



Advanced Design Tools for Ocean Energy Systems Innovation, Development and Deployment

Deliverable D8.3

Feasibility and cost-benefit analysis

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Part of this work has been published in the journal *Energies* as a paper on implementing radical innovation in renewable energy experience curves, considering wave energy as an example technology [1].



EXECUTIVE SUMMARY

This report is the outcome of Task 8.3 “Feasibility and cost-benefit analysis” of the DTOceanPlus project. The aim of this task is to conduct an economic feasibility and cost-benefit analysis, to assess the technologies and funding frameworks to support attractive business cases for both public and private funders. The task focuses on an investigation of the public funding to reduce the costs of ocean energy using both technology push and market pull funding mechanisms. ‘Push’ policies aim to increase the supply of innovation predominantly through research, development, and demonstration actions. ‘Pull’ policies, on the other hand, increase demand for innovation, often through subsidy for deployment. The balance between these types of funding policies is explored together with the overall balance of costs and benefits.

Ocean energy remains a nascent energy industry, with tidal stream technology at a pre-commercial stage and wave technology at demonstration level. These technologies require further research and development effort and significant cost reductions to partake in the highly competitive markets for grid power. Consistent cost reductions with increasing deployment have been seen in other renewable energy technologies, such as wind turbines and solar photovoltaics, and it is expected that a similar trend will be seen in future for ocean energy. Therefore, ocean energy has the opportunity to play a crucial role in the transition to net-zero, especially with the predictable nature of the tides and complementary generation profiles of wave to wind and solar.

This required reduction in the costs of ocean energy technologies could occur through some combination of two mechanisms:

- ▶ **Incremental reductions in the Levelised Cost of Energy (LCOE)** facilitated by **subsidised deployment** of technology, and
- ▶ **Step-change cost reductions** resulting from directed **innovation programmes**.

A range of ‘what-if?’ scenarios are used to illustrate the costs of different policy mixes within a range of input assumptions. These consider including, or not:

- ▶ Policies to increase the incremental cost reduction ‘learning rate’ to 15% from a baseline 13%.
- ▶ Innovation programmes that deliver a 25% step-change reduction in LCOE.
- ▶ Delaying subsidised deployment until after the step-change cost reduction has been demonstrated.

These scenarios all have the target of meeting cost-parity assuming an average European wholesale market price of 50 €/MWh. The inputs come from published literature, case studies of other renewable energy technology development, and experience of the industrial partners within the DTOceanPlus consortium.

The benefits of ocean energy are assessed both in monetary terms using Gross Value Added (GVA) plus a review of other wider socio-environmental benefits. These are compared with the costs to society of developing ocean energy, using country case-studies of the commercialisation of four other energy sectors to add context. The case studies illustrate the balance of policy mechanisms used



historically in the development of other energy sectors, namely German solar PV, Japanese solar PV, German onshore wind, and Danish wind (onshore & offshore).

The costs and benefits calculated in this study are not the direct costs associated with deployment of devices nor benefits in terms of market revenues. Instead, they consider the higher-level costs and benefits to society/the economy as a whole. These are used to illustrate different balances of policy mechanisms available globally to reduce LCOE in the ocean energy sector.

This work **highlights the need for a mix of policies to drive down the LCOE of ocean energy whilst minimising the overall investment needed for wide-scale deployment of these technologies**. The most attractive scenarios considered in the cost modelling included both faster incremental cost reductions (higher learning rate) and a step-change cost reduction from a structured programme of innovation in the early stages. These actions would both be funded through technology push (TP) type mechanisms. They would also **significantly reduce the overall investment required on subsidised deployment** (a market pull (MP) mechanism) by tens of billion euro for tidal energy and many hundreds of billion euro for wave energy, as discussed in section 5.3.

Although not necessarily presenting an optimal pathway for ocean energy, the country case studies of other energy sectors ranged from spending 25–117 times more on MP subsidies than TP policies, whereas most of the scenarios modelled were lower at between 3 and 51. In terms of the ratios of MP subsidy to deployment, the case studies were in the range of €1.2–2.1 million/MW with most of the cost modelling scenarios around €0.8–2.0 million/MW, i.e. similar or slightly lower than has been seen in other sectors.

This work also shows the **wider benefits to society that can be achieved by ocean energy**, and how **these benefits can outweigh the costs involved**. For the more attractive scenarios considered, the benefits in monetary terms of Gross Value Added outweigh the costs of funding TP and MP policies to reach cost parity by a factor of 2.5–3. It was also seen that GVA results are dependent on the overall spend invested within the project, a higher project investment will lead to a higher GVA benefit. Additionally, there are a wide range of other social and environmental benefits that ocean energy can add. For example, it was seen that the ocean energy sector can potentially create significant social and economic benefits for rural and coastal by providing power, establishing local supply chain networks, enabling linkages to global supply chains and markets, encouraging local skilled workforce, and enabling social inclusion.

In all the scenarios discussed in this report, the **open-source design tools being developed in the DTOceanPlus project can contribute to the development of the ocean energy sector**, facilitating both incremental and step-change cost reductions. The Structured Innovation and Stage Gate tools can assist with step-change cost reductions as part of structured, staged innovation programmes. The Deployment and Assessment tools can then be used to design optimised arrays, facilitating incremental cost reductions through wide scale deployment of ocean energy technologies to generate renewable electricity.



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ABBREVIATIONS AND ACRONYMS

AD	Assessment Design
AEP	Annual Energy Production
CAPEX	Capital Expenditure
CDC	Cumulative Deployed Capacity
CF	Capacity Factor
CfD	Contract for Differences
CORDIS	Community Research and Development Information Service
DD	Deployment Design
DR	Discount Rate
DSD	Sustainable Development Scenario
EC	Energy Capture
ED	Energy Delivery
ET	Energy Transformation
FiT	Feed in Tariffs
FiP	Feed in Premiums
FMEA	Failure Modes and Effects Analysis
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GVA	Gross Value Added
IEA	International Energy Agency
IEC	International Electro-technical Commission
IO	Input-Output
IxI	Industry by Industry
KPI	Key Performance Indicator
LCOE	Levelised Cost of Energy
LMO	Logistics and Marine Operations
LR	Learning Rate
MC	Machine Characterisation
MP	Market Pull
NFFO	Non-Fossil Fuel Obligation
OE	Ocean Energy
OEE	Ocean Energy Europe
OES	Ocean Energy Systems
OPEX	Operational Expenditure
PV	Photo-Voltaic (solar)
QFD	Quality Function Deployment
R&D	Research and Development
RAMS	Reliability Availability Maintainability Survivability
RD&D	Research, Development, and Deployment
ROC	Renewable Obligation Certificates
SG	Stage Gate
SI	Structured Innovation
SIC	Standard Industrial Classification
SK	Station Keeping
SLC	System Lifetime Costs
SPEY	System Performance and Energy Yield
STEPS	Stated Policies Scenario



TP	Technology Push
TRIZ	Theory of Inventive Problem Solving
TRL	Technology Readiness Level
WACC	Weighted Average Cost Capital
WEO	World Energy Outlook
WES	Wave Energy Scotland
WMP	Wholesale Market Price



GLOSSARY OF KEY TERMS

Levelised Cost of Energy (LCOE)	Levelised Cost of Energy represents the ratio of the capital and operational expenditures incurred over the lifetime of a project in relation to the annual energy produced over the operational life. Commonly used to compare energy generating technologies.
Learning investment	The total amount of subsidy required to achieve the cost reductions required to meet the target LCOE.
Learning rate (LR)	Reduction in technology unit costs (often in terms of LCOE) associated with each doubling of cumulative installed capacity.
TRL	The 9-point Technology Readiness Level scale is widely used to measure technology development.
Capital expenditures (CAPEX)	CAPEX costs are the investments made in the initial stages (development, consenting, production, installation, commission) of a project to buy project components, assets, or services.
Operational expenditures (OPEX)	OPEX costs are the regular expenses that incur throughout the project cycle in running and maintaining the project.
Annual Energy Production (AEP)	AEP is the total amount of energy produced by a turbine over a year.
Capacity	Used to denote the amount of ocean energy deployed. Could be annual deployment or cumulative deployment.
Generation	The amount of electricity generated by a project in a year.
Capacity Factor (CF)	CF is the total amount of energy produced by a project during a period, divided by the amount of energy produced at full capacity.
Technology-Push (TP) funding	The investments made during the early stages of a technology that would push it towards commercialisation, e.g. Government grants, RD&D etc.
Market-Pull (MP) funding	The incentives provided to a technology, post commercialisation that would help establishing a stable market around it, e.g. subsidies, tax credits etc.
Gross Value Added (GVA)	Gross Value Added is a popular economic metric and is usually defined as the difference between output (sales) and intermediate consumption (purchases) for a given sector or firm.



1. INTRODUCTION

1.1 SCOPE OF REPORT

Ocean energy remains a nascent energy industry, with tidal stream technology at a pre-commercial stage and wave technology at demonstration level. These technologies require further research and development (R&D) efforts to partake in the highly competitive markets for grid power. The high up-front costs and the embryonic stage of some ocean energy technologies make their development a challenging task. Notwithstanding this, wave and tidal stream technologies have shown significant performance and reliability improvements lately. Coupled with significant resource potential and valuable features such as higher predictability than wind and solar, low land requirements, and a more uniform energy output, wave and tidal stream energy have become an attractive option for the global energy transition.

There has been a resurgence of interest in these ocean energy technologies given the highly ambitious climate-related targets set by different governments worldwide, which has reflected in more R&D funding available from public agencies to ocean energy projects. One of these projects is DTOceanPlus, which seeks to accelerate the growth of the ocean energy sector by developing and demonstrating advanced design tools for the selection, development, and deployment of ocean energy systems, thereby aiding the understanding and identification of future opportunities.

This report is the outcome of Task 8.3 “Feasibility and cost-benefit analysis” of the DTOceanPlus project. The aim of this task is to conduct an economic feasibility and cost-benefit analysis in order to assess the technologies and funding frameworks to support attractive business cases for both public and private funders. The task focuses on an investigation of the public funding to reduce the costs of ocean energy using both technology push and market pull funding mechanisms. ‘Push’ policies aim to increase the supply of innovation predominantly through research, development, and demonstration actions. ‘Pull’ policies, on the other hand, increase demand for innovation, often through subsidy for deployment. These policies are discussed further in section 2. In this study, the balance between these types of funding policies is explored together with the overall balance of costs and benefits, as shown schematically in Figure 1.1.

