheme, was proposed for the Severn jointly by Atkins and Rolls Royce. One of the main issues identified was the need for more efficient bi-directional turbine designs (Atkins & Rolls-Royce, 2010).

The tidal reef and very low-head turbine designs were considered by Mersey Tidal Power (Mersey Tidal Power, 2010a) but were considered unsuitable for this location due to the narrow mouth of the Mersey Estuary. The concept was considered to be more suited to the geometry of the Severn which widens towards the sea and therefore allows for a very long reef which could accommodate a large number of turbines.

2.1.6 Dynamic Tidal Power

Dynamic Tidal Power (DTP) is a concept developed and patented by two Dutch coastal engineers (Kees Hulsbergen and Rob Steijn) in 1997. At a location where the tide runs parallel to the coast (such as along the east coast of the UK in the North Sea or the east coast of China) a 30 to 60 km dam would be constructed perpendicular to the coast, with a shorter barrier along the end of the dam forming a T shape (Figs. 2.9 and 2.10). This would create a difference in head on either side of the dam (Fig. 2.10) which would be fitted with up to 2000 bi-directional turbines enabling the generation of electricity in the same way as a barrage, but without the need for a bay or estuary.

Figure 2.9. Illustration of dynamic tidal power (ARCADIS, 2014)

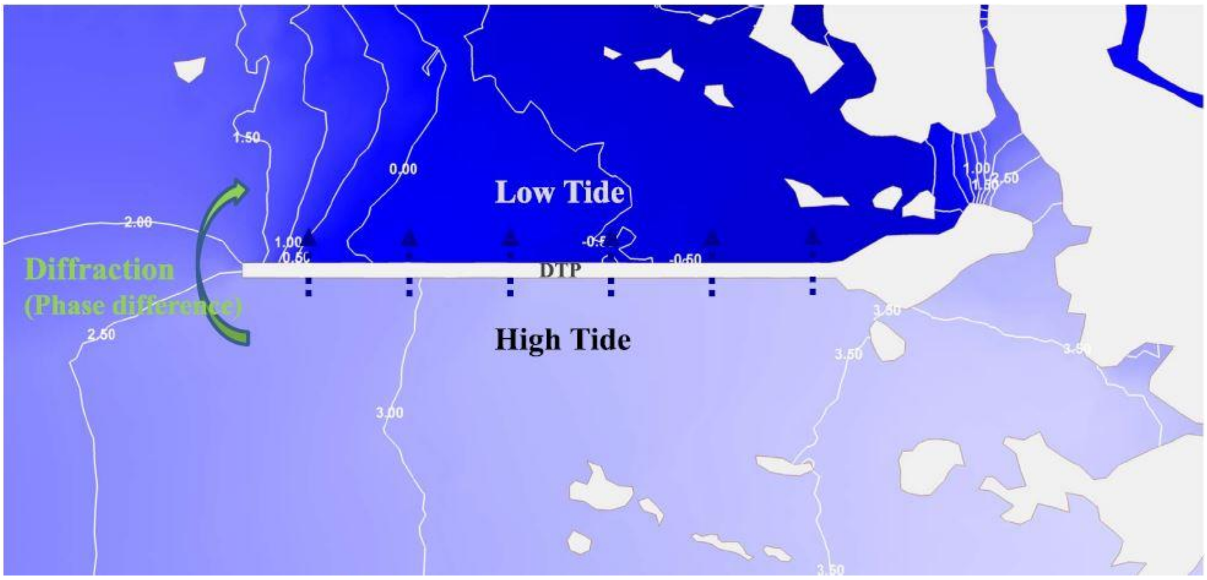


Figure 2.10. Tidal diffraction by Dynamic Tidal Power (Park, 2017)

Although this design is expected to produce a large amount of electricity, the size is restrictive to testing the concept in that, if the barrier is less than 30 km in length, no electricity would be generated. The Dutch government were reported to be supporting a feasibility study in China (ARCADIS, 2014), which was due to report in 2015 - however, there is no further information available at the current time.

A recent study (Park, 2017) modelled the potential energy generation by DTP at a site on the west coast of South Korea. It found that the difference in head increased with the length of the structure, but decreased with distance from the coast. It was found that the width of the structure and the inclusion of a shorter barrier at the end of the main structure had little effect on head difference and therefore these modifications would be unlikely to increase the generating potential of DTP.

The scale of DTP makes it unsuitable for deployment either in the Mersey estuary or Liverpool Bay.

2.2 Tidal stream

The tidal stream (or current) is the horizontal movement of water which accompanies the rise and fall of the tides. This energy can be captured by an underwater turbine, in much the same way as wind energy is captured with a wind turbine. Turbines may be sited individually, or as part of a tidal array which is made up of several individual turbines, equivalent to a wind farm.

There are a wide variety of turbine designs, from a conventional horizontal axis turbine (similar to a conventional wind turbine design), through vertical axis turbines, to energy conversion via an undulating membrane such as the EEL Energy design (EEL Energy, 2015) (Fig. 2.11). In addition to harvesting power from bidirectional tidal currents, these turbines can also be used in unidirectional ocean currents.

Axial flow turbines extract energy by rotating blades mounted on a rotating hub and can be either horizontal or vertical. They may be bare-bladed (Fig. 2.11c), ducted or open-centred with blades attached to an outer rim, such as those designed by Open Hydro (OpenHydro, 2016) and being tested at Paimpol-Brehat, France (Fig. 2.11a).

Cross-flow turbines are those in which blades are orientated horizontally across the flow of the current. An example is the THAWT (transverse horizontal axis water turbine) being developed by a team at the University of Oxford (Fig. 2.11e). The device is scalable and requires fewer foundations, bearing seals and generators than a horizontal axis turbine.

Hydrofoil turbines operate by utilising the lift force which causes an arm to move and drive fluid in a hydraulic system which is then converted to electricity. Tidal kites are tethered paravanes that fly underwater converting kinetic energy to electricity, these require water depths of 60 to 120 m. Other potential designs include the Archimedes screw or fan belt style designs such as Tidal Snails or the Atlantis Solon-K (Borthwick, 2016). Smaller technologies are currently also being developed which could be used for more inland applications or for river current generation, these are described in some of the case studies, below.

Like tidal barrages, tidal stream turbines face economic and environmental barriers. The technology is somewhat unproven, with only one tidal current generation facility at Uldolmok, South Korea (see below) in commercial operation. This, however, is a quickly developing situation with many research projects in deployment, one of which (MeyGen in the Pentland Firth, Scotland) recently started exporting electricity to the national grid. There are also several projects underway worldwide, in countries such as Canada, China, Ireland and Norway (Carbon Trust, 2011). It is expected that costs will reduce as the technology develops in the same way as has occurred with wind energy. Tidal arrays don't have the very high initial costs of a barrage or lagoon and have the advantage that they can be built up and added to over time, so that the initial outlay can be reduced and any impacts can be monitored.

Potential environmental impacts may include physical, acoustic, chemical and electrochemical changes, the most significant effects, however, are likely to be those related to energy removal (Nash and Phoenix, 2017). Marine turbines exert an influence over local flow speeds which can persist over large distances (de Dominicis et al., under review). Single turbines and small arrays are expected to have negligible far-field effects, but larger arrays could have much greater impacts with reductions in current velocities upstream, downstream and within the arrays. Changes to hydrodynamics may have consequential environmental impacts such as changes to mixing and transport processes affecting water quality and the existing flora and fauna (Nash and Phoenix, 2017).

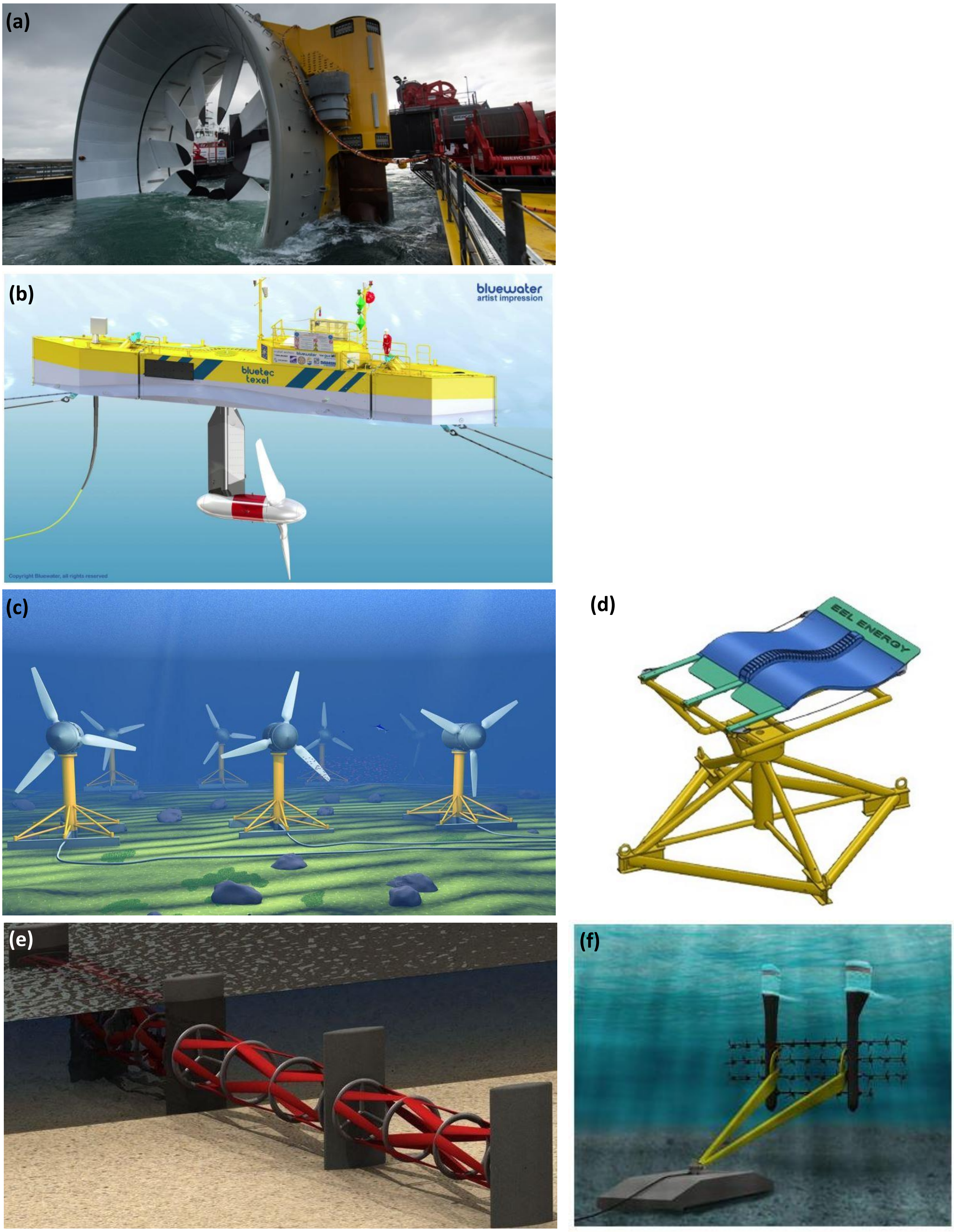


Figure 2.11. Some examples of tidal steam device designs (a) an open-centre turbine being deployed (Openhydro, 2016), (b) a floating tidal energy platform (Bluewater, 2017), (c) a tidal array (Tidal Energy Today, 2015), (d) EEL Energy undulating membrane (EEL Energy, 2015), (e) a cross-flow turbine (Tidal Energy Research Group, 2016) and (f) a single foundation array (Schottel Hydro, 2017)

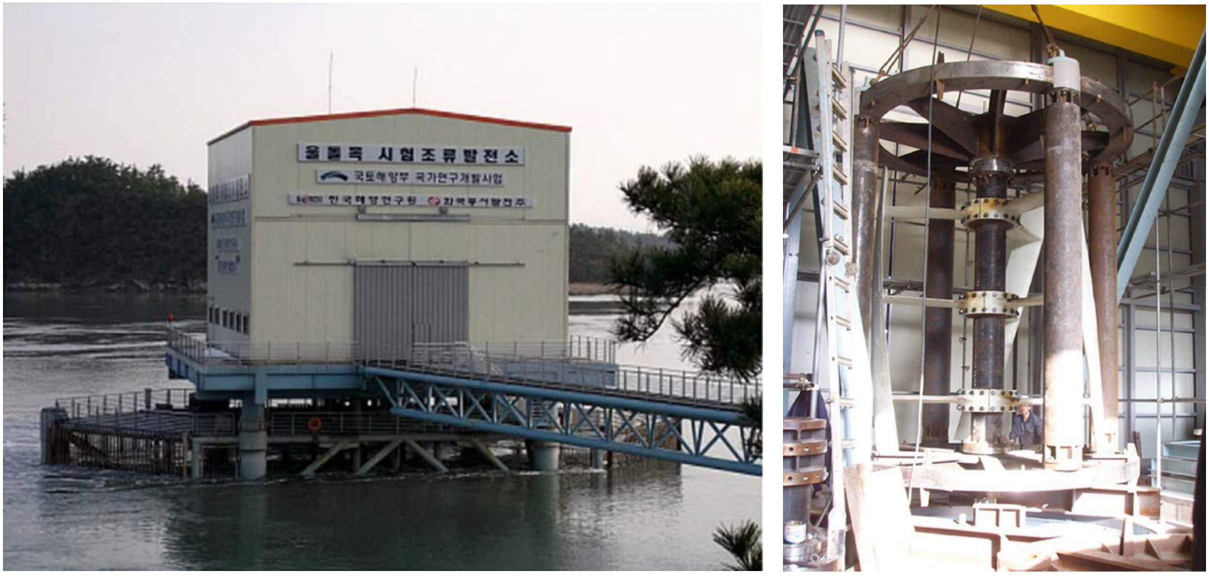


Figure 2.12. Uldolmok power station and one of the triple helical turbines (Park, 2017)

Uldolmok Case Study

Uldolmok is on the west coast of South Korea, with maximum current speeds of 6.7 ms^{-1}; the tidal stream generation facility there was completed in 2009. It comprises two 500 kW Gorlov triple helix turbines (Fig. 2.12), which between them generate 2.4 GWh annually (Park, 2017). Despite the relatively recent construction of two tidal power plants in South Korea (at Lake Sihwa and Uldolmok) all subsequent projects have been abandoned or delayed indefinitely due to objections from environmental groups (Park, 2017).