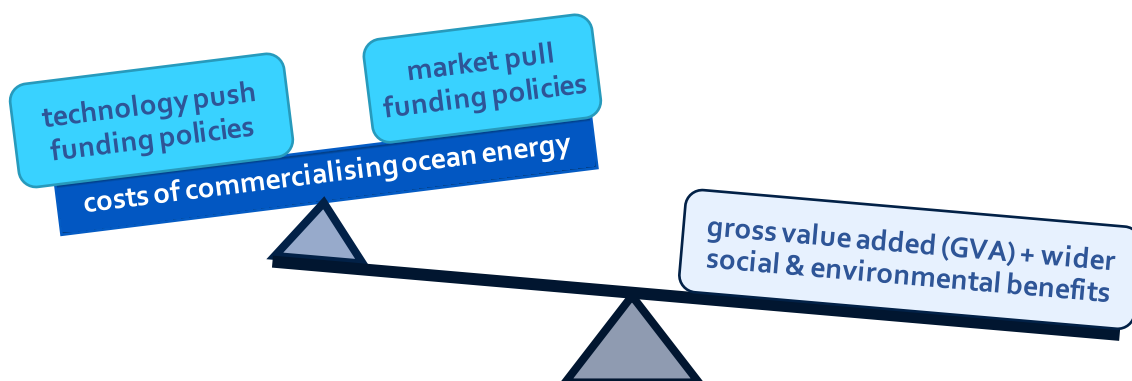


FIGURE 1.1: SCHEMATIC REPRESENTATION OF THE BALANCE BETWEEN FUNDING POLICIES PLUS BALANCE OF OVERALL COSTS AND BENEFITS

The reduction in costs of ocean energy technologies could occur through some combination of incremental reductions in Levelised Cost of Energy (LCOE) facilitated by subsidised deployment and step-change cost reductions resulting from directed innovation programmes. A range of 'what-if?' scenarios are used to illustrate the costs of different policy mixes within a range of input assumptions. These scenarios consider the balances of subsidising deployment through market pull mechanisms, technology push policies to promote increased learning (i.e. larger cost reductions with this deployment) and technology push policies to facilitate step-change cost reductions.

Both wave and tidal stream technologies are considered in line with the scope of the DTOceanPlus project, with the LCOE of each sector estimated from literature – as exact values are unknown for these nascent technologies. It should be stressed that this is not the LCOE of any particular project or device concept.

The wider benefits to society from ocean energy are then assessed, both in monetary terms using Gross Value Added (GVA) plus a review of other wider socio-environmental benefits that can be more difficult to quantify. These benefits are compared with the costs to society of developing ocean energy, using case studies of the commercialisation of four other sectors to add context. The case studies illustrate the balance of policy mechanisms used historically in the development of other energy sectors, namely German solar PV, Japanese solar PV, German onshore wind, and Danish wind (onshore & offshore).

The costs and benefits calculated in this study are not the direct costs associated with deployment of devices nor benefits in terms of market revenues. Instead, they consider the higher-level costs and benefits to society as a whole. These are used to illustrate different balances of policy mechanisms available globally to reduce LCOE in the ocean energy sector. Other work, such as in the ETIP Ocean project¹ has addressed the GVA of ocean energy to the European economy in more detail, which is beyond the scope of this task.

This work highlights the need for a mix of policies to optimally drive down the LCOE of ocean energy. It also shows the wider benefits to society that can be achieved by ocean energy, and how these benefits can outweigh the costs involved.

1.2 OUTLINE OF REPORT

This report is structured as follows,

- ▶ **Chapter 1 introduces the scope of the study** and summarises the DTOceanPlus tools.
- ▶ **Chapter 2 provides background** on funding options, cost reductions in renewable energy technologies more broadly, sectorial LCOE estimates for wave and tidal, and future deployment scenarios for these two technologies.

¹ European Technology and Innovation Platform for Ocean Energy, ETIP OCEAN 2, <http://www.etipocean.eu/>



- ▶ **Chapter 3 introduces four case studies** showing the balance of policy mechanisms in other energy sectors, namely German solar PV, Japanese solar PV, German onshore wind, and Danish wind (onshore & offshore).
- ▶ **Chapter 4 presents the methodology to estimate the costs of ocean energy** starting with an overview of the methodology, incremental cost reduction through subsidised deployment, and finally step-change cost reduction from targeted innovation programmes.
- ▶ **Chapter 5 presents the results of the cost modelling** in terms of incremental cost reduction through subsidised deployment, adding step-change cost reductions, and illustrating the balance of funding policies.
- ▶ **Chapter 6 covers the benefits of ocean energy**, with methodology and results of the GVA modelling, and an assessment of other socio-environmental benefits.
- ▶ **Chapter 7 provides discussion of the results.** The modelling is compared to the case studies, along with discussion of the case studies and lessons that can be learnt. Limitations and further work are summarised.
- ▶ **Chapter 8 summarises the benefit of the DTOceanPlus tools to the sector**, and how these can help achieve both the incremental and step-change cost reductions discussed in the modelling.
- ▶ **Chapter 9 provides conclusions and perspectives**, followed by references and annex tables.

1.3 THE DTOCEANPLUS TOOLS

DTOceanPlus will accelerate the commercialisation of the Ocean Energy sector by developing and demonstrating an open-source suite of design tools for the selection, development, deployment, and assessment of ocean energy systems (including sub-systems, energy capture devices and arrays).

At a high level, the suite of tools developed in DTOceanPlus will include:

- ▶ **Structured Innovation Tool (SI)**, for concept creation, selection, and design.
- ▶ **Stage Gate Tool (SG)**, using metrics to measure, assess and guide technology development.
- ▶ **Deployment Tools**, supporting optimal device and array deployment:
 - *Site Characterisation (SC)*: to characterise the site, including metocean, geotechnical, and environmental conditions
 - *Machine Characterisation (MC)*: to characterise the prime mover
 - *Energy Capture (EC)*: to characterise the device at an array level
 - *Energy Transformation (ET)*: to design PTO and control solutions
 - *Energy Delivery (ED)*: to design electrical and grid connection solutions
 - *Station Keeping (SK)*: to design moorings and foundations solutions
 - *Logistics and Marine Operations (LMO)*: to design logistical solutions operation plans related to the installation, operation, maintenance, and decommissioning operations
- ▶ **Assessment Tools**, to evaluate projects in terms of key parameters:
 - *System Performance and Energy Yield (SPEY)*: to evaluate projects in terms of energy performance
 - *System Lifetime Costs (SLC)*: to evaluate projects from the economic perspective



- *System Reliability, Availability, Maintainability, Survivability (RAMS)*: to evaluate the reliability aspects of a marine renewable energy project
- *Environmental and Social Acceptance (ESA)*: to evaluate the environmental and social impacts of a given wave and tidal energy projects

Underlying common digital models and a global database will support these tools, as shown graphically in Figure 1.2.

The benefits of DTOceanPlus in assisting with commercialisation of the ocean energy sector are discussed further in section 8, considering both incremental cost-reduction through subsidised deployment as well as step-change cost reductions achieved through structured and staged innovation programmes.

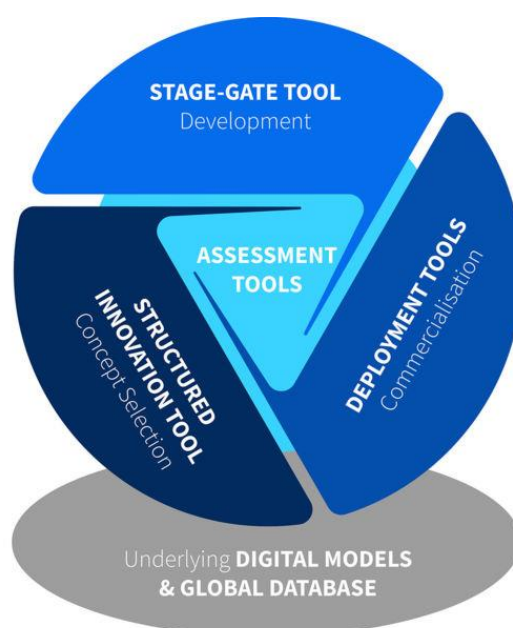


FIGURE 1.2: REPRESENTATION OF DTOCEANPLUS TOOLS

2. BACKGROUND

This section covers the background on several topics pertinent to the assessment of the costs and benefits of ocean energy. Firstly, there is an overview of funding mechanisms used in renewable energy split along the technology push–market pull dichotomy, plus funding sources for ocean energy technologies. A few key themes for cost reduction assessment are then covered: levelised cost of energy (LCOE), learning investment, and radical or step-change cost reductions. LCOE estimates for ocean energy (wave and tidal) are collated in section 2.3, with scenarios of future deployment of these discussed in section 2.4.

To meet the long-term climate and sustainability goals under the Paris Agreement, it has become increasingly more important to decarbonise the economy and transition the world towards net-zero carbon emissions. With numerous governments setting targets to reduce their emissions and achieve net-zero, inclusion of other technologies beyond the existing ones have become more pertinent. Net-zero transition calls for unprecedented innovation not just in advancing existing technologies, but also in fostering new technologies. While the existing renewable energy technologies in use today are fundamental for achieving climate goals, they are insufficient on their own to bring the world to net zero [2]. With the predictable nature of the tides and the complementary generation profiles of wave to wind and solar, ocean energy can play a crucial role in this global effort. While still at a nascent stage, ocean energy can bring in significant cost reductions and development if supported with consistent and strong funding policy support.

While many different models of innovation exist, the Research, Development, Demonstration and Deployment (RDD&D) paradigm combining ‘technology-push’ and ‘market-pull’ activities is a common thread in energy innovation literature [3]. This could be taken to suggest a simple, one-way progression from R&D to commercial deployment. However, the ‘innovation chain’ is a complex process with feedback loops and knowledge spill overs [4, 5]. As a renewable energy technology develops, different effects drive the technology progress. In a nascent stage, progress is mainly driven through R&D and knowledge transfer. As the technology develops, feedback effects through deployment also become key drivers of performance improvement (see Figure 2.1) [6].

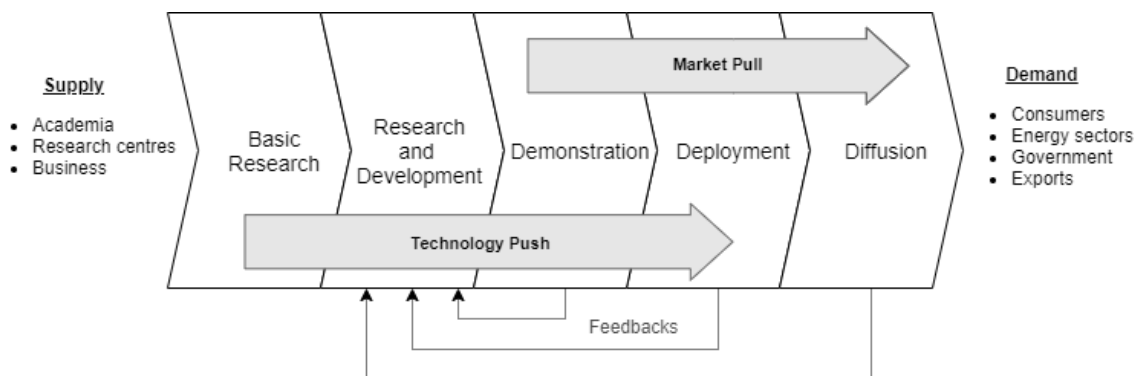


FIGURE 2.1: THE 'INNOVATION CHAIN' (ADAPTED FROM IEA [5])

2.1 OVERVIEW OF RENEWABLE ENERGY FUNDING MECHANISMS

While policy instruments are influential in supporting technology development and commercialisation, their effects vary depending on the stage of the technology innovation chain, in which they are applied. Figure 2.2 below shows the different policy instruments that can be used within an energy technology innovation process.