MeyGen Ltd., Pentland Firth Case Study

MeyGen Ltd. intends to install a 398 MW tidal array in the Pentland Firth by the early 2020s (MeyGen, 2015). The first phase (Phase 1A) of the MeyGen project, a 6 MW tidal array in the Inner Sound of the Pentland Firth with four 1.5 MW turbines installed, was recently accredited by Ofgem (TidalEnergy Today, 2017). The project has one Atlantis and three Andritz Hydro Hammerfest turbines all of which are three blade horizontal axis turbines with an 18 m diameter. The turbines are positioned on the seabed using a tripod gravity-base support and are expected to have a 25-year lifespan. MeyGen has secured a 15 MW connection to the local distribution network managed by Scottish Hydro Electric Power Distribution plc., and a further connection to the high voltage transmission network with Scottish Hydro Electric Transmission Ltd. (MeyGen, 2015). This is the first tidal array to be connected to the UK grid, although in 2016 Nova Innovation deployed the world's first array of turbines in the Bluemull Sound, in the north of the Shetland Isles which is supplying electricity to the Islands (Nova Innovation, 2017).

A total of £51.3 million for Phase 1 of the MeyGen project was secured by a funding syndicate which included: Atlantis Resources; the Department of Energy & Climate Change; The Crown Estate; Scottish Enterprise via the Renewable Energy Investment Fund (REIF); and Highlands and Islands Enterprise. And approximately 50 direct and 70 indirect jobs have been created (MeyGen, 2015).

SeaGen S, Strangford Lough Case Study

SeaGen S, was designed, built and installed by Bristol based company Marine Current Turbines (MTC), now wholly owned by Atlantis Resources Ltd. It was the world's first commercial-scale tidal turbine, commissioned in Strangford Lough in 2008. The device comprised two 600 kW horizontal-axis turbines attached to a single support, which was bolted to the sea floor. A key design feature of the SeaGen S are rotor blades which can be pitched through 180 degrees to optimise energy capture and operate in bi-directional flows (Fig 2.13) (Marine Current Turbines, 2014).

The powertrains were removed from the device in June 2016 and it is currently being decommissioned, a process which should be completed by spring 2018 (Atlantis Resources, 2017).

Essentially a research and design platform, the SeaGen project produced valuable environmental information relating to effects on marine mammals, the benthic community and breeding seabirds (Keenan et al., 2011). The monitoring programme ran from May 2005 to December 2010 and apart from a temporary displacement of harbour porpoises during the construction phase and avoidance of the turbine by seals, no discernible effects were observed (Keenan et al., 2011).

Figure 2.13. SeaGen S turbine (Keenan et al., 2011)

The Humber Estuary Case Study

Following a period of testing a nearshore, estuarine, vertical axis turbine, floating tidal stream device - the Neptune Proteus NP1000 - was deployed in the Humber estuary in 2012 (Fig. 2.14). The device consisted of a 6.0 x 6.0 m turbine housed in a Venturi duct which acts to accelerate the flow of the water through the turbine. The entire structure (overall dimensions 20.0 x 12.8 x 6.5 m (L x W x D)) was designed to float so that the turbine remained below the water surface and kinetic energy was converted to electricity on both the ebb and flood tides (Hardisty, 2012).

Dock tow trials (in which the device was towed behind a tug to simulate the current) were carried out in October 2010. These led to a predicted annual yield of approximately 1050 MWh. However, following deployment, peak currents were found to be much lower than expected (1.2 ms^{-1} compared to 2.5 ms^{-1}) and the power output was only 10-30 kW (Hardisty, 2017, pers. comm. 20th March 2017). The device was removed in 2014 due to investment shortages.

Figure 2.14. Neptune Proteus NP1000 (Hardisty, 2012)

Texel Floating Turbines Case Study

BlueTEC is a collaborative project between the Royal Netherlands Institute for Sea Research (NIOZ) and private companies (Bluewater, Damen, Van Oord/Acta Marine, Torcado, Schottel Hydro, TKF, Vryhof and Nylacast) with funding from the Netherlands Enterprise Agency and the European Union via the Life program.

The BlueTEC platform (Fig. 2.11b), a floating tidal current energy converter, was installed in the Marsdiep inlet, Texel in the Wadden Sea in the summer of 2015 with a Torcado T1 turbine (6.3 m diameter, 100 kW), this was upgraded to a T2 (9.9 m diameter, 300 kW) in early 2016 (Ponsoni et al., 2016). The platform went from the drawing board to operation as a demonstration model over a period of just six months (Ponsoni et al., 2016).

Research was carried out prior to installation to understand the variability of the tidal current (de Vries et al., 2015) and determine the best location for the platform, which needed to be outside of the navigation channel whilst providing a high power output. The platform, which is made up of three sections, each of standard shipping container dimensions to allow for easy shipping of the platform worldwide, houses the electrical equipment (allowing for easy access and dry storage). Additionally, it contains equipment to monitor, amongst other things, the impact of energy extraction on local flow and sediment distribution and turbine efficiency under varying tidal, discharge and wave conditions. The platform is secured by four mooring lines attached to drag anchors, which maintain its position even under storm conditions.

In order that the turbine can operate on both the ebb and flow tides Torcado turbines are designed with a bi-directional rotor to allow the blades to rotate 180 degrees for reverse flow operation.

There have been some issues with marine growth on the device. Although the platform has been coated with antifouling paint, mussels were found attached to the mooring equipment and power cable which could impact the behaviour and lifespan of the device. This highlights the need for research into local marine growth and implementation of sufficient antifouling and maintenance plans.

Eastern Scheldt Tidal Turbines Case Study

The Dutch company Torcado (who are also involved in the Texel project) installed five turbines in the Eastern Scheldt in September 2015. These hang into the water from an existing storm surge barrier, operating on the flood and ebb tide to generate a total of 1.25 MW (Fig. 2.15).

Torcado are also planning a further installation of five 250 kW turbines in the Minas Passage in the Bay of Fundy, Canada, in late 2017. These will be held on a semi-submersible floating platform held in place by a catenary mooring system.

There is the potential for these smaller turbines to be manufactured at shipyards local to the installation site (Torcado B.V., 2015b).

Figure 2.15. Torcado turbines in the Eastern Scheldt (Torcado B.V., 2015a)

Schottel Hydro instream turbine

Schottel Hydro (another company involved in the Texel project) have an instream axial flow turbine, available with blade diameters of between 3 and 5 m, suitable for deployment in river and estuarine locations (Schottel Hydro, 2017). Multiple turbines can be installed on a single foundation (Fig. 2.11f) or suspended from floating platforms.

2.2.1 *Suitability of tidal stream turbines for the Mersey*

The National Oceanography Centre (NOC), in Liverpool, have produced a 'quick-look' tidal array scenario for the Mersey Estuary and part of Liverpool Bay to understand whether horizontal axis turbines could be deployed in this location (De Dominicis, 2017, pers. comm., 2nd June). Horizontal axis rotors range from 1.5 to 20 m in diameter, and the smallest size was assumed to be deployed here. This, along with the height of the hub and the requirement for a minimum water depth of 5 m above the device at low tide, gives a minimum required water depth of 7.5 m. The only location with suitable water depth, current power density and a minimum capacity factor for an array is at the mouth of the Mersey, near New Brighton, represented by black triangles in Figure 2.16. For an array of 130 small turbines at this location (the outlined areas could together accommodate about 100 times that number) the annual energy output would be over 1 GWh, enough for approximately 300 homes. Whilst this is a rough estimation of the potential output of a tidal array, using one of the available turbine designs, in the Mersey, it demonstrates potential to generate energy from the tidal stream.

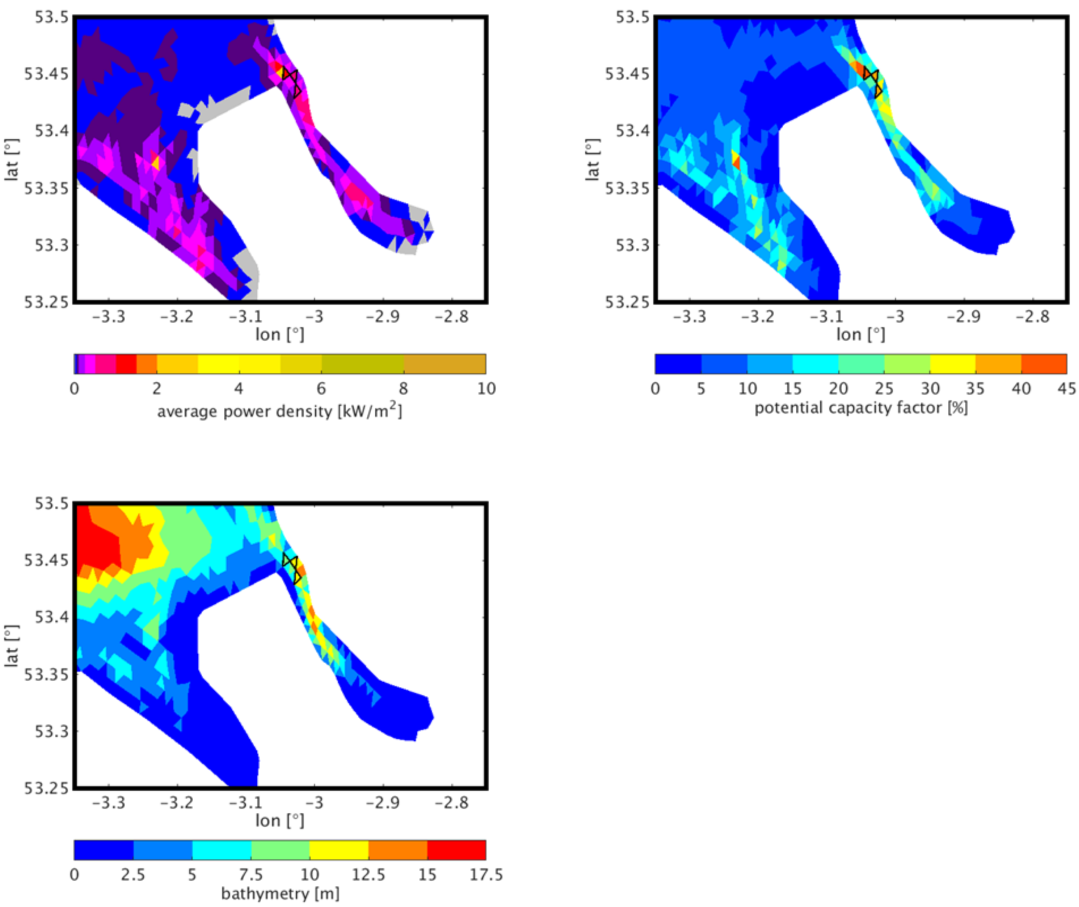


Figure 2.16. Average power density (kWm^{-2}), potential capacity factor (%) and water depth (m) for the Mersey estuary and Liverpool Bay. Suitable locations for the siting of horizontal axis tidal stream turbines are marked with triangles (De Dominicis, 2017, pers. comm., 2nd June)

2.3 Combined tidal range and stream (i.e. Tidal fence)

The tidal fence concept aims to exploit a combination of tidal current and range. By using vertical axis turbines connected within a fence structure, a small hydraulic head is created behind the fence so that energy is generated through a combination of tidal stream and range. This could be a full barrier (which would allow the inclusion of a road or rail transport link) or a partial barrier (which would maintain a navigable channel for shipping). Tidal fences would allow near natural tidal flow to be maintained, thereby potentially avoiding the main environmental objection to a barrage. Initial costs are also likely to be much lower than for a barrage design. However, the technology is relatively untested as there are currently no examples of tidal fences in operation (Waters and Aggidis, 2016).

2.4 Potential for tidal power in the Mersey

It has been shown that there is the potential to extract energy from the Mersey using either tidal range or tidal stream technology.

Previous studies (Sustainable Development Commission, 2007; Burrows et al., 2009a; Mersey Tidal Power, 2011a; Aggidis and Benzon, 2013) have predicted that a tidal barrage in the Mersey could generate somewhere in the range of about 1.0 to 1.5 TWh of electricity per year. This would represent between half and two-thirds of Liverpool's electricity requirement or between a sixth and a quarter of LCR's annual electricity usage.

Similarly to barrages, tidal lagoons are expected to provide large amounts of energy, with the variously suggested configurations expected to have annual outputs from about 0.4 to 5.0 TWh, dependent on their size and position (Sustainable Development Commission, 2007; Burrows et al., 2009a; Lyddon et al., 2015; Angeloudis et al., 2016). The largest of these designs, stretching across the mouth of the Dee, all the way from New Brighton to Prestatyn, would provide 2.5 times the annual electricity requirement of Liverpool and most of that of the LCR. Whilst some of these designs are very ambitious and would require a lot of further design consideration, particularly in light of other offshore activity and energy production in the form of offshore wind, they demonstrate the potential from this type of scheme.

A small tidal array at the mouth of the Mersey is estimated to provide a much more modest additional 1 GWh annually to the local renewable energy mix (De Dominicis, 2017, pers. comm., 2nd June 2017).

The fundamental differences between tidal range and tidal stream projects, in terms of the technology and commercial viability, are that tidal range (particularly in the form of barrages) is a proven technology, there are successful schemes which have been in existence for many years, whilst tidal stream technology does not yet have that track record and there are still many competing designs. On the other hand, tidal range has very high upfront costs and each new scheme has very individual design constraints dictated by the estuary and its existent uses. Tidal stream technology developments have come a long way in recent years, could be deployed incrementally, and it is likely that costs will reduce as the technology matures and commercial confidence increases.

The nature of the Mersey Estuary, fairly shallow and with a narrow mouth, would appear to make a barrage a cost-effective option and it has previously been identified as being the lowest cost site for a barrage in the UK (Burrows et al., 2009a). The shallow depth of the estuary makes it less suitable for tidal stream generation, although it is likely that a number of turbines could be sited within the estuary, these would not generate as much energy as a barrage. It may be possible to site some tidal stream turbines in addition to a barrage, but the feasibility of this would need to be investigated in light of the effect any barrage would have on the tidal current.

Whilst tidal lagoons are not suitable for construction within the estuary itself, they may have potential within the wider Liverpool Bay area and this would be worthy of further investigation. Additionally, it should be noted that even if tidal stream or lagoon installations are not suited to the immediate estuary area, they may offer an economic opportunity due to the facilities and expertise within the region as a consequence of its ship-building past.

Tidal range schemes could also provide additional benefits in terms of flood protection (lagoons and barrages) and additional amenity in terms of transport links and cultural facilities (barrage). Additional benefits should be fully investigated as part of any future feasibility studies as these may go some way towards mitigating the costs of large infrastructure projects.

3. Other renewable electricity options

This section will provide a brief description of some other renewable electricity generating options, which may be suitable to the Mersey Estuary or Liverpool Bay location. These range from currently under-developed technologies such as wave energy conversion, to very well developed (and currently used) technologies such as wind.

3.1 Wave

Capturing the energy from waves is a concept that has been in development for about 40 years (Falcão, 2010) and is now in a phase of full-scale testing, pre-demonstration and commercial demonstration.

There are three main types of wave energy converters: oscillating water column (OWC), oscillating body convertors (OBC) and overtopping convertors (Fig. 3.1) (Falcão, 2010). These can be further subdivided according to the technology used to convert the wave energy (rotation or translation), their structures (fixed, floating or submerged) and positioning within the ocean (shoreline, near-shore or offshore). All this variability means there are more than 50 types of wave energy convertor under development (Borthwick, 2016).

In OWC devices there is a semi-submerged chamber which traps a pocket of air above the sea surface. Wave-induced changes of water level inside the cavity cause compression and decompression of the air, which is pushed through rotor blades, driving an air turbine to produce electricity (Fig. 3. 1).

OBCs are usually floating (but sometimes fully submerged) devices which are used to exploit wave regimes in deeper (>40 m) water. They have more complex power take off (PTO) systems than OWC devices, and there are a considerable number of design variations with no clear technology yet having emerged (Pérez-Collazo et al., 2015). The simplest of these is a single-body heaving buoy, which is attached to the sea-bed or bottom-fixed structure. The relative motion between the buoy at the surface and the fixed bed activates the PTO system, for example a piston pump which supplies high pressure water to a hydraulic turbine (Falcão, 2010). More complex multi-body OBCs convert energy from the relative motion of two differently-oscillating bodies.

In overtopping devices, water is collected in a reservoir, which is higher than the external sea level, as waves crest the device. This creates a difference in head height and potential energy, which is used to drive a low-head hydraulic turbine converting potential to electrical energy (Fig. 3.1).

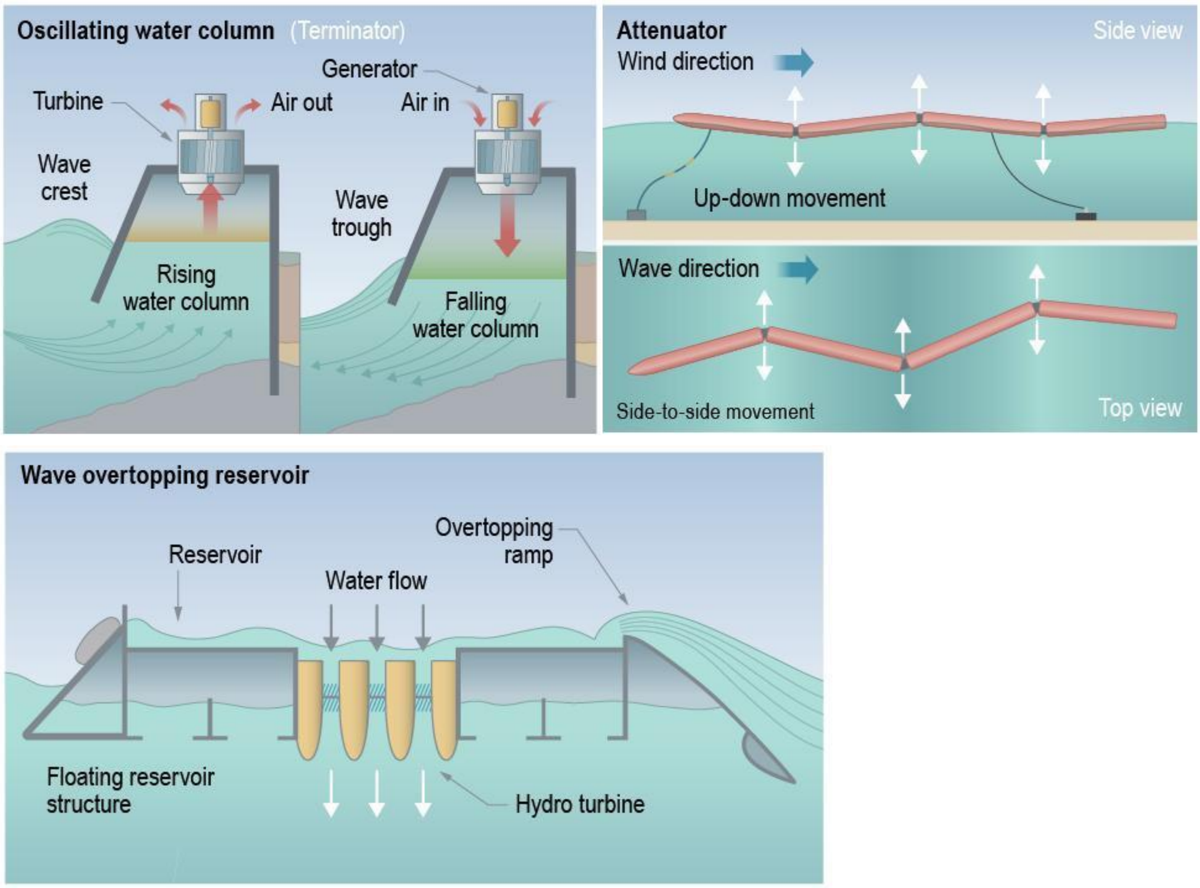


Figure 3.1. Examples of oscillating water column (OWC), oscillating body convertor (OBC) and overtopping convertor devices (Open EI, 2013)

A major disadvantage of wave power is that (like wind power from which it is originated) it has a large variability with sea state and from month to month (although there is some seasonality). As with other forms of renewable energy (e.g. solar and wind), to avoid intermittency of supply it would require the ability to store the electricity generated. Alongside other offshore generation (wind and tidal current), wave energy would also require investment in infrastructure to connect arrays to the grid.

The current levelized cost (the ratio of the sum of costs over a lifetime to the sum of electricity over a lifetime) of wave energy, for a 10 MW array, is estimated at between €330 and €630 per MWh which is more than either offshore wind or tidal current technology (Kempener and Neumann, 2014). This is partly due to the stage of development; arrays of 10 MW have not yet been demonstrated.

The potential to combine wave and offshore wind generating devices has recently been explored (Pérez-Collazo et al., 2015). The report identified shared challenges, for example in grid connection, foundations and maintenance, between the sectors, which could be addressed simultaneously to reduce costs.

Waves in Liverpool Bay are not large, being fetch-limited (Wolf et al., 2011). Whilst there may be viable wave resource in Liverpool Bay, it is felt that this technology is not yet far enough developed to comment further on generating potential.

3.2 Wind

Electricity generation from wind energy is the most well-developed of all the renewable energy technologies (IEA-ETSAP and IRENA, 2016). The deployment of wind turbines in the LCR has been reviewed by ARUP (2009b) and more recently in Liverpool by ASC Renewables Ltd. (2015), for these reasons electricity generation from wind energy will only be given limited consideration here.

Turbines have become larger (Fig. 3.2) and are made from lighter, more durable materials (TRC Energy Services, 2016). The economics of wind power projects are now more dependent on the fluctuating cost of energy production than infrastructure costs (IEA-ETSAP and IRENA, 2016).

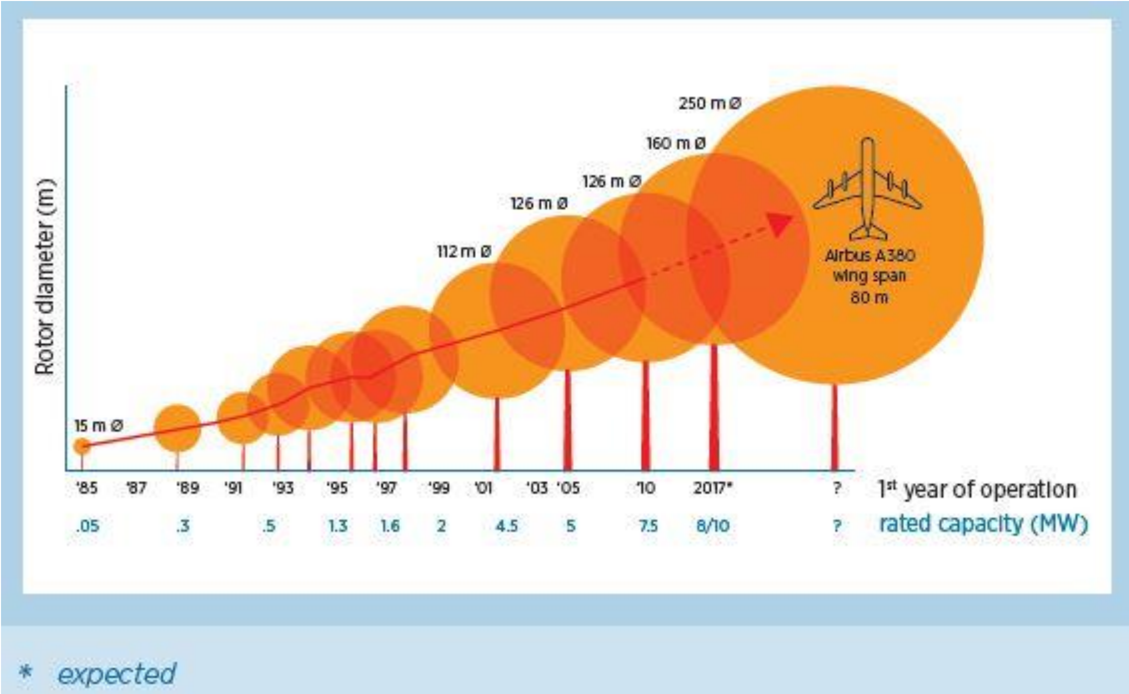


Figure 3.2. Growth in capacity and rotor diameter of wind turbines, 1985-2016 (IEA-ETSAP and IRENA, 2016)

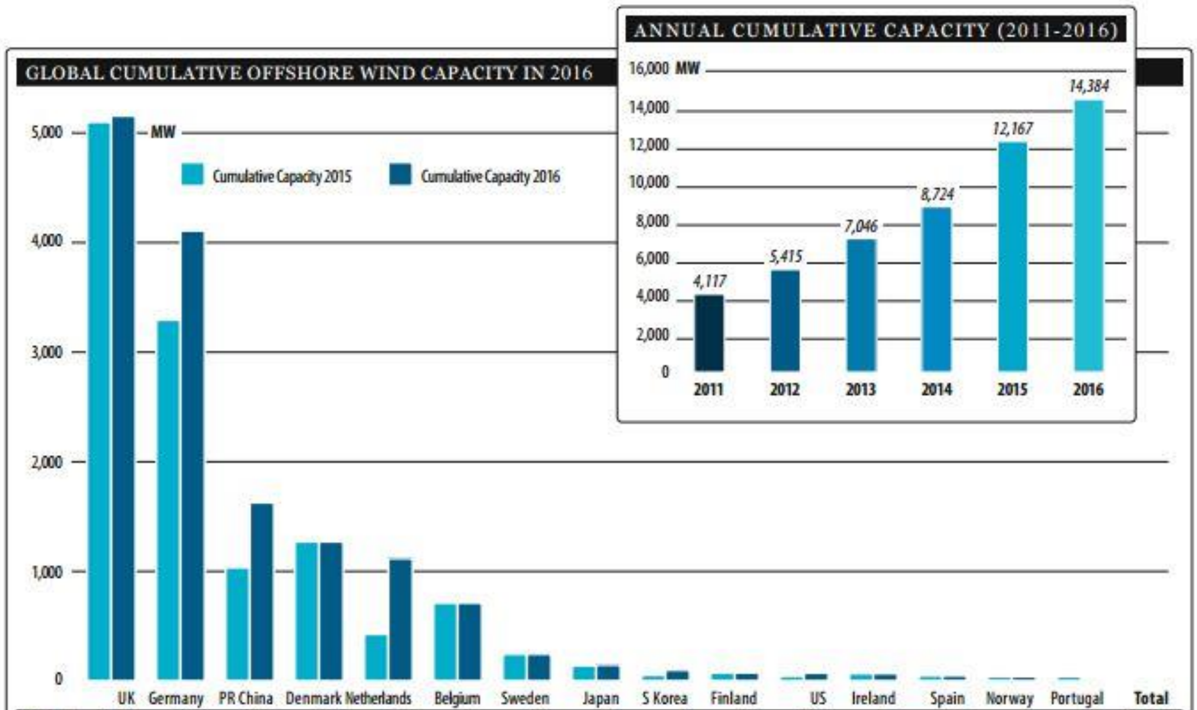
At a basic level, wind turbines capture the energy from the wind and generate electricity by turning a rotor, operating an internal generator (TRC Energy Services, 2016). There are two types of wind turbine: horizontal-axis and vertical-axis. Horizontal-axis turbines consist of (usually three) propeller type blades attached to the top of a tower, with the rotation axis parallel to the wind, they may point up-wind, or down-wind (IEA-ETSAP and IRENA, 2016). Up-wind turbines are the more common type, they face into the wind and have a yaw mechanism at the back to keep them aligned with the wind direction. They do not suffer any shading from the tower (IEA-ETSAP and IRENA, 2016). Down-wind turbines do not require a yaw system, and the blades can be positioned more closely to the tower as they flex away from it in strong winds. Down-wind turbines are generally noisier and suffer from a drop in power as the blades pass behind the mast due to the wind shadow (Power-Talk, 2010).