Funding support for the innovation process can be split or classified into many types or along various axes depending on context. One of the most ubiquitous and high-level classification of renewable energy funding mechanisms, being push and pull [7], is discussed in the sections below, but in summary:

- ▶ **(Technology) push** policies allow innovation to be carried out at lower cost and/or time (increases innovation supply).
- ▶ **(Market) pull** policies reward the outcomes of successful innovation (increases innovation demand).

Technology push (TP) is mostly funded through government budgets, whereas market pull (MP) is often funded through energy bills. A summary of funding mechanisms specifically for ocean energy technologies is given in section 3.4 of DTOceanPlus D8.1 Potential Markets for Ocean Energy [8].

Sections 2.1.1 and 2.1.2 illustrate some of the broad range of TP and MP funding mechanisms available, although this is in no means an exhaustive list. The UK is used as a case study for many examples, although similar mechanisms will be available in other countries.

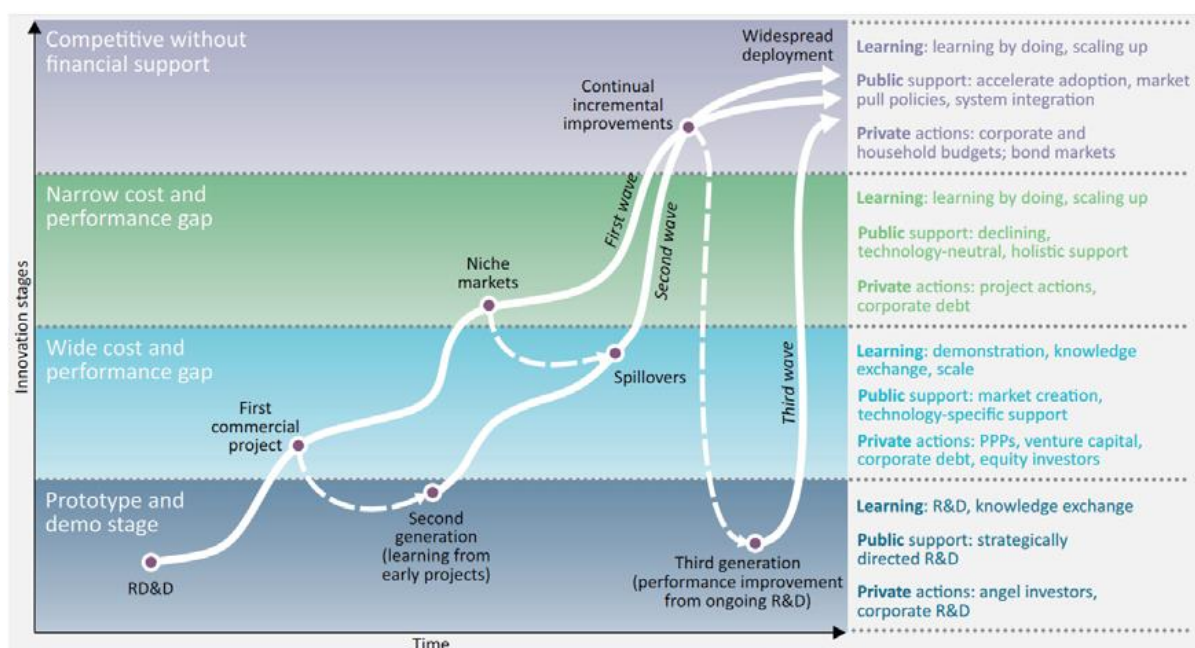


FIGURE 2.2: THE ENERGY TECHNOLOGY INNOVATION PROCESS [6]

2.1.1 TECHNOLOGY PUSH FUNDING MECHANISMS

As seen in Figure 2.1, a TP funding mechanism is used during the pre-commercial stage of a project. Mostly funded through government budgets, it allows innovation to be carried out at lower cost/time while facilitating increasing efficiency and learning. Thus, it is particularly useful in developing new radical technologies during a sector's nascent stages. Some common examples are government sponsored R&D, tax credits for companies to invest in R&D, enhancing the capacity for knowledge exchange, support for education and training, and funding demonstration projects etc. [7]. Some of these are discussed more in detail below:

Government R&D funds/grants

Government support in the form of R&D funds or grants is often needed for high-risk pre-commercial projects to find radical new solutions. The EU provides several direct funds to its member states when it comes to technological innovation, which can be accessed by many innovative technologies including wave and tidal energy. As seen in Figure 2.3 below, these cover early stage (Horizon Europe), demonstration stage (Innovation Fund) and commercial stage (Invest EU and CEF). Providing around €10 bn of support over 2020-2030, the Innovation Fund is one of the world's largest funding programmes for the demonstration of innovative low carbon technologies [9]. The InnoFin Energy Demo, NER300, Cohesion Fund etc. are some other forms of funds provided by the government for technological innovation.

For the wave sector, the Wave Energy Scotland programme uses a funding mechanism of pre-commercial procurement combined with a 'stage gate' approach to allocate funding to technology developers. This approach will also be used for the upcoming Europe Wave programme.

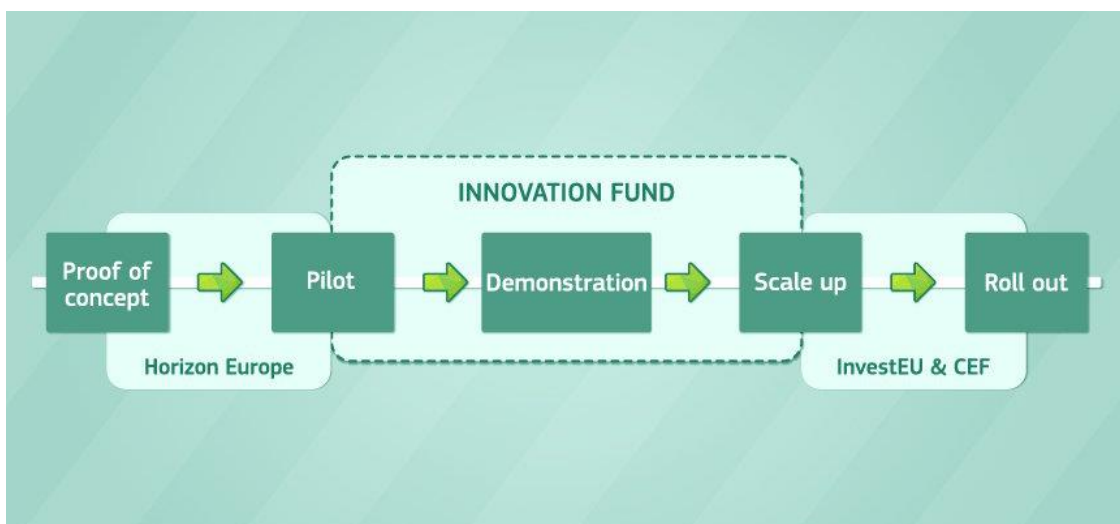


FIGURE 2.3: FUNDING FOR RD&D UNDER EU FUNDING MECHANISMS [9]

Universities and Research and Innovation Organisations

Universities and Research and Innovation Organisations both play key roles in driving technological innovation. As seen in the Japanese solar PV industry from 1940s to the 1990s, public research and development conducted in universities fuelled most basic science breakthroughs. This is accepted as being a key part of the early formative development stage of technology development [4]. Funding for academic research is often carried out through competitive bids for government funding programmes and independently managed research councils.

Universities are generally responsible for carrying out a higher proportion of basic research and further engage themselves in 'knowledge exchange' activities; one of the main ways in which knowledge is transferred and feeds into innovations. Research and Innovation Organisations, on the other hand, are mostly responsible for supporting industrial innovation, creating, and maintaining infrastructure, and developing and implementing public policy [10]. For example, the UK Research and Innovation (UKRI) brings together different research councils while supporting research and knowledge exchange at higher education institutions [11].

Competitive grants

The process of competitive grants involves awarding funds based on a competition where applicants are required to meet certain challenges. For example, the UK Energy Catalyst program set up in 2014 is a type of competitive grant that aims to meet energy trilemma, energy access, plus gender equality and social inclusion. Funded by the government, the programme supports businesses to develop highly innovative, sustainable energy technologies and business models, that can enable clean energy transition in Sub-Saharan Africa and South/South East Asia [12].

Repayable Advances/Loans

This is a kind of blend between a loan and a grant, where the condition for the reimbursement depends on the outcome of the project [13]. Along with grants and loans, repayable advances make up the three financial support mechanisms offered under European structural and investment funds [14]. Under the EU framework, these do not have a payback period or an interest rate.

Tax incentives for R&D

A form of indirect support, these are government incentives awarded to companies for investing in innovative projects. To drive more R&D activity, firms participating in certain fields of research are given a tax rebate based on the cost of R&D that they carry out.

In the UK, two principal tax reliefs are available to companies undertaking research and development: R&D Expenditure Credit (RDEC) is a payable tax credit (subject to tax) equivalent to 13% of qualifying R&D costs claimed; R&D tax relief for SMEs is a 230% deduction of qualifying R&D costs from a profitable company's yearly profit [15]. In France, support is provided to private companies for supporting their own R&D costs through tax relief. This support reaches 30% of all declared R&D costs including human resources, investments, sub-contracting and is recognised as a major incentive for the private sector to invest in R&D [16, 17].



Support for education and training

This is another indirect form of public funding mechanism that aims to increase the skillset within a country. In the UK, a mixture of UK and EU public funds finance the marine renewable energy-based centres for doctoral training (CDTs) and PhD. Some examples of training networks in the UK that are linked to wave energy are Industrial Doctorate Centre in Offshore Renewable Energy (IDCORE), Centre for Doctoral Training in Wind & Marine Energy Systems (WMES) and Centre for Doctoral Training in Renewable Marine Structures (REMS).

2.1.2 MARKET PULL FUNDING MECHANISMS

A MP funding mechanism involves rewarding the outcome of a successful innovation while attempting to 'pull' the technology through commercialisation. It realises the technology's benefits through deployment, while facilitating incremental cost reductions. MP mechanisms are often paid out directly in relation to energy production; therefore, they incentivise not only competitive CAPEX/OPEX but also increased device performance. TP, on the other hand, usually does not have any requirements for device performance and so does not incentivise the same dimensions. Some common examples of TP funding mechanisms are intellectual property protection, tax credits and rebates for consumers of new technologies, government procurement, technology mandates, regulatory standards, and taxes on competing technologies [7]. Some of these are discussed more in detail below:

Renewable energy portfolio standards

There are standards that require electricity suppliers to produce a certain percentage of their portfolio from sustainable or renewable energy sources. Examples include the Renewable Obligation standards (ROs) of the UK (2002–2017) and USA portfolio standards (2000–present). The UK Renewable Obligation Certificates (ROCs) are issued to sustainable energy generators based on the MWh produced. The electricity suppliers are obligated to gather a certain number of certificates per MWh that they supply (over a year) or face a 'buy out' charge to Ofgem [18].