Vertical-axis turbines have a rotor shaft perpendicular to the wind, with the main components at the turbine base (this makes for easier service and repair as well as lower installation costs). Vertical-axis turbines do not have to face the wind direction, they can operate with any wind direction (TRC Energy Services, 2016). Some generate at relatively low wind speeds and they are low noise, so suited to urban areas (IEA-ETSAP and IRENA, 2016). However, vertical-axis turbines are much less efficient than horizontal axis because there is more drag on the rotor blades. The horizontal-axis turbine is most common, largely because it allows more effective capture of high wind speeds at a higher elevation (TRC Energy Services, 2016).

Offshore wind farms operate in the same way as onshore, using large horizontal-axis turbines. Offshore wind power is more efficient than onshore because wind speeds are generally higher and there are fewer obstacles. However, there are challenges related to working at sea, with higher construction and operating costs (Kaldellis et al., 2016).

Wind turbines come in a wide range of scales, with small vertical axis turbines for urban settings with capacities of about 4 kW, to large offshore horizontal-axis turbines with rated capacities of up to 8 MW (IEA-ETSAP and IRENA, 2016).

The UK has been at the forefront of offshore wind development and is the world leader in terms of cumulative installations, with 27 offshore windfarms and a total capacity of over 5.1 GW (Fig. 3.3) (GWEC, 2017). Liverpool Bay has been a front-runner in this respect with the UK's first offshore wind farm built at North Hoyle in 2004 (MHI Vestas, 2015) and most recently, in May 2017, the world's largest offshore turbines (8 MW with a 195 m rotor diameter) went online at the Burbo Bank extension (MHI Vestas, 2017).



	UK	Germany	PR China	Denmark	Netherlands	Belgium	Sweden	Japan	S Korea	Finland	US	Ireland	Spain	Norway	Portugal	Total
Total 2015	5,100	3,295	1,035	1,271	427	712	202	53	5	32	0.02	25	5	2	2	12,167
New 2016	56	813	592	0	691	0	0	7	30	0	30	0	0	0	-2	2,219
Total 2016	5,156	4,108	1,627	1,271	1,118	712	202	60	35	32	30	25	5	2	0	14,384

Source: GWEC

Figure 3.3. Global cumulative installed capacity in offshore wind energy, 2016 (GWEC, 2017)

To date, offshore installations have been installed mainly in shallow water depths, using bottom-fixed supports such as monopiles and gravity-based foundations (Kaldellis et al., 2016). Floating substructures, which can be deployed in deeper water, so far make up only 0.1% of European installations (Kaldellis et al., 2016). The use of floating turbines in the open sea represents an opportunity to utilise a higher and steadier wind speeds and is the focus of current research and development (IEA-ETSAP and IRENA, 2016).

The potential to combine offshore wind with other generating technologies, e.g. wave (Pérez-Collazo et al., 2015), or with energy storage (Slocum, 2015; Bassett et al., 2016) are also current areas of investigation.

3.2.1 More wind power for Liverpool?

Wind energy is a well-developed renewable technology which is currently deployed within the Mersey Estuary and Liverpool Bay environs both onshore, as a windfarm at Frodsham Marsh and individual turbines on dock walls in the North Docks, and offshore at Burbo Bank.

Outputs from wind turbines are determined by wind speeds and topography. Constraints for the siting of onshore wind turbines include, amongst others, parks and gardens, areas with environmental designations (Fig. 1.4), locations with 100 m of listed buildings and green belt land. A 2009 report for LCR suggested there was potential to site onshore windfarms in areas with a good wind resource such as Sefton and Wirral (ARUP, 2009a). However, stage 2 of the reporting process considered “locally valued landscapes” as an additional siting constraint in the case of Wirral and no potential locations were identified (ARUP, 2009b). The same report identified two sites in Sefton, south east of Formby as potential locations for onshore windfarms; these have not yet gone ahead.

The constraints on siting of wind turbines mean that it is unlikely that wind turbines could be sited within Liverpool. A recent report (ASC Renewables Ltd, 2015) did identify a potential site near Liverpool Airport, however, although technically feasible, flightpath restrictions would need to be overcome. Additionally, there may still be the potential and to site additional individual turbines at locations such as the soon to be redeveloped docks at Wirral Waters. There is also the possibility of co-siting wind turbines with tidal energy technology, for example they could be sited on top of a barrage or on lagoon walls. Wind turbines have an expected lifespan of about 25 years and it is likely, with improvements in turbine technology, that when this period is reached existent turbines could be replaced with larger, more efficient models.

3.3 Solar Photovoltaic (PV)

Solar photovoltaics (PV) convert sunlight directly into electricity; it is an established technology and can be installed with few moving parts. To maximize energy conversion, panels should be installed directed toward the sun and angled perpendicular to the sun’s rays. There are three types of solar PV currently on the market: polycrystalline-silicon, monocrystalline-silicon and thin film amorphous.

Polycrystalline-silicon are the most common type of panel, monocrystalline-silicon cells are a newer technology and have a higher silicon content. Conversion efficiencies for these cells are similar, however, it has been found that increasing temperatures increase the efficiency of polycrystalline cells, whilst reducing that of monocrystalline cells (Elibol et al., 2017).

Thin film solar cells are made from amorphous silicon or materials such as cadmium telluride. They are lightweight and flexible and can be used to replace roof tiles. They currently have the lowest conversion efficiency (Elibol et al., 2017), however there is work being done to improve this with the efficiency of laboratory devices increasing from 16.7% in 2012 to 20.5% in 2015 (Major et al., 2016).

Conversion efficiencies, as measured in the laboratory, are carried out under standard test conditions (STC), at temperatures of 25 ^{o}C and radiation level of 1000 Wm^{-2} (Jordehi, 2016). However, in addition to differences caused by regional and seasonal variation in solar radiation, performance is affected by conditions of temperature, wind speed and humidity, as well as dust and air pollution deposits on cells (Al-Waeli et al., 2017). A large amount of research effort is currently being expended in increasing the efficiency of PV cells which will in turn reduce the cost of electricity they produce (Jordehi, 2016).

Although photovoltaics is a comparatively mature technology, there continue to be developments. Research carried out at the University of Liverpool (Major et al., 2016) has shown that magnesium chloride ($MgCl_2$) can be used to replace the cadmium chloride ($CdCl_2$) coating currently used in photovoltaic cell manufacture. The advantages of this are that $MgCl_2$ is available in seawater and, unlike $CdCl_2$, is non-toxic; this means that it is cheaper to obtain and manufacturing costs are reduced, potentially reducing the cost of PV cells in the future.

3.3.1 Floating solar photovoltaics (PV)

Floating solar PV panels or “floatovoltaics” operate in the same way as land-based solar panels, but instead of being attached to a roof or mounted on ground-based racks or frames, they are supported on floating frames. This is a recent idea using proven technology in a new setting, which is being quickly adopted. Prior to 2014 there were only three floating solar plants worldwide; by the end of 2016 there were more than 70, 45 of which are in Japan (Minamino, 2016). The large uptake in Japan is a consequence of the need to increase electricity generation from new sources, following the 2011 tsunami and subsequent disaster at Fukushima nuclear plant.

Inland, floating solar plants can be constructed quickly, within a few weeks or months depending on the scale of the installation. Floating solar panels have additional advantages over their land-based counterparts in that the water body on which they are installed provides cooling directly to the panels and may improve their efficiency. PV panels have a negative temperature coefficient which dictates that for every 1 ^{o}C increase in temperature the efficiency of the panel decreases. This differs with panel technology, but could mean up to a 4% efficiency improvement in summer for floating panels over their ground- or roof-mounted counterparts (Trapani, 2014). There can also be advantages to the water body on which they are installed, as shading from the panels reduces evaporation and algal growth, both of which are particularly advantageous for water supply reservoirs.

In the UK, two recent significant floating solar PV installations have been completed: on Godley Reservoir, Greater Manchester (completed January 2016) and Queen Elizabeth II Reservoir, Surrey (completed March 2016, Fig. 3.4). These are owned by United Utilities and Thames Water respectively, however, both were developed by Ciel and Terre - a leading company in floating solar

PV, responsible for more than half of the world's existing developments. United Utilities have plans for a further installation at Wayoh Reservoir in Lancashire. Payback times on these reservoir installations are estimated to be about seven years (Ciel & Terre, 2015).

Godley Reservoir, Greater Manchester, Case Study

Godley Reservoir was briefly, at 3 MW capacity, the second largest installation in the world and the first operational (i.e. non-demonstration) project in the UK. 10,494 panels cover 45,500 m^2 and should generate 2.7 GWh per year to partially power United Utilities water treatment plant at the site.

Queen Elizabeth II Reservoir, Surrey, Case Study

The installation at Queen Elizabeth II Reservoir took 13 weeks to construct. It comprises 23,046 panels, covering 57,000 m^2, with bottom anchoring at a maximum depth of 18.4 m (Ciel & Terre, 2016). With a projected annual generation of 5.8 GWh, it is currently the largest installation in the UK.

Figure 3.4. Floating solar plant at Queen Elizabeth II Reservoir, Surrey (Ciel & Terre, 2016)

It should be noted that all the above examples have been installed in inland waters, thereby avoiding issues of saltwater corrosion, more complex anchoring systems, and greater water movement due to waves and tides (which could damage the panels), all of which are relevant to offshore installations. The issues of anchoring and water movement are of lesser concern in more sheltered estuarine or dock locations, but it may still be necessary to modify materials for a saline environment. There have also been recent studies into the development of thin film PV, which would flex on the surface of the water (Trapani and Redõn Santafé, 2015).

Other issues which must be addressed in the siting of any floating solar PV installation is the potential for shading, by either buildings or vegetation (Sahu et al., 2016), and possible ecosystem impacts. Whilst the reduction in algae growth, for example, might be of benefit for some water bodies, it could be a problem where algae is the primary food resource (Sahu et al., 2016).

A problem sometimes cited in objections to solar PV installations is the potential for the glass covering to reflect large amounts of light, creating an issue of glare. Reflection of light is undesirable, for panels to operate efficiently they must absorb as much light as possible. To reduce reflectance the glass can be textured or covered with an anti-reflective coating (Kandt and Romero, 2014).

There may be areas of dock suitable for siting this technology, particularly in the Liverpool North Docks which are surrounded by fewer tall buildings than those further south and would therefore be less subject to shading. The docks at Wirral Waters and reservoirs at St. Helens could also provide good locations for floating solar PV and there is the potential for this technology to be co-located within tidal lagoons.

3.3.2 Floating solar photovoltaics (PV) in Liverpool Docks

A quick estimate of the output from a solar array can be calculated from the following equation (Clark et al., 1984):

$E = A \times r \times H_e \times PR$

where E is the annual energy output (kWh), A is the area of solar panels (m^2), r is the panel efficiency, H_e is the annual radiant energy per unit area (kWh m^{-2}) and PR is the performance ratio.

The area of West Waterloo Dock (Fig. 3.5) was chosen as an example location as the surrounding area is currently undeveloped and shading of panels would therefore be minimised. This has an area of approximately 16810 m^2, of which it was estimated 40% (6724 m^2) could be used to site solar panels (this would prevent access to the panels from the dock walls and reduce shading). Panel efficiency was estimated as 13%, which is the lower end of efficiency for commercially available solar panel modules (IEA-ETSAP and IRENA, 2013). Annual average solar irradiance was calculated as 876 kWh m^{-2} using an average daily irradiance for Liverpool of 2.42 kWh m^{-2} (Fig. 3.6) (RenSMART, 2010). Finally, a performance ratio, which accounts for all losses including those caused by shading, dust on panels and cable losses, of 0.75 was selected. The estimated annual output from deployment of floating solar PV in West Waterloo Dock is, therefore, 0.6 GWh, enough to power approximately 150 homes. Whilst this is a rough estimation at a single location, it demonstrates the potential of a quick to install, proven renewable energy technology to supply electricity in Liverpool.