Investment and production subsidies

Investment subsidies incentivise installation of new forms of renewable energy either through tax rebates, grants, or favourable loan terms. They allow an individual, a utility, or consortia to deduct a percentage of their investment costs from their tax liability. Some popular forms include the federal investment tax credits (ITC) of the USA, the Second Energy Plan grant subsidies of Denmark [19, 20].

Mostly paid through energy bills, production subsidies are standard market support mechanism; these include Feed in Tariffs (FiT), Feed in Premiums (FiP), Contract for Differences (CfD) and production tax credits. A popular production subsidy, the CfD was introduced in the UK in 2014, with a move to replace ROCs. Tendered through competitive auction, they work by fixing a set price for energy purchased from developers for a duration of 15 years. These are allocation in rounds where a competitive auction format allocates CfD payments to the bidding developers (starting with the lowest cost first) until either the budget or capacity cap is met [21]. In the UK, the FiT, RO and the CfD are funded through the Levy Control Framework (LCF) and paid through the consumer's energy bills.



Emissions/supply trading schemes

This cap-and-trade system sets a cap on emissions for selected sectors in a certain geographical area. Emissions allowances or credits for the right to emit greenhouse gas equivalent are then auctioned or sold by member states to carbon emitters. Published in 2005, the EU ETS is the world's largest emissions trading scheme and a cornerstone of EU emissions reduction policy [22].

Regulatory standards on competing technologies

For energy generating technologies, regulatory standards are mostly seen in the form of a carbon tax, fuel duty etc. In the UK, some common examples would be the Carbon Tax, Climate Change Levy, Non-Fossil Fuel Obligation (NFFO) levy etc.

The NFFO was the first attempt by the UK to support the generation of low-carbon energy in a liberalised energy market. It was introduced in 1990 essentially to support nuclear power generation following privatisation of the electricity markets in 1989, as the private sector was unwilling to buy nuclear power plants from the UK government [23].

Tax incentives on IP gains

Tax incentives on IP gains is a form of indirect policy incentive for innovation activities. It increases the payoff of a successful innovation by providing payoff to companies that profit from owned Intellectual Properties (IP). For example, in the UK, the Patent box (launched in 2013) encourages companies to commercialise IP in the UK by providing a lower corporation tax rate of 10% on profits derived from qualifying patents and other similar IP [24]. In conjunction to the Patent Box incentive, the UK also provides other incentives like R&D tax relief, R&D tax credit and R&D allowance, which allows a company to effectively receive a mix of push and pull incentives for R&D in the UK [25].

While both funding mechanisms are used in different stages of technology development, it is seen that a balance of both technology push (supporting RD&D) and pull policies (supporting market formation) are required for successful innovation in energy technologies [26, 27, 5].



2.2 COST REDUCTIONS AND LEARNING INVESTMENT IN RENEWABLE ENERGY TECHNOLOGIES

Cost estimates for ocean energy technologies are currently much higher than other renewable or conventional electricity generation methods, and as such need to be reduced for these to compete in the market for grid power. Experience from other renewable energy generation technologies shows a pathway of cost reduction over time with increasing volume of production. This process of learning and how it can be modelled using learning investment and learning rates is discussed below. This forms the basis of the cost modelling work undertaken, described fully in sections 4 and 5. The cost reductions seen in other sectors are further illustrated by the four case studies in section 3.

2.2.1 LEVELISED COST OF ENERGY REDUCTION

A key metric used to determine the attractiveness of ocean energy technology is the LCOE, as defined in equation (2.1). This is a standard way of comparing the cost-effectiveness of energy generation technologies. A reduction in LCOE may be achieved through either a reduction in costs (CAPEX or OPEX), an increase in annual energy production (AEP), or an increase in the project lifetime. As LCOE is based on the present value, changing the discount rate used will also have an impact; change in investor confidence and the perceived risk of a technology will influence the cost of capital available to developers, and this may vary over time as the technology becomes more mature [28]. All these factors contributing to reduction in LCOE are included within the single factor learning rate used in the modelling.

$$LCOE = \frac{\sum_{t=1}^T \frac{CAPEX_t + OPEX_t + DECOM_t}{(1 + DR)^t}}{\sum_{t=1}^T \frac{AEP_t}{(1 + DR)^t}} \quad (2.1)$$

Where:

- ▶ $CAPEX_t$ is the Capital Expenditures in year t
- ▶ $OPEX_t$ is the Operational Expenditures in year t
- ▶ $DECOM_t$ is the Decommissioning cost in year t
- ▶ AEP_t is the Annual energy production in year t
- ▶ T is the lifetime of the system in years
- ▶ DR is the discount rate

2.2.2 LEARNING INVESTMENT

A graphical representation of typical technology cost-reduction curves is shown in Figure 2.1. These curves tend to show a (relatively) consistent cost reduction with every doubling of cumulative installed capacity, described mathematically below. The 'learning investment' is the total amount of subsidy required to achieve the cost reductions required to meet the target LCOE.

The consistent cost reduction curve is assumed to occur after the first commercial-scale array projects, with a certain cumulative deployed capacity CDC_c and an associated levelised cost $LCOE_c$.



Therefore, the base point for the cost modelling in section 4 is defined in terms of $(CDC_c, LCOE_c)$. Before this point, LCOE estimates may be uncertain for various reasons, including:

- The LCOE estimate could be based on deployments of individual devices and/or demonstration arrays that will likely have a higher cost than future commercial scale arrays.
- There may not be sufficient operating experience to justify assumptions used for the long-term availability, capacity factor, project lifetime, etc.
- There can often be a decoupling of costs and prices in the early stage of technology development, leading to a price umbrella. [29, 30].

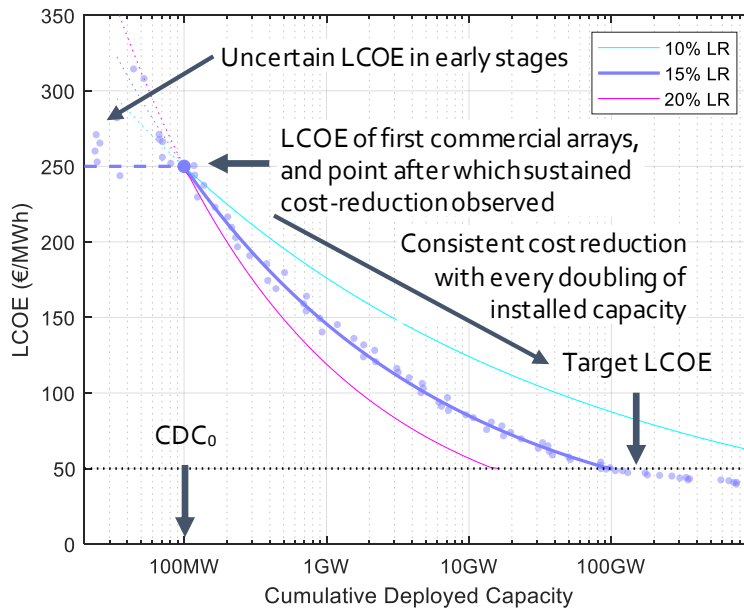


FIGURE 2.4: REPRESENTATION OF LEARNING CURVE SHOWING COST REDUCTIONS WITH INCREASING CUMULATIVE DEPLOYED CAPACITY

In renewable energy technology applications, experience curves can be used to describe technology performance (usually cost) as a function of output or experience (usually cumulative deployed capacity) [31, 32]. This relationship between costs ($Cost$) and output (Q) is shown in equation (2.2), where $Cost_q$ is an initial cost at output Q_q , and LR is the learning rate, which describes the fractional decrease in cost ($Cost_i$) for every doubling of cumulative output (Q_i):

$$Cost_i = Cost_q \left(\frac{Q_i}{Q_q} \right)^{-b} \text{ where: } b = -\frac{\log(1-LR)}{\log(2)} \quad (2.2)$$

The cost modelling in section 4 uses a single factor learning rate, using LCOE as the dependent variable, with an independent variable of cumulative capacity deployed in MW [33, 34]. This learning rate is a proxy that aggregates several factors shown to contribute towards cost reduction in other sectors, including:

1. **Learning by searching** – improvements through research and development (R&D)
2. **Learning by doing & Learning by using** – improvements in product manufacturing mechanisms, labour efficiency, etc.

3. **Learning by interacting** – improvements in network interactions between research institutes, industry, end-users, policy makers, etc. that improve knowledge diffusion
4. **Upsizing/downsizing** – changing the scale of the technology may reduce specific costs and will also impact performance
5. **Economies of scale** – product standardisation and upscaling of production facilities

If the LCOE is the dependent variable, the learning rate will also include the changes in the Weighted Average Cost Capital (WACC) associated with reduced perceived risk by financiers and insurers. That is because the LCOE represents the lifetime costs of a project over lifetime energy production, discounted to their present values. The WACC is equal to the discount rate DR used in LCOE calculations [28], as shown in equation (2.1). As technologies gain proven operational time and are regarded as more mature, significant LCOE reductions are also achieved through reductions in cost of finance (WACC) as investment risk premiums reduce [28].

Given an LCOE for ocean energy above the wholesale market price (WMP) of electricity (i.e. where we are today), this difference needs to be subsidised in order to drive commercial deployment of the technology, which will then result in the desired cost reduction. The total amount of subsidy, or 'learning investment', is shown graphically in Figure 2.5. Region ③ represents the cost of incumbent technologies, i.e. the wholesale market price for electricity, region ② is the 'learning investment' or subsidy costs for the novel technology above this, and region ① shows uncertain LCOE estimates for early-stage technologies, which may be above the base LCOE. Given the uncertainty, and limited contribution to the total learning investment, these are considered to be subsidised at the base LCOE.