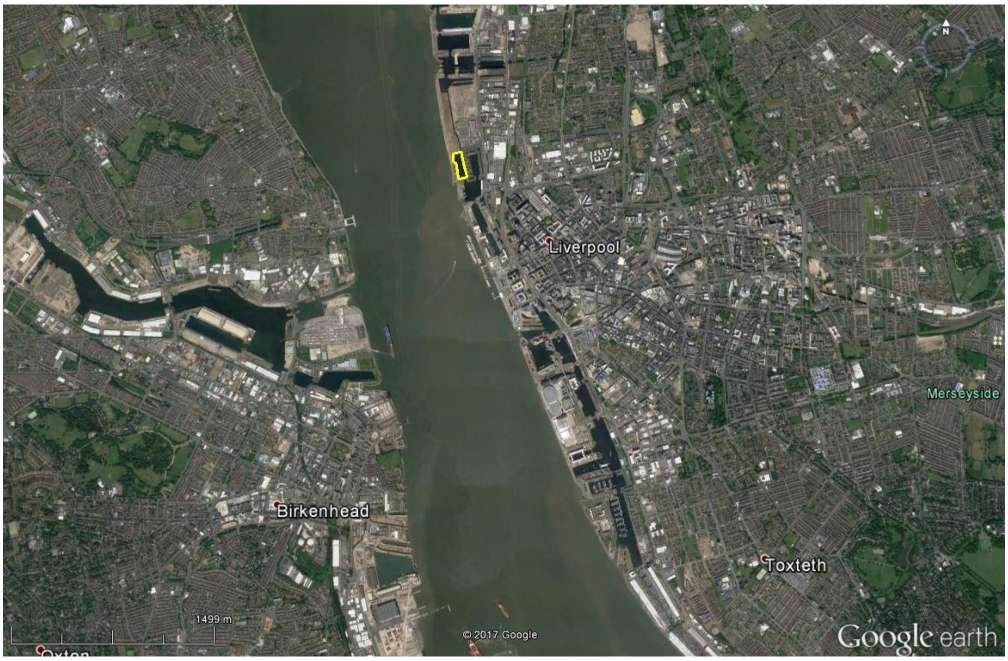


Figure 3.5. Location of West Waterloo Dock, 53°24’50”N, 3°0’8”W. Maps from Google Maps

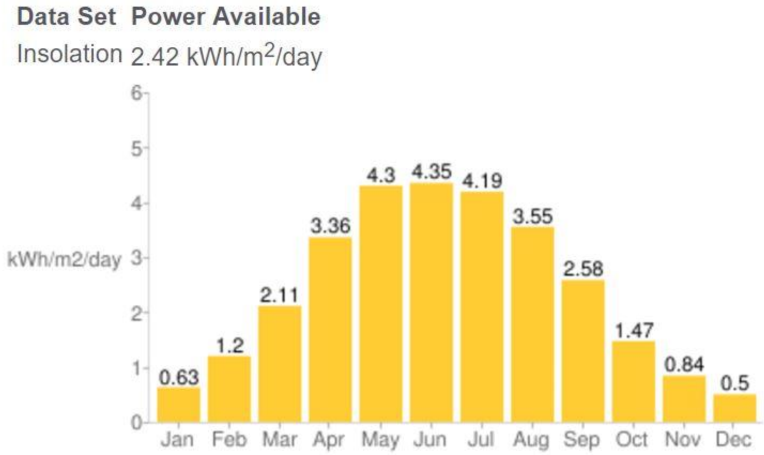


Figure 3.6. Average daily solar irradiance in Liverpool on a monthly and annual basis (RenSMART, 2010)

4. Renewable heat option

4.1 Water source heat pumps

There is a relatively long history of using water as a heat source or sink. The first description of water used as a heat source appears in 1930, when Graeme Haldane described the technology based on his experiments at his home in Perthshire, Scotland in 1927–28 (Banks, 2015). Although Haldane's design used heat exchange with water, the water was drawn from a local borehole, so the system may be more accurately described as a ground source heat pump. However, in his paper describing the system (Haldane, 1930), he recognised the potential for the use of rivers or canals as heat sources for large buildings. 1945 saw the completion of the construction of a water source heat pump (WSHP), using water from the River Wensum to supply heat to the stores and workshops of the City of Norwich Electricity Department (Sumner, 1948). Measurements made over the winter of 1945-46 showed this system to have a coefficient of performance (COP) of 3.45. COP is the ratio of useful heating or cooling to work required, with a higher rating representing lower operating costs. Although the use of heat pumps to supply heating and cooling to buildings has been largely overlooked in the UK, probably due to the supply of cheap fossil fuels (Banks, 2015), it is now experiencing renewed interest due to the need to reduce CO_2 emissions.

Surface water is defined as a body of water exposed to the air and therefore includes ponds, lakes, rivers, canals and oceans (Mitchell and Spitler, 2013). There are various configurations for surface water heating and cooling systems which can be divided into three broad categories: water source heat pumps (WSHP); direct surface water cooling (DSWC); and hybrid surface water heat pumps (HSWHP) (Mitchell and Spitler, 2013). WSHPs, which may also be referred to as surface water heat pumps (SWHP), use heat pumps and/or chillers, alongside the surface water heat source or sink, to provide heating and/or cooling dependent on the location or application. WSHPs may also be used to provide hot water. DSWCs use surface water to provide cooling without the use of heat pumps or chillers (Newman and Herbert, 2009). HSWHP systems use heat pumps or chillers to provide heating and/or cooling, but can also be run, when water temperatures allow, for direct cooling without chillers (Mitchell and Spitler, 2013).

Systems may be either closed- or open-loop. In open-loop systems water is pumped from the source water body past a heat exchanger and then discharged to the water body at a slightly lower or higher temperature (dependent on if the water is used for heating or cooling) than when extracted (Spitler and Mitchell, 2016). These systems require screening at the intake pipe to prevent the pipe becoming blocked with debris and the entrainment of biological organisms. To prevent the screen becoming blocked with seaweed or other floating debris, backwash systems should also be considered (Spitler and Mitchell, 2016).

Intake and outlet pipes must be placed a sufficient distance apart to prevent a thermal "short circuit" where water in the inlet mixes with that from the outlet, affecting its temperature and reducing the COP (Banks, 2012). Additionally, as return water will be hotter or colder than extracted temperature, there may be heat pollution issues (Spitler and Mitchell, 2016). It should also be noted that water extracted at depth may have higher nutrient concentrations than surface water, so discharge near the surface could cause algal blooms to occur (Spitler and Mitchell, 2016).

Pumps in open-loop systems may be either wet (in the water) or dry (on land), the type of pump used should be decided with consideration of water properties (e.g. salinity, suspended solids, pH and temperature) and extraction depth (Mitchell and Spitler, 2013).

In the UK, open-loop systems may also require extraction and discharge consents supplied by the Environment Agency for extraction above 20 $m^3 d^{-1}$ (DECC, 2015).

In closed-loop systems energy is exchanged with surface water through heat exchangers submerged in the water body (Sarbu and Sebarchievici, 2014). Closed loop systems typically circulate an antifreeze solution between the surface water body and the heat pumps or chillers used to meet heating or cooling needs. An issue with this is that ice may form around the outside of the circulation pipes, causing buoyancy and decreasing performance, although this is less likely to be a problem where the system is installed in saline water (Spitler and Mitchell, 2016). Closed-loop systems have the advantage that there is no requirement to filter the surface water. There are a range of surface water heat exchange designs available, amongst these are bottom sediment heat exchangers; high-density polyethylene (HDPE) pipe bundles; and flat plate heat exchangers (Banks, 2012). Open-loop systems may be slightly more efficient than closed-loop as there is no temperature drop across the pipe (Mitchell and Spitler, 2013).

Design of WSHP systems requires a good understanding of the temperature profile of the water body and how this might change on a seasonal basis (Spitler and Mitchell, 2016). Biological fouling may present an issue as algae biofilms and colonisation by molluscs could increase thermal resistance of heat exchangers, therefore mitigation must be considered (Mitchell and Spitler, 2013). Additionally, as with any deployment of equipment in saline water, there is a potential issue with corrosion (Mitchell and Spitler, 2013).

Examples of heating and cooling using surface water are given in sections 4.1.1 and 4.1.2, below.

4.1.1 Heating from water source heat pumps

Kingston Heights, Kingston-upon-Thames Case Study

Kingston Heights is a mixed-use development a few hundred meters from the river Thames in Surrey, completed in 2014, comprising 137 apartments and a 142 bedroom hotel and conference centre. A WSHP was installed during construction to provide underfloor heating and hot water for homes and heating, cooling and hot water for the hotel. Additionally, waste heat generated in the hotel is circulated back into the system for water heating.

Water is abstracted from 2.5 m below the surface of the Thames, where its temperature is 8-10 ^oC. The open-loop system has a two-stage filtration process to exclude fish, elvers and debris from entering the pump house. At a heat exchanger, heat from the water is transferred to an internal closed-loop, which carries on to the heat pump, whilst the river water is discharged with a less than 3 ^oC temperature difference from when it was abstracted. The heat pump raises the temperature to 45 ^oC and this goes on to feed mini plant rooms where additional heat pumps further increase the temperature to meet water and space heating requirements. This design allows flexibility in heating different buildings, although there are potential efficiency losses at each step.

Electricity for the scheme is provided by wind turbines, making it zero carbon, with a projected COP of 4 to 6. Although the installation of the system is estimated to have cost 15% more than an equivalent biomass boiler scheme, it is also estimated that residents will save around 15% on energy bills.

Information on this installation was sourced from Mitsubushi Electric (2013), Smith (2014) and Atkins Ltd. (2015).

Plas Newydd, Gwynedd, Case Study

Plas Newydd, an 18th century mansion, home of the Marques of Anglesey and a National Trust property since 1976, is situated on the Menai Strait in North Wales. The property, parts of which are open to the public, requires conservation heating and a hot water supply, which was previously supplied by two oil boilers. The National Trust installed a WSHP in 2013 as part of its Renewable Energy Investment Programme.

An open-loop system was chosen as it was felt that this would be less invasive than putting closed-loop coils on the sea bed. In this design, seawater is pumped 53 m to a pump-house on the shoreline where it passes through a titanium heat exchanger and returns to the sea. The heat exchanger passes the heat to water-glycol which is piped up the cliff (30 m) to a heat pump. The water-glycol is evaporated in the heat pump and the gas is compressed, increasing the temperature. A second heat exchanger transfers the heat from the gas to the heating and hot water system. Gaseous glycol returns to its liquid state on cooling and travels back to the pump-house for reheating.

The seawater used has an average temperature of between 6 ^oC and 17 ^oC, this returns heating water, which is maintained at a constant 60 ^oC. The WSHP uses 130 MWh of electrical input annually (45 MWh of which is provided by an on-site photovoltaic system) to generate 626 MWh of heat and hot water annually. It has a gross COP of 4.03 and a seasonal performance factor (SPF, the ratio of heat delivered to energy consumed over the season) of 2.8. The system cost approximately £600,000 to install, with about £3,000 annual maintenance cost, however, it saves the National Trust £40,000 per annum in heating oil costs.

Information on this installation was sourced from the National Trust (2015).

4.1.2 Using surface water for cooling

Whilst cooling can be provided alongside heating using a WSHP, as in the Kingston Heights example described above, DSWC uses lake or seawater to provide cooling to individual buildings or district systems without the use of a heat pump to further lower the temperature. Rivers are generally seen as unsuitable for DSWC as river temperature tends to track average air temperatures, however this is less likely to be the case with larger, estuarine waterbodies.

Toronto Case Study

Enwave's deep water lake cooling system began operating in July 2004, with the Air Canada Centre and the Metro Toronto Convention Centre acting as the first customers, it now provides cooling to approximately 160 customers in downtown Toronto (Kennedy, 2015).

Water is abstracted from Lake Ontario, from a depth of 83 m, via three 5 km pipes, at a temperature of about 4^{o}C, to a pumping station where heat exchangers cool a closed loop, which cools the buildings. The abstracted water, which has now been slightly warmed, goes on to supply the cities drinking water thereby avoiding the issue of returning warmed water to the lake. The depth of abstraction is an advantage for the drinking water supply in that it avoids algal blooms which can taint the drinking water in summer (Newman and Herbert, 2009). The abstraction depth also means that the water is cold year-round and therefore the need for further chilling is avoided.

The cooling system uses 90% less electricity than conventional air conditioning and initially reduced CO_2 emissions by around 79,000 tonnes (this saving is now less as coal fired power stations are closed and renewables have come online) (Enwave, 2007). The project cost over $235 million and by 2005, at 51% capacity, was generating sufficient cash-flow to cover operating and financial costs (Newman and Herbert, 2009). It was initially a public private partnership owned jointly by the City of Toronto (43%) and the municipal pension fund (57%), however the City was bought out in 2012 by an asset management company (Kennedy, 2015).

4.1.3 Water Source Heat Pumps in Liverpool

The Liverpool Docks have been identified by LCC as a potential location for generation of heat using WSHPs. A funding bid for a feasibility study has been submitted to the BEIS Heat Network Development Unit (HNDU). The study will investigate the potential for heat generation from the docks area, outlined below (Fig. 4.1).

There is additional potential to include water source heat as part of the regeneration project at Wirral Waters, as well as extension to the North Docks and other water bodies in the LCR.

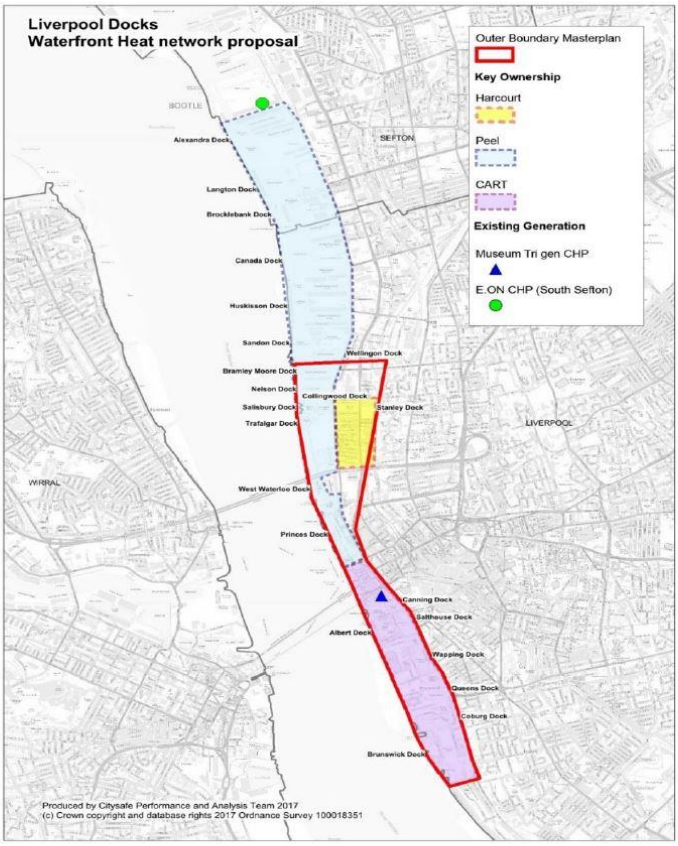


Figure 4.1. Location plan for WSHP feasibility study

5. Energy storage

An acknowledged issue with sources of renewable power such as the solar and wind energy is that the period during which power is produced is not controllable or even always predictable. Renewable sources do not produce power in synchronisation with demand. Even a power source such as the tides do not supply a constant steady stream of energy. In the case of tidal energy in the UK, it was hoped that electricity production could be maintained over a full 24-hour period through a series of tidal range installations deployed at several locations along the west coast, however it has been shown that this is not fully achievable (Burrows et al., 2009a). In addition to intermittency due to tide times, there would be variation in power output from tidal range due to the spring - neap cycle, with less power produced during neap tides due to a reduced difference in head (Fig. 5.1).