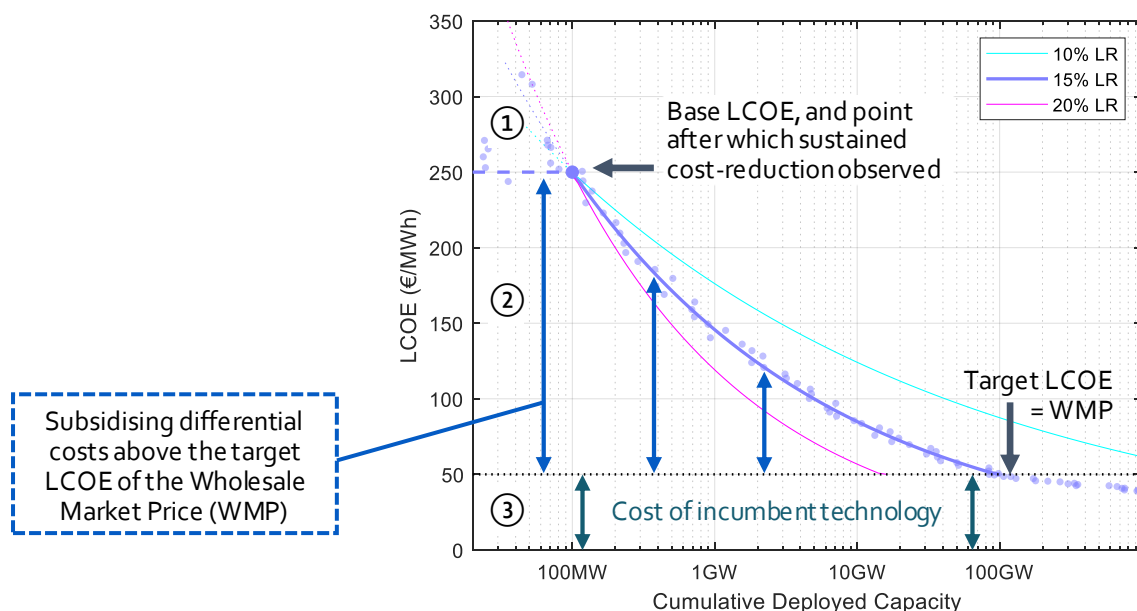


FIGURE 2.5: GRAPHICAL REPRESENTATION OF LEARNING INVESTMENT

2.2.3 RADICAL OR STEP-CHANGE COST REDUCTIONS

The cost modelling in this study investigates the effects of integrating radical innovation in experience curve analysis. This builds on the concept of step-change innovation enabling shifts between experience curves [31, 35] as shown in Figure 2.6. These experience curves can represent an incumbent technology (curve A) and a technology variant (curve B) which is enabled through step-change innovation. It is important to note that these step-changes are the result of new and novel technologies (devices and/or subsystems) being developed. The private energy sector is generally more inclined to improve existing technologies locking itself in to current portfolios, rather than to pursue higher-risk speculative R&D, which could lead to radically new technologies with a reduced cost. This point highlights the need for funding programmes to drive radical innovation.

This integration of step-change cost reduction into the experience curve analysis allows us to construct scenarios comparing the investment required to meet an LCOE target including step-change innovation (line B) compared to the counterfactual of incremental cost reductions alone (line A). It is assumed that accumulated experience is transferred from the incumbent to the novel technology.

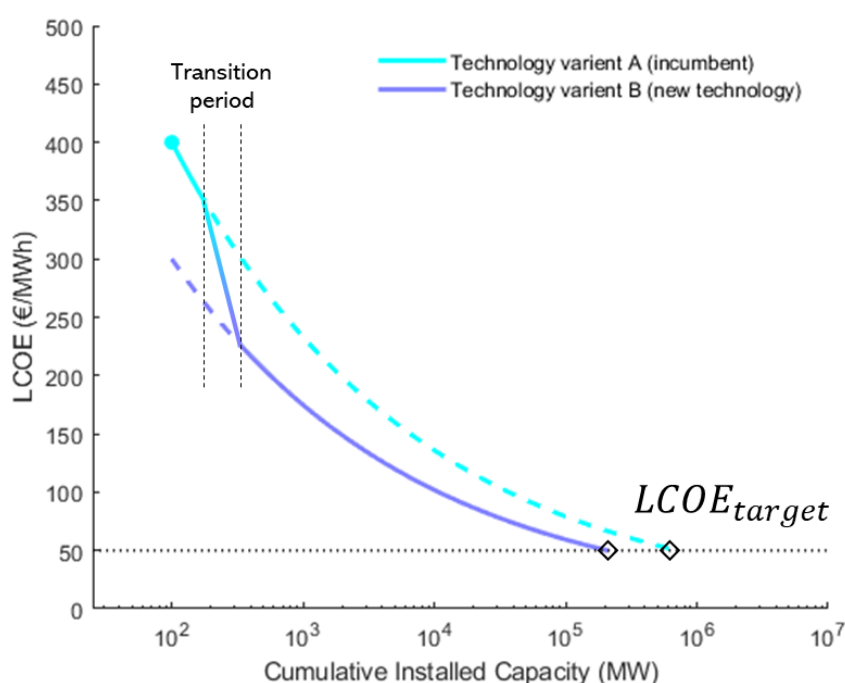


FIGURE 2.6: EXPERIENCE CURVE WITH TRANSITION BETWEEN TECHNOLOGY VARIANTS. BASED ON [31]. SOLID LINE SHOWS SECTOR WIDE COST CURVE. THE TECHNOLOGY VARIANTS ARE ASSUMED TO HAVE EQUAL LEARNING RATES.

2.3 LEVELISED COST OF ENERGY ESTIMATES OF OCEAN ENERGY

A wide range of cost estimates have been published for ocean energy technologies. There is significant uncertainty at this nascent stage of the sector, where only single demonstration devices or small arrays have been deployed, and few devices have been operated for many years. It is also important to note there is uncertainty due to the reliance on projected costs for operating these arrays, which could be $\pm 30\%$ for simplified cost estimates for pilot plants [36, 37].

Estimates from the following studies are presented in Table 2.1 and Table 2.2 for wave and tidal, respectively, and shown graphically in Figure 2.7 and Figure 2.8.

- ▶ Ernst & Young / Black & Veatch (2010) Cost of and Financial Support for Wave, Tidal Stream, and Tidal Range Generation in the UK [38]
- ▶ SI Ocean (2013) Ocean Energy: Cost of Energy and Cost Reduction Opportunities [39].
- ▶ IEA OES (2015) International Levelised Cost of Energy for ocean energy technologies [36].
- ▶ Jenne, Yu & Neary (2015) Levelized Cost of Energy Analysis of Marine and Hydrokinetic Reference Models [40].
- ▶ JRC (2018) Ocean Energy Technology Development Report [41].
- ▶ Offshore Renewable Energy Catapult (2018) Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit [42].
- ▶ BEIS (2020) Electricity generation costs [43]

These studies are reported in different currencies (EUR, GBP, USD) and have been calculated for a range of base years. Therefore, three estimates are shown for LCOE: (1) in reported currency, (2) converted to euro, and (3) corrected for inflation to 2020 (report publication date used if no currency date stated). Conversion factors of EUR 1.00 = USD 0.83 and EUR 1.00 = GBP 1.11 have been used based on the 3-month average to end 2020². Historical inflation based on UK ONS Data [44]. Different studies quote either a single number, a range, or high/medium/low estimates.

Note also that these studies represent varying levels of sector commercialisation, some give values for 100 MW of cumulative deployed capacity (CDC), whilst others quote 'first commercial arrays' or 10 MW project (which is assumed to be similar). They are not directly comparable due to differing input assumptions, etc. However, the broad trends from these studies have been used to inform the estimate of LCOE at sector commercialisation (assumed to correspond with 100 MW of CDC for each sector). Representative values from the literature of 350 €/MWh for wave and 200 €/MWh for tidal stream have been used. These two values are used as case studies to illustrate possible trends in future investment. It is important to note that this is a representative for the whole sector (wave or tidal) and encompasses a range of values across different devices and developers.

² <https://www.xe.com/currencyconverter/convert/?Amount=1&From=USD&To=EUR>



TABLE 2.1: LCOE ESTIMATES FOR WAVE ENERGY CONVERTERS

Source	Wave Sector Maturity	LCOE ¹ (£/MWh)	LCOE ² (€/MWh)	LCOE ³ (€ ₂₀₂₀ /MWh)
Ernst & Young / Black & Veatch (2010)	10 MW commercial array in 2020	177–253 (GBP)	195–278	263–376
SI Ocean (2013)	10 MW deployed	(EUR)	330–625	393–744
	100 MW deployed	(EUR)	230–435	274–518
Jenne, Yu & Neary (2015)	Small commercial array (RM3 10 MW)	980 (USD)	804	908
IEA OES (2015)	First commercial array, Reference studies	280–480 (USD)	230–394	259–445
	First commercial array, Developer responses	120–280 (USD)	98–230	111–259
JRC (2018)	Estimate of sector costs in 2015	(EUR)	470–1400	531–1582
	Estimate of sector costs in 2018	(EUR)	560	594
BEIS (2020)	9 MW project in 2025	169–338 (GBP)	188–375	212–424

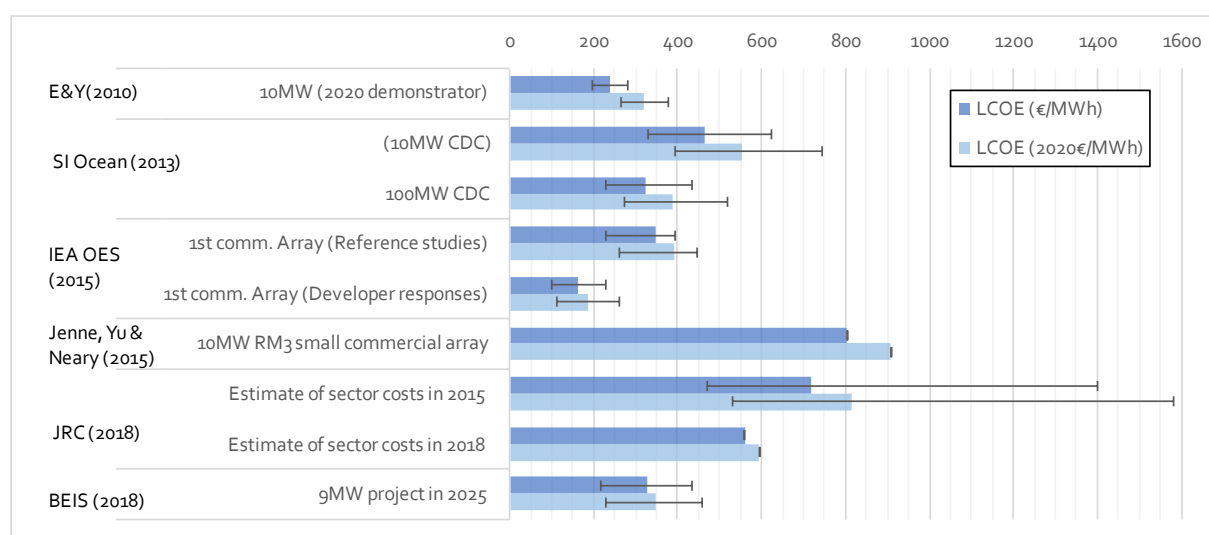


FIGURE 2.7: LCOE ESTIMATES FOR WAVE ENERGY CONVERTERS
ERROR BARS SHOW RANGE BETWEEN LOW & HIGH VALUES QUOTED,
SHADED BARS SHOW MID-POINT ESTIMATE WHERE AVAILABLE OR MEAN OF RANGE WHERE NOT

TABLE 2.2: LCOE ESTIMATES FOR TIDAL STREAM TURBINES

Source	Tidal Sector Maturity	LCOE ¹ (£/MWh)	LCOE ² (€/MWh)	LCOE ³ (€ ₂₀₂₀ /MWh)
Ernst & Young / Black & Veatch (2010)	10 MW commercial array in 2020	141–211 (GBP)	155–232	209–313
SI Ocean (2013)	10 MW deployed	(EUR)	245–470	292–559
	100 MW deployed	(EUR)	180–350	214–417
Jenne, Yu & Neary (2015)	Small commercial array (RM1 10 MW)	420 (USD)	344	389
IEA OES (2015)	Commercial scale project	140–270 (USD)	115–221	130–250
	10 MW project (<500kW trend)	145–280 (USD)	119–230	134–259
	10 MW project (>500 kW trend)	305–580 (USD)	250–476	283–537
JRC (2018)	Estimate of sector costs in 2015	(EUR)	470–1020	531–1153
	Estimate of sector costs in 2018	(EUR)	400	424
OREC (2018) (in 2012 GBP)	10 MW deployed	300 (GBP)	333	410
	100 MW deployed	150 (GBP)	167	205
	200 MW deployed	130 (GBP)	144	177
BEIS (2020)	9 MW project in 2025	195–391 (GBP)	216–434	229–460

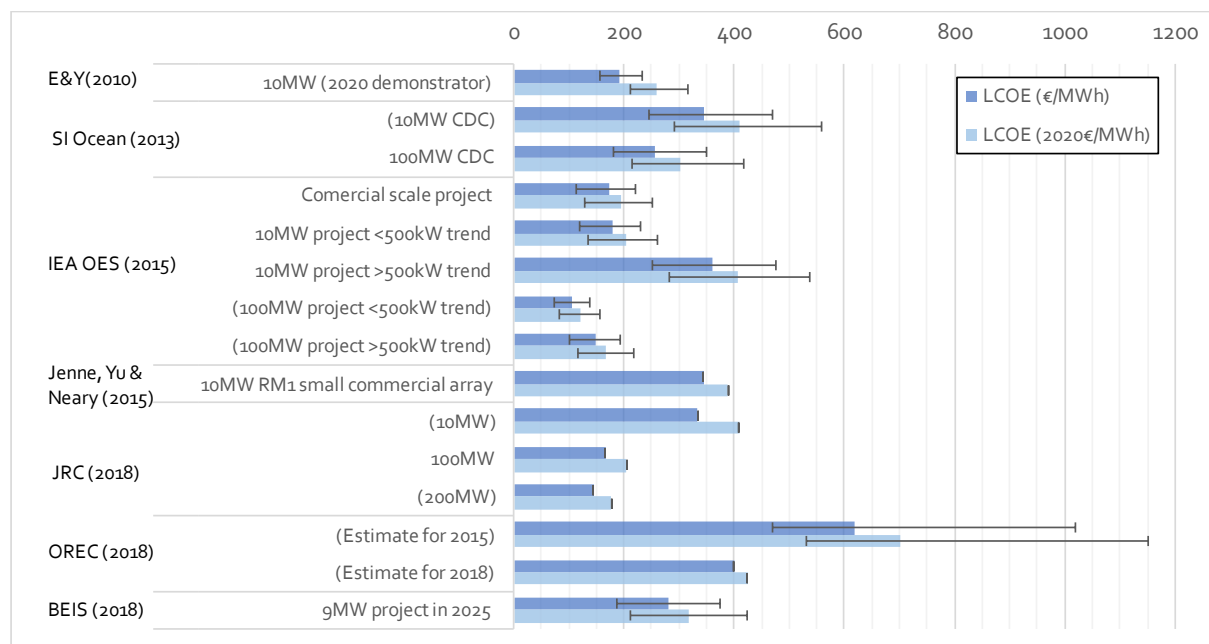


FIGURE 2.8: LCOE ESTIMATES FOR TIDAL-STREAM ENERGY CONVERTERS
ERROR BARS SHOW RANGE BETWEEN LOW & HIGH VALUES QUOTED,
SHADED BARS SHOW MID-POINT ESTIMATE WHERE AVAILABLE OR MEAN OF RANGE WHERE NOT

2.4 FUTURE SCENARIOS FOR DEPLOYMENT OF OCEAN ENERGY

The current cumulative global deployment for wave and tidal energy is approximately 25 MW for wave and 40 MW for tidal stream. This is based on reported deployments over the period 2001–2020 [45] [46], excluding redeployment of existing devices.

The focus of this study is on the costs and benefits of commercialising the ocean energy sector and reducing LCOE to a level competitive with other technologies. The results in section 5 show that the total investment required to achieve a competitive LCOE is not strongly linked to the deployment rate, however the temporal aspect has to be considered in the modelling.

Exponential growth in cumulative deployed capacity has historically been observed in other renewable energy technologies, including wind and solar, as covered in the case studies in section 3. For the base cases of the modelling, the increase in cumulative deployed capacity is assumed to increase exponentially at 30% increase/year, as seen in capacity addition rates for solar PV and onshore wind energy from 2006 to 2018 [47]. An 'aggressive deployment' scenario is also considered with a 60% increase/year, based on solar PV capacity additions from 2006–2013 [47].

These scenarios have been used to explore the likely timescales involved, although it should be noted that exponential deployment is highly sensitive to the initial capacity and deployment in the early years. The rate of deployment for wave and tidal is also unlikely to be equivalent as these technologies are at different levels of maturity and have different resource available globally.

It is beyond the scope of this study to model future deployment of technology in any detail. Therefore, the modelling in this study assumes this exponential growth in the cumulative deployment over time. The following caveats apply:

- ▶ This may not be fully accurate at the early stages prior to commercial scale roll-out of a technology. Exponential growth might over-estimate how much can realistically be deployed in the next few years. Conversely, it may be possible for the sector to roll out faster than these exponential trajectories when the absolute number of devices/MW installed is low.
- ▶ The rate of exponential growth is likely to reduce as the market matures and the rate of annual deployment approaches limits in the supply chain, availability of good deployment sites, etc. Therefore, the faster 60%/year exponential growth might be unlikely for a prolonged period.

Where related to calendar years, the first year of the exponential deployment trajectories is taken to be 2022. There is significant uncertainty over how fast the ocean energy sector can start to deploy technology, especially when subsidy mechanisms are not yet in place. However, some deployment will occur in 2021, which smoothens the transition to the exponential deployment.

The two exponential deployment scenarios used for the modelling have been compared against two projections from the IEA 2020 World Energy Outlook (WEO) [48]. These projections show the balance of global electricity generation by various technologies, including marine energy, for two possible future scenarios:



1. **Stated Policies Scenario (STEPS)** reflects the impact of existing policy frameworks and today's announced policy intentions, to provide a detailed sense of the direction in which existing policy frameworks and today's policy ambitions would take the energy sector out to 2040.
2. **Sustainable Development Scenario (SDS)** which shows a possible future course working backwards from the achievement of energy-related UN Sustainable Development Goals and shows what would be required to meet them.

The WEO notes that even the SDS is not sufficient to achieve the goal of net-zero emissions by 2050, this would require significant additional renewable energy generation above that in SDS, in combination with behavioural changes across society [48].

The classification of marine energy in the WEO includes tidal range, of which there are currently three significant schemes worldwide totalling approximately 0.5 GW. Tidal range schemes are very site specific and have potentially large environmental impact, so there is limited availability for additional tidal range deployments worldwide and thus have been excluded from this analysis.

Figure 2.9 shows the two exponential deployment scenarios projected forwards from the end of 2021, for wave, tidal, and total cumulative deployment, compared against the IEA WEO projections for marine energy (minus existing tidal range) and Ocean Energy Europe (OEE) targets for 2030 under low and high growth scenarios, shown in Table 2.3. The cumulative total deployments are also presented in Table 2.4. Indicative annual capacity additions are shown in Table 2.5, noting these are not shown every year due to the sensitivity of the exponential deployment and the fact that projects are not likely be deployed with equal growth per year.

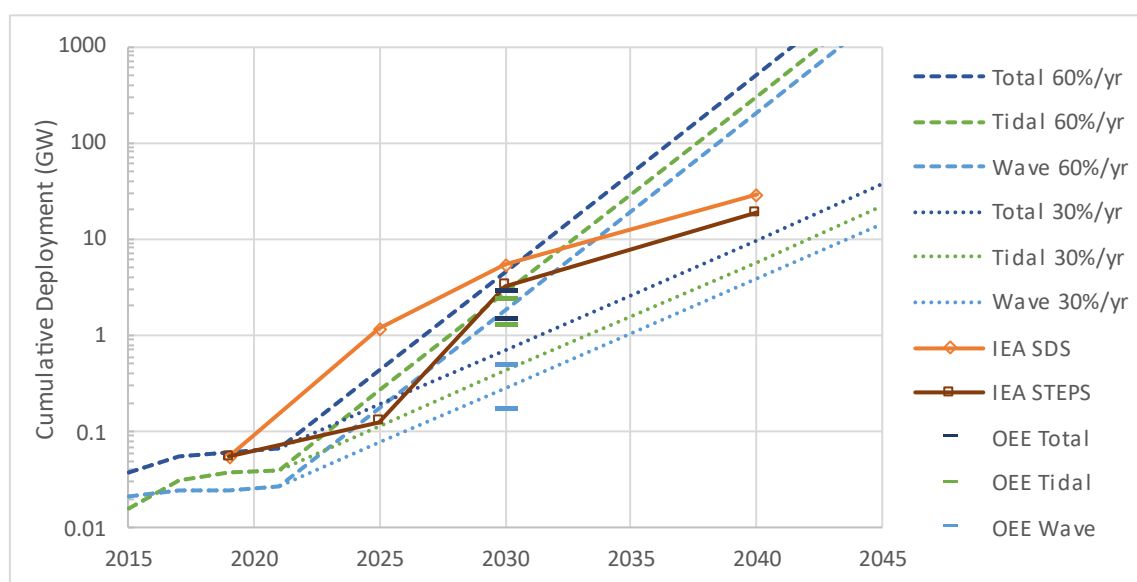


FIGURE 2.9: COMPARISON OF FUTURE GLOBAL CUMULATIVE DEPLOYMENT TRAJECTORIES
NOTE THAT APPROXIMATELY 0.5 GW OF EXISTING TIDAL RANGE CAPACITY HAS BEEN REMOVED FROM THE IEA SCENARIOS WHICH CONSIDER ALL TYPES OF MARINE ENERGY IN A FUTURE ELECTRICITY GENERATION MIX. SDS IS THE SUSTAINABLE DEVELOPMENT SCENARIO, STEPS IS THE STATED POLICIES SCENARIO.