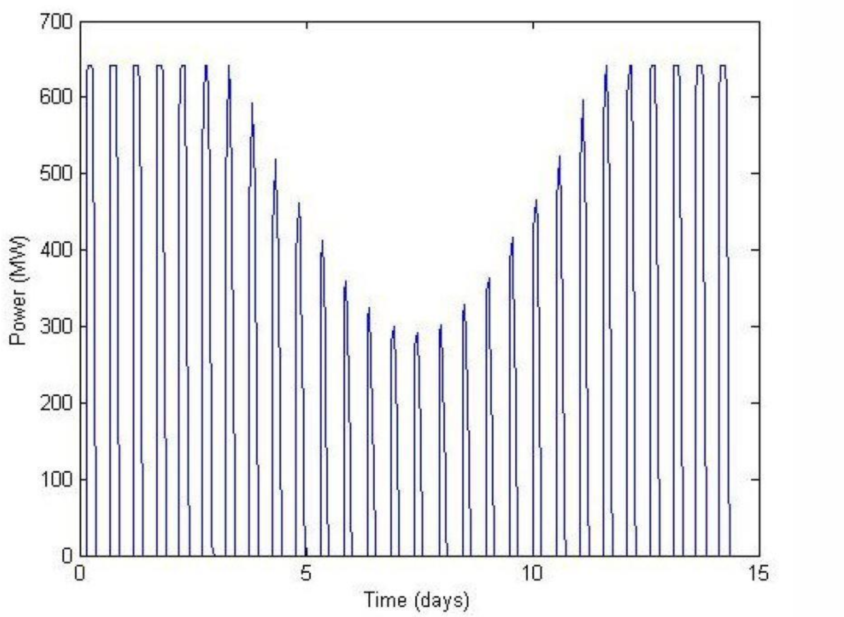


Figure 5.1. Power output from a Mersey Barrage (ebb generation) over a spring-neap tidal cycle (Burrows et al., 2009a)

In terms of renewable energy as a whole, it is envisaged that harnessing a range of sources supply will be more consistent. However, even with consistent supply there remains the issue of varying demand causing a problem of wasted energy production, i.e. energy being generated at times when it is not required. In order to harness the maximum amount of energy, for use as and when it is needed, there is a need to store that energy in a manner that ensures it is readily available when required.

Currently some of issues of supply and demand are addressed through interconnection with Europe, which enables the import and export of electricity across the North and Irish Seas, to and from France, the Netherlands and Ireland, and pumped hydroelectric storage (see section 5.1.1). In the future, demand side management (DSM) is also likely to play a part. DSM works through citizen engagement and the use of smart meters and small-scale storage. It is hoped that, by encouraging consumers to manage their electricity use, patterns can be shifted and peaks in demand reduced. In a DSM scenario, electric cars could become part of the solution to the problem of energy storage. If these are charged overnight (when other demands are low), it has been estimated, by the US Department of Energy, that two million vehicles could store up to 10 GW (IEA-ETSAP and IRENA, 2012).

Despite these measures, it is envisaged that greater flexibility will also be required if we are to increase electricity supply to meet the rising demand from decarbonisation of transport and heating sectors, whilst continuing to reduce our reliance on fossil fuels for electricity generation. Increased flexibility is expected to reduce generation operating costs by reducing renewable energy curtailment and increasing utilisation of wind power (Lehmann et al., 2016).

There are a wide range of options for energy storage, which are currently in either in use or development (Fig. 5.2). These range from the mechanical to the chemical and differing widely in scale, capacity, efficiency and cost. Electrical energy storage refers to a process in which electrical energy is converted into a storable form of energy to be converted back to usable, electrical energy when needed. Different storage options have different advantages in terms of power and energy capacity, how quickly the energy can be stored and released (ramp rate), how often the charge/discharge process can be repeated (cycle life) and the round-trip efficiency, i.e. how much energy is lost during the charge/discharge cycle. There are also considerations of cost, space, safety and the proven nature of the technology.

Energy storage can be subdivided into three types: bulk (storing large quantities of energy such as pumped hydro and compressed air), distributed (scalable technologies which require less space such as flow batteries and pumped heat storage) and fast (providing an instantaneous response, e.g. flywheels and supercapacitors) (Lehmann et al., 2016).

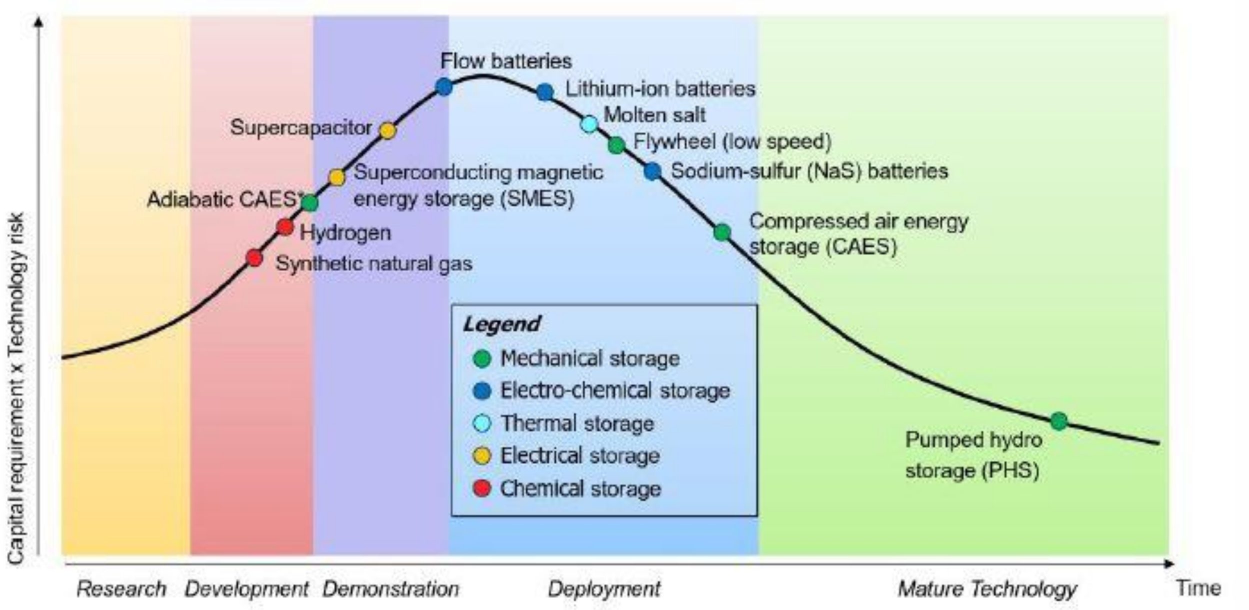


Figure 5.2. Energy storage technology maturity curve (AECOM Australia Pty Ltd., 2015)

The following sections will review some types of energy storage. It is by no means exhaustive as there are so many types and variations in development. The main focus is on storage for electricity although there is also some reference to heat storage.

5.1 Gravitational/ mechanical/thermomechanical

5.1.1 Pumped Hydro

This method was developed in Italy and Switzerland in the 1890s (IEA-ETSAP and IRENA, 2012), it simply involves pumping water from a lower to a higher reservoir (using cheap electricity during off peak periods) and storing it in the upper reservoir until electricity is required. The water can then be released through turbines in a dam and electricity generated for immediate use. Electricity can be generated at short notice and the efficiency (the amount of energy retained) is good, at up to 80% (Dodds and Garvey, 2016). The major drawbacks of pumped hydro storage are a lack of suitable sites (this is topographically dependent) and the environmental impacts related to large hydropower impoundments. This form of energy storage is widely used, accounting for 95% of current storage capacity worldwide (IEA-ETSAP and IRENA, 2012); in the UK there are facilities in Scotland and Wales.

There has been a recent resurgence of interest in pumped hydro storage in the UK with planning permission granted for two sites, one in Wales and one in Scotland. The 99.9 MW proposed Glyn Rhonwy Pumped Storage scheme in North Wales will utilise two disused slate quarries as the upper and lower reservoirs. The scheme gained planning permission for 49.9 MW in 2014, however a new application has been submitted to increase the facility's output by increasing the capacity of the underground turbines (Snowdonia Pumped Hydro, 2017). Similarly, SSE gained planning consent for a new 600 MW pumped hydro scheme at Corie Glas in 2013, however it has also now reapplied to increase the scheme to 1500 MW (SSE, 2017).

In addition to the traditional form of pumped hydro in mountainous areas, there is the potential to include it in tidal energy schemes by using a double-basin barrage design (O'Rourke et al., 2010).

5.1.2 Ground Breaking Energy Storage (GBES)

Ground Breaking Energy Storage (GBES), also referred to as gravity storage, is a derivative of pumped hydro which, instead of transporting a mass of water to a greater height, for storage as potential energy, uses water to raise and lower a large solid mass hydraulically.

Energy is stored when water is pumped beneath the mass, raising it up, and is released when the mass is allowed to drop, pushing the water through hydroelectric turbines. This method would be less site-dependent than pumped hydro and could also be smaller and less expensive. This type of storage has the potential to be incorporated within a tidal lagoon or barrage, accommodated within a public water supply reservoir or as part of a floodwater impoundment scheme (Escombe, 2016).

There are no GBES installations at present, although there are firms such as Heindl Energy, in Germany (Heindl Energy, 2017), and Gravity Power, in the USA (Gravity Power, 2017), currently developing the technology.

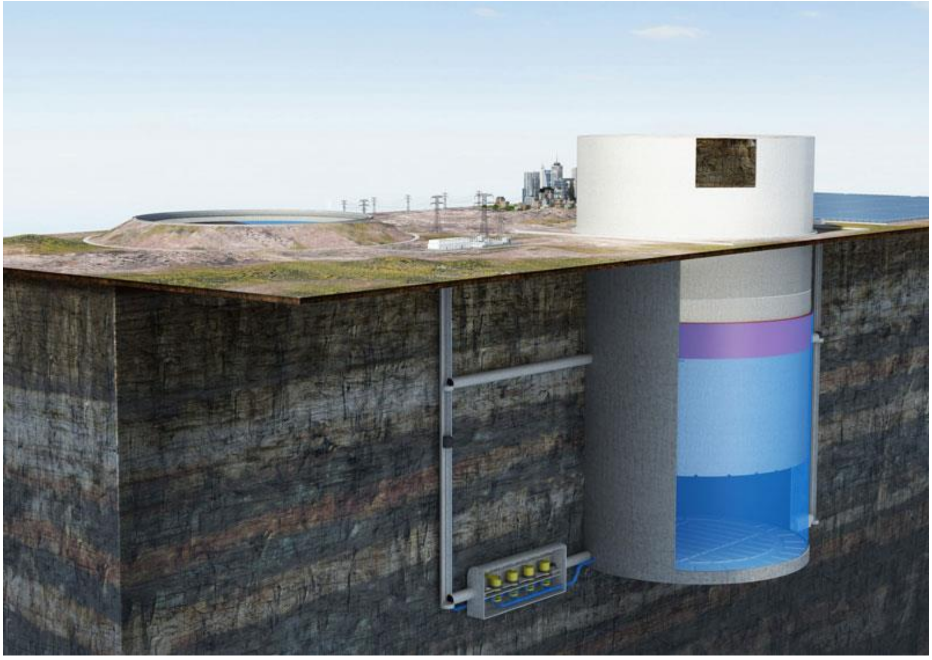


Figure 5.2. Ground Breaking Energy Storage (GBES) (Heindl Energy, 2017)

5.1.3 Advanced Rail Energy Storage (ARES)

Like pumped hydro storage and GBES, ARES raises a mass (in this case a heavy electric train) to a greater elevation to store energy. Energy is released as the train is returned to its original elevation. The technology has been developed by ARES LLC (www.aresnorthamerica.com) in the USA. The system is predicted to be 80% efficient, comparable to pumped hydro and there are no energy losses over time once the train has reached the higher elevation (Dodds and Garvey, 2016). The technology is more suitable for dry locations than either pumped hydro or GBES, and is said to be less environmentally disruptive (Cava et al., 2016).

The first commercial ARES project, a 50 MW storage system, is currently under construction in Nevada and is due for completion in 2017 (Cava et al., 2016).

5.1.4 Compressed Air Energy Storage (CAES)

Electricity is used to compress air, converting electrical to potential energy. The compressed air can then be stored at a constant pressure or volume in vessels above or below ground until it is required. On release, the expanding air is used to drive a turbine to generate electricity.

During the compression process heat is generated, the air under compression warms up and in doing so becomes more difficult to compress. This has been resolved by capturing the heat (adiabatic compressed air energy storage, A-CAES) for storage and reuse to heat the air prior to combustion or by preventing heating (isothermal compressed air energy storage, I-CAES) usually by spraying the air with a liquid (Budt et al., 2016).

Compressed air must be stored in airtight vessels and, due to the high cost of metal containers, storage is usually underground in former salt mine systems. Natural aquifers also present suitable storage sites although there may be issues if the oxygen reacts with the rock or there are microorganisms present. CAES is therefore limited due to the lack of natural storage sites (IEA-ETSAP and IRENA, 2012).

Currently there are two CAES facilities in operation, one in Huntorf, Germany, which has been in operation since 1979, and the other, in Alabama, USA, in operation since 1991. These are both diabatic CAES (D-CAES) facilities, which are hybrid electricity generating and storage facilities in that natural gas is combusted to provide additional heat for discharge. There are plans to build several new CAES facilities in both Europe and the USA, for example a proposed facility in Larne, Northern Ireland would compress air into 1400 m deep salt caverns, enabling a 330 MW output for up to six hours. There is also potential for CAES in Cheshire, where there are large salt deposits (Storelectric, 2016).

5.1.5 Flywheel

Flywheels store electrical energy as kinetic energy in a spinning disc or cylinder. They are an old technology, historically used to smooth power delivery to the potter's wheel. Technological advances have seen changes in materials, from steel to carbon fibre, and increases in rotational speeds, which mean that, in a low-pressure vacuum, supersonic speeds can be achieved (Parfomak, 2012).

During charging, electrical energy drives a rotor to accelerate the flywheel to very high speeds. On discharging, the flywheel drives a generator to produce electricity. Energy may be lost through friction, which is minimized by operating the flywheel in a vacuum and using mechanical bearings. This enables a storage roundtrip efficiency of about 85%, albeit at an increased cost (IEA-ETSAP and IRENA, 2012). Flywheels have a long operational lifetime with low maintenance costs (Parfomak, 2012). Storage capacity is determined by mass, rate of rotation and size, the greater the flywheel diameter, the greater the storage capacity. Rotational speed is the most important determinant of storage, with a doubling of speed resulting in a quadrupling of energy storage (Parfomak, 2012).

Flywheels can respond quickly as both a source and sink and have low performance degradation (unlike chemical batteries), meaning they can go through numerous charge and discharge cycles without loss of capacity. Both these qualities make flywheels useful in frequency regulation of power grids and power smoothing where supplies (such as those from wind power) fluctuate.

Flywheel technology is currently being used in the USA for frequency regulation at three sites in Massachusetts, New York and Pennsylvania (Beacon Power, 2014) and the first flywheel energy storage facility in Europe is currently under development in Ireland (Schwungrad Energie, 2017).

5.1.6 *Liquid Air Energy Storage (LAES)*

Liquid air energy storage (LAES) is also known as cryogenic energy storage; it was first proposed in 1977 at University of Newcastle-upon-Tyne (Ding et al., 2016). LAES is a three-stage process: firstly, excess electrical energy is used to compress and cool air till it liquefies. It is then stored in an insulated tank at -196^{o}C and ambient pressure. Finally, to release the energy, the liquefied air is allowed to warm and expand 700-fold in volume, turning a turbine and generating electricity. Heat generated during the liquefying process and cold from the re-gasification process are stored separately and used to warm and cool the air, improving performance.

LAES has a long discharge time (hours) and a good energy storage density of 60-120 W h l^{-1} (compared to 0.5-1.5 W h l^{-1} for pumped hydro). It does not have the geographical restraints of some storage systems, but, at 50-60%, it has a lower roundtrip efficiency (a measure of the overall loss of electricity from storage in power-to -power systems) than other options (Ding et al., 2016).

LAES is currently at the pre-commercial demonstrator phase of development. A project funded by BEIS to build a 5 MW LAES system, at Viridor's landfill gas generation plant at Pilsworth, Greater Manchester, is expected to be operational in 2017. The company responsible, Highview Power Storage, are also currently designing a 200 MW facility (Highview Power Storage, 2017).

5.2 Electrochemical (batteries)

Batteries storage is highly versatile, it can be used for short and long-term applications and is highly scalable and efficient. Batteries can be installed at all levels of the energy system, from generation to the consumer, as part of distributed or centralised systems. Widespread deployment of battery technology is restricted by issues related to energy density (storage per unit volume), loss of charge when idle and capacity over time, environmental and safety concerns and costs (AECOM Australia Pty Ltd., 2015; Dodds and Garvey, 2016).

The most prominent battery types, their stage of development and current uses are described below.

5.2.1 *Conventional batteries*

Lead-acid

These are the oldest (invented over 150 years ago) and most commonly used rechargeable battery technology (AECOM Australia Pty Ltd., 2015). Uses include vehicles, uninterruptible power supplies and off grid power systems. Lead-acid batteries have efficiencies of 70 to 90% and lifetimes of about 5 to 15 years (Akinyele and Rayudu, 2014). They produce toxic remnants and, therefore, have disposal issues and are environmentally harmful.

Lithium-ion (Li-ion)

Lithium-ion (Li-ion) battery technology has been in development for about 40 years and is becoming the predominant battery type for both stationary and portable applications. They have high energy density (compared to other types of battery), low self-discharge rates and a very high efficiency of almost 100 % (Akinyele and Rayudu, 2014). The main disadvantages are the relatively high cost and the possibility of thermal runaway, the latter is being solved by protective circuits (Vetter and Lux, 2016), whilst cost are reducing (AECOM Australia Pty Ltd., 2015).

Li-ion batteries are beginning to be used for storage with three facilities in California (Randall, 2017) and one in Copenhagen, Denmark (ABB, 2017) going live in 2017. Work is about to start on a storage facility in Wales and a storage facility in Liverpool Bay has also been announced, see below.

Upper Afan Valley, Wales, Case study

In July 2017 work will begin to install a lithium-ion battery storage scheme next to the existing Pen y Cymoedd windfarm in the Upper Afan Valley. The 22 MW facility, to be built by the Swedish company Vattenfall, will consist of six shipping containers housing lithium-ion batteries made by BMW's electric car division. The batteries are co-located with the windfarm, also run by Vattenfall, which enables the use of existent infrastructure and reduces cost. The batteries will not store electricity produced by the windfarm, but will respond to grid fluctuations releasing power if the frequency drops and storing it if the frequency is too high, helping maintain the system at an optimum 50 Hz (Faull, 2017).

Burbo Bank, Liverpool Bay, Case study

In June 2017, it was announced that Dong Energy will be installing a 2 MW battery storage system to offer frequency response from Burbo Bank offshore windfarm. The batteries will be supplied by ABB. This will be the first time that battery storage has been combined with offshore wind (DONG Energy, 2017).

Sodium Sulphur (NaS)

Sodium sulphur (NaS) batteries are classed as high temperature batteries. They have molten sulphur at the cathode and sodium at the anode, separated by electrolyte, and are maintained at temperatures of 300 to 350 ^oC. They have a high power and energy density, four times that of lead-acid (Akinyele and Rayudu, 2014). Problems with the technology include the need for an external heat source and safety issues (AECOM Australia Pty Ltd., 2015); despite this they have been used for grid-scale storage in Japan and the USA (IEA-ETSAP and IRENA, 2012).

5.2.2 Flow batteries

A flow battery has two chemical components dissolved in liquid and separated by a membrane. Ion exchange occurs across the membrane. The most mature flow cell technology (in the pre-commercial stage of development) are vanadium redox flow batteries (VRB).

VRBs are based on the ability of vanadium to exist at four different oxidation levels. They have a storage efficiency of 65 to 80 % and a lifespan of about 10 years, or 12,000 charge/discharge cycles. A cooling system is required as the charge and discharge processes release heat and they are unsuitable for mobile applications due to the complexity of the system (IEA-ETSAP and IRENA, 2012). Several projects using vanadium redox flow batteries associated with wind farms are currently in operation in Japan, Australia, Ireland and the USA (IEA-ETSAP and IRENA, 2012)

5.3 Electrical

Electrical storage technologies, which store electricity directly, include supercapacitors and superconducting magnetic energy storage (SMES).

5.3.1 Supercapacitor

Supercapacitors use static electricity to store energy between two parallel plates separated by an electrolyte solution (propylene carbonate) (Akinyele and Rayudu, 2014). They have a much lower energy density than batteries, even lead-acid and a short discharge time and high losses through self-discharge limit their use to applications with short timescales. They are most useful in situations requiring many rapid charge/discharge cycles which they can withstand without material degradation. They have been used as instantaneous voltage compensators in power systems and regenerative breaking in vehicles (Dodds and Garvey, 2016). Supercapacitors have a lifespan of around 20 years and are 80 to 95% efficient (AECOM Australia Pty Ltd., 2015).

5.3.2 Superconducting magnetic energy storage (SMES)

SMES store energy in a magnetic field created by the flow of direct current electricity into a super-cooled coil. Electric currents encounter almost no resistance in low temperature superconducting materials and can therefore cycle for a long time without loss of energy (AECOM Australia Pty Ltd., 2015). They have a high storage efficiency of more than 90 %, a high energy density and an almost instantaneous response time (IEA-ETSAP and IRENA, 2012).

SMES are currently in the early demonstration phase. They have high energy requirements to keep the system refrigerated to very low temperatures and high costs which are the primary barrier to commercial use (IEA-ETSAP and IRENA, 2012).

5.4 Chemical

Chemical storage options include hydrogen and aluminosilicate minerals called zeolites.

Hydrogen is much cheaper and easier to store than electricity. It can be produced through electrolysis, splitting water into hydrogen and oxygen. The process can then either be reversed using a fuel cell and electricity fed back to the grid, or it can be used to replace natural gas and produce heat or electricity. The efficiencies of these processes are fairly low at only 30 to 45 % and 20 to 35 % respectively (AECOM Australia Pty Ltd., 2015). Fuel cells are often the preferred method as they have a slightly higher efficiency and can be used in a range of applications including hydrogen powered vehicles (Port of Long Beach, 2016b). Additional considerations are high capital costs and safety concerns due to the volatility of hydrogen gas (AECOM Australia Pty Ltd., 2015).

Zeolite crystals absorb water in an endothermic reaction, when the crystals are heated the water is desorbed. So long as there is no water present, long-term losses of this stored heat are negligible. The energy density is also higher than for sensible or latent heat storage, see below (Dodds and Garvey, 2016).

5.5 Thermal

Thermal storage involves the storage or removal of heat for later use, it utilises materials that can be maintained at high or low temperatures. The working principle of thermal storage depends on the operating temperature of the storage medium compared to room temperature.

5.5.1 Sensible Heat Storage

In sensible heat storage a liquid or solid storage medium is heated or cooled. The most common of these is the water in hot water storage tanks (Dodds and Garvey, 2016).

5.5.2 Latent Heat Storage

Latent heat storage uses phase change materials to store heat through the reversible conversion from solid to liquid phases. It can be used to store and release heat, or to store energy as heat and convert it to electricity as with molten salts.

Molten salts are used to store heat in concentrated solar thermal power facilities. These are solid at room temperature and atmospheric pressure, but turn to liquid when heated. When electricity is required the molten salts are passed through a heat exchanger to create super-heated stream which then powers a conventional turbine to produce electricity.

Many other phase change materials for latent heat storage have been developed with a variety of characteristics for different applications.

Sunamp case study

Sunamp are a Scottish company based near Edinburgh who have developed heat batteries which can be used at a wide range of scales from the individual home to community- or commercial-scale storage. The batteries use a phase change material, an alkali soluble polymer, which melts at around 60 ^{o}C. When water flows past a heat exchanger it is heated to provide hot water or heating. In the home, this can be used in a similar way to a hot water tank, but requires a much smaller space. On a larger scale, they can store heat from renewable generation, such as heat pumps or biomass, or recovered heat, from refrigeration or anaerobic digestion processes. This stored heat can then be moved, in the battery containers, to a new location for use (Sunamp, 2017).

5.6 Summary

As our energy mix moves towards more renewable technologies and the requirement for electricity increases as heat and transport systems are decarbonised there is an urgent need to consider energy storage at all scales of the system. Additionally, as was shown in the recent Carbon Trust report (Lehmann et al., 2016), this could also have long-term economic benefits.

Although pumped hydro storage currently makes up most of the world's current electricity storage capacity (AECOM Australia Pty Ltd., 2015), there are a wide range of storage options of varying efficiency available at a wide range of scales. Many of these are currently immature (Fig. 5.2) and therefore expensive technologies, although costs are expected to reduce in the future.

The wide range of characteristics presented makes the range of available technologies difficult to compare. Important features may be: the time periods over which charge/discharge cycles operate; storage duration; size; lifespan; roundtrip efficiency; energy and power density; and cost. Figure 5.3 compares some of these qualities.

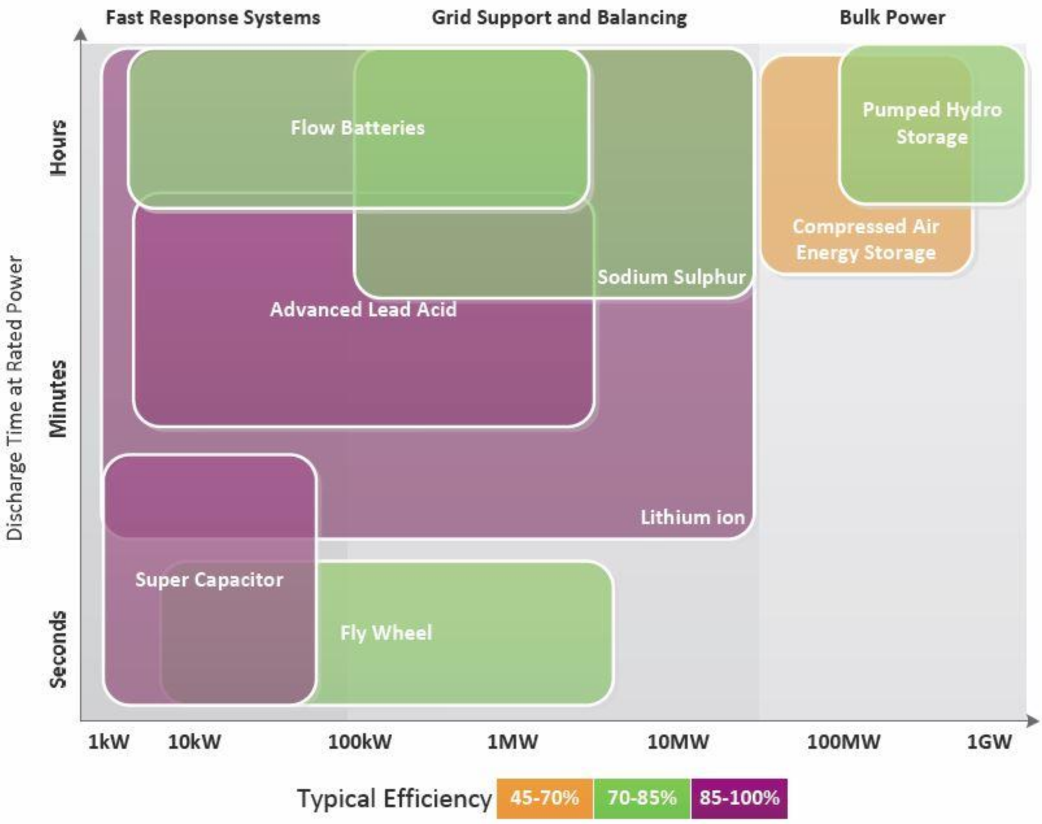


Figure 5.3. Electricity storage technologies comparison showing discharge time against power capacity, typical efficiencies and potential uses (AECOM Australia Pty Ltd., 2015)

Port of Long Beach Case Study

The Port of Long Beach, California, is looking to implement a range of energy storage technologies as part of its “Energy Island” concept. This initiative seeks to provide reliable, resilient and economically competitive energy to the port complex and marine terminal clients through local generation and storage (Port of Long Beach, 2016a). As an initial step towards this goal the port has published a range of white papers detailing renewable and storage technologies (MacKinnon and Samuelson, 2016; Muni-Fed - Antea Group Energy Partners and Port of Long Beach, 2016; TRC Energy Services, 2016; Port of Long Beach, 2016b). One of the main recommendations is that the immediately feasible options of solar PV and flywheel storage should be pursued and the foundations laid to install currently emergent technologies in the future (TRC Energy Services, 2016).