TABLE 2.3: OCEAN ENERGY EUROPE 2030 DEPLOYMENT TARGETS (MW)

Year	Growth Scenario	Wave	Tidal	Total
2030	Low	178	1,324	1,502
2030	High	494	2,388	2,882

TABLE 2.4: POTENTIAL FUTURE GLOBAL CUMULATIVE DEPLOYMENT TRAJECTORIES (MW)

	30%/year increase			60%/year increase			IEA WEO2020 Marine Energy	
Year	Wave	Tidal	Total	Wave	Tidal	Total	STEPS	SDS
2019	25	38	63	25	38	63	564	564
2020	25	40	65	25	40	65	–	–
2025	71	114	186	164	262	426	623	1,671
2030	265	424	689	1,718	2,749	4,467	3,737	5,907
2035	984	1,575	2,559	18,014	28,823	46,837	–	–
2040	3,655	5,848	9,502	188,895	302,231	491,126	19,228	28,514

TABLE 2.5: INDICATIVE FUTURE GLOBAL ANNUAL DEPLOYMENT (MW)

	30%/year increase			60%/year increase		
Year	Wave	Tidal	Total	Wave	Tidal	Total
2025	16	26	43	61	98	160
2030	61	98	159	644	1,031	1,675
2035	227	363	591	6,755	10,809	17,564
2040	843	1,349	2,193	70,835	113,337	184,172

3. CASE STUDIES SHOWING BALANCE OF POLICY MECHANISMS IN OTHER ENERGY SECTORS

A broad background review covering a variety of funding mechanisms across different energy sectors and countries has been conducted. This review aims to build country-specific sectoral case studies to understand how different funding mechanisms have been used at different stages of technological maturity and how the markets around these sectors have developed. In turn, these case studies would help assess what a good balance of technology-push (TP) and market-pull (MP) mechanisms is and thus provide learning for the ocean energy sector. Additionally, the case studies will also help benchmark the assumptions used in the investment cost modelling (sections 4 and 5).

The framework behind these case studies and their inputs are discussed in detail below. Overall discussion of the case studies and resulting lessons that could be learnt for the ocean energy sector is given in section 7.1.

Based on the availability of information under the background review conducted, four case studies have been selected based on the availability of information, technological maturity, and the success of the sector. The case studies are:

- ▶ German solar PV,
- ▶ Japanese solar PV,
- ▶ German (onshore) wind, and
- ▶ Danish (onshore and offshore) wind.

The data behind these case studies are entirely based on secondary research, sourced from relevant research papers, journals, government studies, reports, websites etc., which have allowed us to build a robust database for our analysis. The period between 2000-2018 has been selected for this study to capture the most recent and relevant developments of these energy sectors. The data collated has been grouped under the below-mentioned indicators and is further defined in Table 3.1 below:

Technical Indicators include cumulative capacity deployed, cumulative generation, LCOE, and capacity factor (CF), to help us assess the maturity of the sector.

Financial Indicators include various TP (R&D grants, government funding etc.) and MP (FiT, tax credits, subsidies, ROCs, etc.) funding mechanisms, as well as capital investment (where available) to help gauge the funding support required for the commercial development of the sector.

Economic Indicators such as GVA, annual turnover or business value and jobs created, to help assess the economic performance/benefits generated from the sector.



TABLE 3.1: DESCRIPTION OF THE INDICATORS USED WITHIN THE CASE STUDIES

Indicator	Unit	Description
Cumulative capacity	GW	Cumulative capacity installed of a specific technology between 2000 and 2018.
Cumulative Generation	GWh	Cumulative energy generated from a specific technology until 2018.
Capacity factor	%	Ratio of actual electrical energy output over one year to the maximum possible electrical energy output over that same period.
Levelised cost of energy	€/kWh	Average lifecycle cost per unit of energy produced.
Investment in construction	€ m	Capital investment available for the construction of power plants
Technology-Push funding	€ m	Total funding provided to a specific energy sector in the form of TP support mechanisms between 2000 and 2018.
Market-Pull funding	€ bn	Total funding provided to a specific energy sector in the form of MP support mechanisms between 2000 and 2018.
Turnover	€ bn	Total returns in the form of economic stimuli or turnover generated between 2000 and 2018 by a specific energy sector.
Business value	€ bn	Amount of capital investment made including the turnover from the import of specific components
Spend	€ bn	Sum of funding provided to a specific energy sector between 2000 and 2018 in the form of TP and MP support.
Jobs created	Nº	Total number of employment or jobs created in a specific energy sector between 2000 and 2018.
Penetration level	%	Share of electricity generated by the energy sector in the national energy mix in a specific year.

The above indicators are used to generate two sets of metrics: absolute numbers and ratios between the indicators. The absolute numbers are absolute representations of the cumulative figure under each indicator. For example, the cumulative capacity is the sum of the total capacity installed between the period. These numbers are further used to generate the ratios, which are defined in Table 3.2 below.

TABLE 3.2: DESCRIPTION OF THE RATIOS USED WITHIN THE CASE STUDIES

Metric/ Ratio	Unit	Description
Employment to generation	Jobs/GWh	Number of jobs created within the 2000 – 2018 period per energy generated.
Turnover to generation	€/MWh	Economic return or added value created by an energy sector respective to the amount of energy generated between 2000 and 2018.
Market-pull to technology-push	—	The ratio of amount invested in technology innovation to amount invested to foster demand in a specific energy sector within 2000 – 2018.
Technology-push to generation	€/MWh	Cumulative investment in technology innovation per energy generated between 2000 and 2018.
Market -pull to generation	€/MWh	Cumulative sum of subsidies and premiums offered to foster demand in an energy sector per energy produced between 2000 and 2018.
Spend to generation	€/MWh	Cumulative investment, both in terms of TP and MP, between 2000 and 2018 per energy generated.
Turnover to spend	—	Economic return generated per investment in both TP and MP between 2000 and 2018. This ratio is virtually a return-on-investment.
Jobs to spend	Jobs/€	Number of jobs created between 2000 and 2018 per total investment in both TP and MP.
Learning rate	%	Reduction in technology unit costs associated with each doubling of installed cumulative capacity.

It is important to highlight that the basis of our analysis is very much dependent on the ratios that have been calculated. A limitation in our analysis is that each case study has different indicators available, and the methodology used to calculate them differs as well. Also, the fact remains that each of these case studies will have a different point of initiation and commercialisation, which means that our study period 2000-2018 might capture a different market situation for each one of them. This makes it difficult to draw a direct comparison between the case studies. However, the case studies do provide an interesting context when compared with the ocean energy sector, by helping understand the balance of technology-push and demand-pull funding that would be required to generate similar benefits in this sector.

A detailed overview of these case studies will be discussed in the sections below. Each case study begins with an overview of the data inputs, their sources, assumptions and identified gaps. This is followed by a discussion section drawn on an analysis of the inputs, ratios, and findings.

3.1 CASE STUDY 1: GERMAN SOLAR PV

Germany's energy transition plan ("Energiewende") has contributed to transforming the country's energy system. The main target of this plan is to supply most of Germany's energy from renewable energy sources and without electricity generation from nuclear by 2022. Currently, the transition to renewable energy sources is visible in Germany's electricity sector. The country has experienced rapid growth in both its solar and wind capacity since the introduction of the Renewable Energy Sources Act ("Erneuerbare-Energien-Gesetz" or EEG) in the early 2000s. Through a combination of TP and MP



mechanisms, Germany has made funding available towards more competition and cost efficiency in the solar PV sector. This section reviews the evolution of this energy sector and presents a detailed breakdown of the various indicators, the data used, the sources, assumptions, and the existing gaps under this case study. A discussion section is also included analysing the effect of TP and MP support mechanisms on the development of the sector and the benefits derived from the investment and operation of solar PV plants in Germany. No significant gaps exist under this case study except an incomplete set of LCOE numbers (available from 2011-2018 only).

3.1.1 TECHNICAL INDICATORS

The technical indicators used in our analysis are summarised in Table 3.3 and include annual deployment capacity, generation, LCOE and estimated CF.

TABLE 3.3: DESCRIPTION OF TECHNICAL INDICATORS AND SOURCES FOR THE GERMAN SOLAR PV SECTOR

	Capacity	Generation	LCOE	CF
Year	2000-2018	2000-2018	2010-2018	2010-2018
Units	MW	MWh	€/kWh	%
Data Source	Working Group on Renewable Energy Statistics Report [49]	Working Group on Renewable Energy Statistics Report [49]	IRENA Report [50]	Estimated as per Equation (3.1)
Conversion Factor	None	None	0.85€ = \$1	None
Calculations	None	None	None	Equation (3.1)
Assumptions	None	None	None	None
Gaps	None	None	2000-2009; 10 yrs.	None

The figures corresponding to cumulative installed capacity (MW) and electricity generation (GWh) were obtained from the report “Time series for the development of renewable energy sources in Germany” published by the Working Group on Renewable Energy-Statistics (AGEE-Stat) [49]. The data is directly available for the years 2000–2018 and, thus, no assumptions or calculations were necessary.

The data for LCOE in \$/kWh was procured from the 2019 IRENA Report “Renewable Power Generation Costs” [50] for the years 2010-2018. An exchange rate of €0.85 to \$1.00 was assumed. There is a gap of 10 years (2000–2009) for this metric as the values are only available from 2010 onwards.

Lastly, the average annual capacity factors were estimated based on the generation and cumulative capacity previously described as per Equation (3.1), where t is the specific year between 2000 and 2018.

$$CF_t = \frac{\text{Energy Generation (MWh)}_t}{\text{Cumulative Capacity (MW)}_t} \times \frac{8766 \text{ hours}}{\text{year}} \quad (3.1)$$

3.1.2 FINANCIAL INDICATORS

Our analysis considers federal energy research programmes as the main TP funding mechanism and total annual FIT spend as the most prominent and relevant MP funding mechanism. For this case study, we have also compiled information regarding the annual investment in the construction of power plants. The summary of these indicators is presented below in Table 3.4.

TABLE 3.4: DESCRIPTION OF FINANCIAL INDICATORS AND SOURCES FOR THE GERMAN SOLAR PV SECTOR

	Investment	Federal Energy Research Funding	FIT and Premiums Spent
Year	2000-2018	2000-2018	2000-2018
Units	€ m	€ m	€ m
Data Source	Working Group on Renewable Energy Statistics Report [49]	Evaluation of Energy Research Programme, Renewable Energies Reports and Federal Ministry for Economic Affairs and Energy Report [51] [52] [53]	Federal Ministry of Economics and Energy Report [54]
Conversion Factor	None	None	None
Calculations	None	None	None
Assumptions	None	None	None
Gaps	None	None	None

The data for federal energy research funding has been procured from periodic reports put together by the German government and, also, supported by research papers [51] [52] [53]. No assumptions were made nor were any conversion factors used. The time series is complete.

The data for the annual investment and FIT spent have also been procured from reports put together by the German government and does not involve any assumptions or conversion factors [54]. The time series is complete.