In addition to the main “Energy Island” concept the port is reducing air emissions by requiring ships to plug into the electrical grid whilst at berth in a process known as shore power (Port of Long Beach, 2014). The concept of sustainable ports is being pursued in other port cities, such as Amsterdam, which aims to supply shore power from wind and solar PV generation (Klimaatbureau Amsterdam, 2010).

6. Governance and strategic planning

It is widely accepted that, to ensure legitimacy, there is a need in the forming and implementing of policies, to: adopt integrated approaches; allow the mediation of conflict between public and private interests by consensus building; and include the participation of stakeholders and civil society (European Commission, 2001). This has resulted in a recent emphasis on governance, a concept which has been shifting to more collaborative processes. Resource management can be improved by better co-ordination between public, private and non-governmental organisations. The aim is to operate effectively through a network of organisations and stakeholders. Models of governance are extremely important in estuaries because of their complexity (Carvalho and Fidélis, 2013).

The Mersey Estuary, from mouth to tidal limit, covers a large area and runs through six council areas, four of which (Sefton, Liverpool, Halton and Wirral) are within the LCR and two (Cheshire West and Chester and Warrington) which are not. Additionally, it is in the nature of rivers that they are connected across wide areas, so that actions taken within the estuary will have effects upstream and into the Eastern Irish Sea. This interconnection throws up complex issues of governance and planning.

The River Mersey and Liverpool Bay have the potential to provide a proportion of the region's energy needs. However, in addition to this and other economic benefits (e.g. navigation and tourism), the estuary is an important environmental resource, as evidenced by the numerous designations it has been awarded. The various benefits of the estuary are, to some extent, in competition with each other and any future development would require good governance, with the coming together of a range of stakeholder groups.

In addition to the competition between the estuary's numerous benefits, there is some competition between the energy extraction technologies. For example, it has been calculated that in the Severn estuary, were both a barrage and a lagoon at Cardiff Bay to be constructed, the energy output from the barrage would be reduced by about 13 % whilst the lagoon output would be reduced by about 60 % (Falconer and Binnie, 2017). This highlights the need for strategic planning of renewable energy extraction alongside the other estuary uses.

The ongoing EPSRC-funded EcoWatt2050 project (in which NOC is a partner) has the overarching objective to determine the ways in which marine spatial planning and policy development, for offshore renewable energy, can enable maximum energy extraction whilst minimising environmental impacts. The NOC research uses oceanic and coastal hydrodynamic and biogeochemical models to understand the interactions of tidal stream arrays with the wider ocean circulation.

Issues of governance and planning are being addressed in other estuarine areas in the UK, notably in the Severn Estuary (where there are also ambitions to extract renewable energy from the system) and in London and the Thames by the Thames Estuary Partnership (http://thamesestuarypartnership.org/) and the London Waterways Commission. The Severn Estuary Partnership (http://www.severnestuarypartnership.org.uk/) and events such as Sustainable Severn (http://www.sustainablesevern.co.uk/) bring together stakeholders to address issues of energy, the environment and economy. A report detailing the estuary's current uses and features (Fig. 6.1)

(Severn Estuary Partnership, 2011) and a strategic plan for the estuary have also been produced (Severn Estuary Partnership, 2017).

There is a previous model for addressing these issues within the Mersey catchment itself in the form of the successful Mersey Basin Campaign, which ran from 1985 to 2010. It took a "catchment to sea" approach and engaged with social, economic and environmental issues to clean up the Mersey River. This work is being continued, to some extent, by its sister organisation, the Healthy Rivers Trust (http://www.healthywaterwaystrust.org.uk/). There is the potential for this organisation to join with other existing groups within the area, for example: Mersey Maritime (http://www.merseymaritime.co.uk/), which represents the interests of the ports and maritime sector and is a partner in the Maritime Knowledge Hub (https://www.ljmu.ac.uk/business/maritime-knowledge-hub); the Mersey River Task Force (http://www.meas.org.uk/1092); and other stakeholders. Many groups were previously consulted as part of the Mersey Tidal Power barrage feasibility study which, as well as consultation with statutory bodies, included community consultation. This took the form of public exhibitions, briefings to local groups and online information, inviting views during the initial stages of the study (Mersey Tidal Power, 2010c). This previous engagement could inform future governance of the Mersey Estuary.

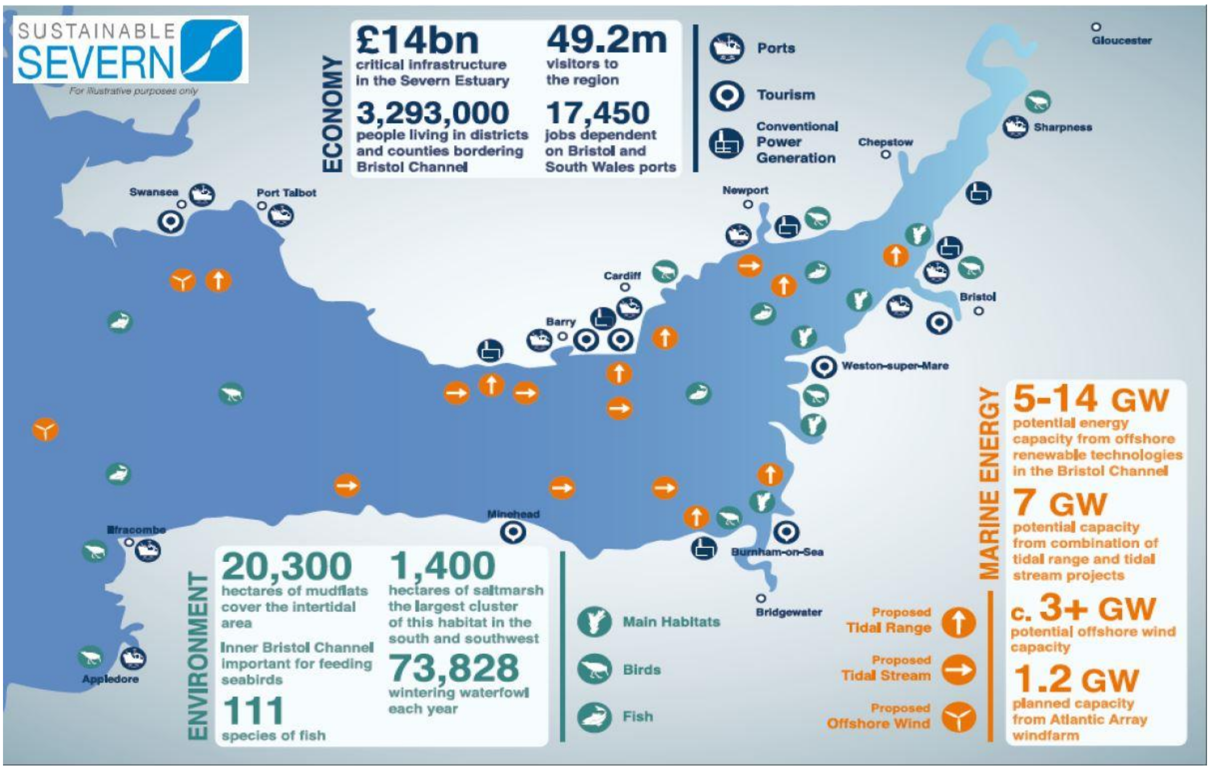


Figure 6.1. Strategic plan for the Severn Estuary (Sustainable Severn, 2017)

6.1 Identifying stakeholders

In light of the recognised need for good governance, initiatives with a high degree of consultation are on the increase. A recent paper (Newton and Elliott, 2016) provided guidelines on an appropriate framework for stakeholder definition and engagement. It set out a typology of stakeholders (Table 6.1), which will be useful in identifying the relevant stakeholders to the issue at hand. The paper goes on to define a road map to improving the participatory process.

Table 6.1. Typology and roles of stakeholders with illustrative examples (Newton and Elliott, 2016)

Type	Definition/Role	Examples
"Extractors" Drivers, activities, and pressures	Those using space or taking biotic and abiotic resources from the marine system	Fishers, aggregate extractors, space occupiers, or removers (by habitat loss), water abstractors, salt extractors, etc.
"Inputters" Drivers, activities, and pressures	Those discharging or placing materials or infrastructure into the marine system	Builders of infrastructure, pollutant dischargers, industries, fishing discards, thermal discharges from power plant cooling water, ballast water discharges introducing non-indigenous species
"Beneficiaries" (of Ecosystem services, of the Drivers, and reduction of adverse changes)	Those benefitting from the ecosystem services and goods created by the system and delivered by the users	Society, all other relevant stakeholders. However, an industry benefitting from the cheapest option of discharging waste may also be a beneficiary.
"Affectees" (by Impact on human welfare)	Those affected by the uses and users, affected by the policy decisions, impacted by the decisions whether positive or negative	Society, all other relevant stakeholders, NGO's Externalities, those who incur costs rather than acquire benefits
"Regulators" Responders (using Measures) of society	Those giving permission to occupy space or extract/input materials, those with a controlling role on the users of the system; "hard" and "soft" regulators	Government Administrative, legislative bodies, international policy makers, national and European legislators, statutory bodies
"Influencers" Represent or are concerned about the State of the environment and ecosystem	Those influencing policy and use/users	Expert groups, NGOs, lobby groups (WWF/RSPB), scientists, educators, public

7. Conclusions

For Liverpool and the LCR to meet their commitments to reducing CO_2 emissions it is necessary to identify and exploit new sources of renewable energy. The situation of the city on the Mersey Estuary provides the ideal opportunity to generate renewable electricity by harnessing the tidal resource.

Of the two types of tidal power, range and stream, exploitation of the tidal range would provide the most energy, with approximately a thousand times as much energy available from a barrage as opposed to a tidal stream array. A barrage is likely to be the most suitable form of tidal range technology for the Mersey, due to the shape of the channel. It is likely to have a lower cost than a lagoon due to the smaller length of dam structure required, although that does not account for the cost of navigation locks or the potential loss of revenue due to disruption to shipping. However, it is also recommended that the concept of lagoons be investigated further as they could provide large quantities of energy and may be suitable for other areas of the LCR coast in Wirral and Sefton.

Tidal stream has the potential to provide smaller amounts of energy and it is recommended that this should also be investigated further. There may be the potential for Liverpool to develop expertise in this area, by utilising the existent marine engineering expertise and facilities and the research capabilities within NOC and the universities.

If the commitment of the LCR Mayor to achieve *"the cleanest river standard by 2030"* is to be met, any future barrage must be designed and constructed with the highest regard for the environment. Generating over the flood and ebb tide, although potentially generating slightly less energy than 'ebb only' generation, is one measure towards attaining this.

The construction of a barrage could provide Liverpool with the opportunity to build a showcase of local maritime engineering expertise and through data collection and monitoring, in concert with the universities, an opportunity to add to the knowledge on environmental effects. This could pave the way for future energy capture at other locations in the UK and worldwide.

In addition to exploitation of the large tidal resource, other forms of renewable generation may also be suitable for deployment in and around the estuary and docks. Floating solar PV has great potential, which should be further investigated for the docks, but also, as the technology advances, the estuary. Floating solar PV may also be immediately suitable to other locations in the LCR, for example reservoirs in St. Helens.

There is still some potential to expand energy generation from wind, with previously identified locations in Sefton (ARUP, 2009b) not yet brought forward and the possibility for dock-based turbines at Wirral Waters as part of future development. Any barrage or lagoon structure would also provide the opportunity to co-locate wind turbines.

WSHPs are an excellent opportunity to exploit the heat resource in the docks. The potential for heat storage and transportation to other areas of the city, by a storage system such as is currently being developed by Sunamp (2017), should be considered.

Storage at a range of scales will be essential in the development of the energy system. Whist large installations such as GBES are obviously not suited to a city location, other innovations such as LAES or Li-ion batteries are likely to be feasible. It would be prudent to install storage alongside any large-scale installation, e.g. a barrage, so that costs are kept to a minimum through the sharing of grid infrastructure.

In light of the potential cost savings to consumers, through the opportunity to manage their energy use, and at a wider scale as identified by the Carbon Trust (Lehmann et al., 2016) small-scale household energy storage, of both heat and electricity, should also be encouraged.

Appropriate governance will be essential to achieving these recommendations. In the interests of avoiding and resolving conflicts, all stakeholders should be involved from an early stage. A strategic plan for energy extraction from the estuary, with consideration of the environment and other interests, should be drawn up to enable the balancing of competing interests.

By utilising the river's energy resource and the existing technical expertise and research capabilities, Liverpool and the wider LCR could increase their contribution to the UK's renewable generation, improve regional energy security, maintain the environment, and grow the economy.

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