3.1.3 ECONOMIC INDICATORS

To gauge the benefits of the support mechanisms in the German economy, we reviewed the economic indicators summarised in Table 3.5, which include economic stimuli from the operation of solar PV plants and gross employment numbers under the German solar PV sector. Economic stimuli are a representation of the revenue generated from the German solar PV sector (i.e., manufacturers, suppliers, sales, and service companies) and the economic benefits derived from this sector. The data has been procured from reports put together by the German government [49] [55] and does not involve any assumptions or calculations. No conversion factor has been used and the available data is for the complete set of years.

Gross employment numbers are used as a representation of the gross number of jobs generated under this sector and has also been taken from a German government report [55]. This indicator refers to direct employment and includes temporary jobs and, therefore, is higher than the net employment



generated by the sector (i.e., the figures are not full-time-equivalent adjusted). No assumptions or calculations were required, and the time series is complete.

TABLE 3.5: DESCRIPTION OF ECONOMIC INDICATORS AND SOURCES FOR THE GERMAN SOLAR PV SECTOR

	Economic stimuli	Gross employment
Year	2000–2018	2000–2018
Units	€ m	—
Data Source	Working Group on Renewable Energy Statistics Report [49]	Federal Ministry for Economic Affairs and Energy Report [55]
Calculations	None	None
Assumptions	None	None
Gaps	None	None

3.1.4 DISCUSSION

Key Findings: German Solar PV

- ▶ Solar PV has become a key generation technology in the German energy transition
- ▶ Capital investment peaked in 2010 at €19.5 bn (refer
- ▶
- ▶
- ▶ Figure 3.1).
- ▶ €13.26 bn have been received from economic stimulus triggered in other sectors through personnel demand, auxiliary services, spare parts, fuel, etc. This represents a 14% return on investment in technology-push and market-pull support.
- ▶ 3.8 direct jobs have been created per GWh of electricity generated between 2000 and 2018 from solar PV.
- ▶ Due to the aggressive industrial policy in Asia, particularly China and Japan, the market share of German manufacturers decreased significantly, and the cost competitiveness of the sector collapsed in 2012 and 2013.

- The sector has started regaining strength in 2018 with the constantly decreasing costs of German PV modules, the increasing freight costs, and long delivery times for Asian PV modules.



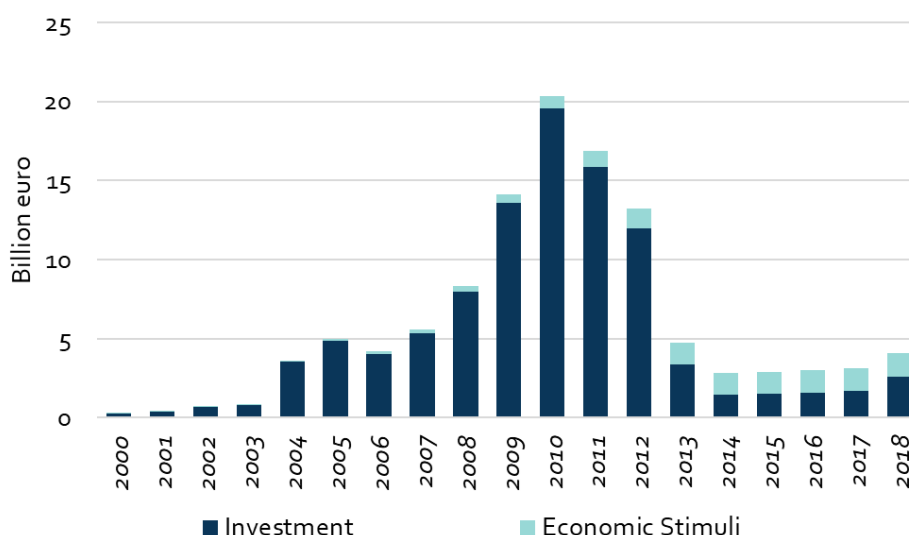


FIGURE 3.1: INVESTMENT AND ECONOMIC BENEFIT UNDER THE GERMAN SOLAR PV SECTOR BETWEEN 2000 AND 2018

- ▶ €1.02 bn have been allocated to energy research between 2000 and 2018.
- ▶ The LCOE has dropped from 0.28 €/kWh in 2010 to 0.09 €/kWh in 2018. This represents a reduction of approx. 67.6%.
- ▶ €94.91 bn have been invested in MP support mechanisms such as FiT and FiP between 2000 and 2018.
- ▶ Germany has spent approx. 93 times more in MP mechanisms for the solar PV sector than in TP mechanisms (refer to Figure 3.2).
- ▶ Total spend in TP and MP support between 2000 and 2018 is equivalent to €60.70 per capita per year.

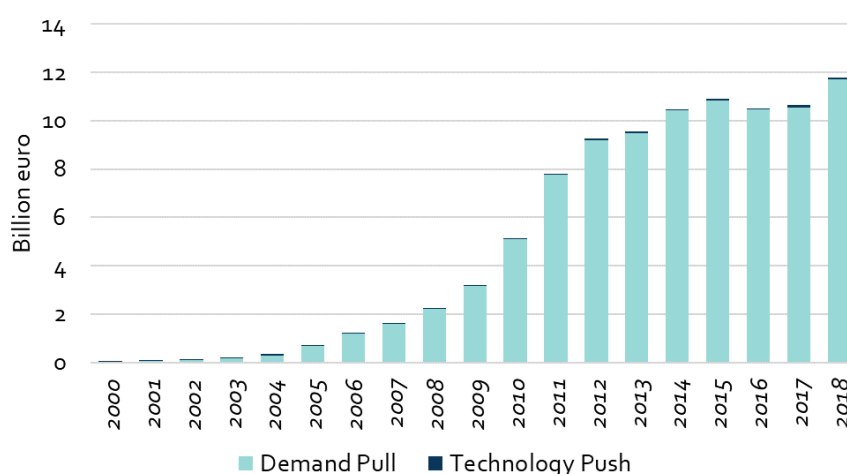


FIGURE 3.2: FUNDING AVAILABLE TO THE GERMAN SOLAR PV SECTOR THROUGH MARKET-PULL AND TECHNOLOGY-PUSH SUPPORT MECHANISMS BETWEEN 2000 AND 2018

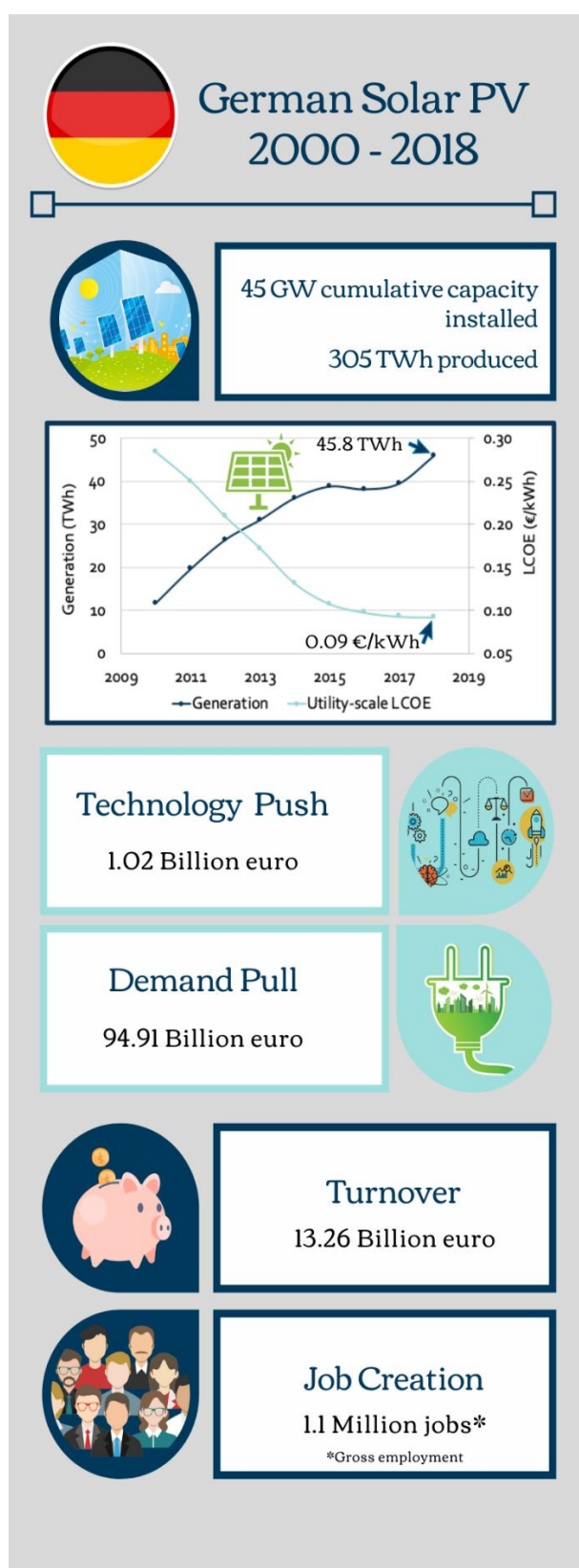


FIGURE 3.3: SUMMARY OF INDICATORS (ABSOLUTE FIGURES OVER THE 2000–2018 PERIOD) FOR GERMAN SOLAR PV

Photovoltaics has become a key generation technology in Germany's energy transition with approx. 45 GW of cumulative capacity installed between 2000 and 2018. This energy sector generated approx. 45.8 TWh of electricity in 2018, accounting for nearly 8% of the gross electricity consumed that year [56]. However, reaching this level of progress and maturity has required time and investment.

Between 2004 and 2012, the solar PV sector was the renewable energy sector with the highest level of investment in the country. In 2010, the investment level in the sector peaked at €19.5 bn (refer to Figure 3.1) [57].

The German federal energy research programmes have provided approx. **€1.02 bn for research** in the solar PV sector. With this support, technological progress, the learning curve, and economies-of-scale, the LCOE has decreased by 67.6%, from 0.28 €/kWh in 2010 to **0.09 €/kWh in 2018** [50]. The annual learning rates have increased from 11% in 2010–2011 to 15% in 2017–2018 as can be seen in **¡Error! No se encuentra el origen de la referencia..** The cost reduction in the German solar PV sector seems to respond to the cumulative deployment, generation, and capacity factors with Pearson correlation coefficients of 0.91, 0.95 and 0.93, respectively.

Additionally, diverse MP policies have supported the rapid market growth. First, the 100,000 Solar Roofs Initiative rolled out in 1999 incentivised the installation of PV systems in the early 2000s [58]. Later, the German Renewable Energy Source Act (Erneuerbare Energien Gesetz EEG) rolled out in 2000, guaranteed plant operators a fixed rate of purchase to obtain an appropriate profit. The EEG has facilitated approx. **€95 bn in demand-pull support through feed-in-tariffs and premiums** [49]. The strong investment carries along considerable economic importance

given the **economic stimulus triggered in other sectors** through the demand for personnel, auxiliary services, spare parts, fuels, etc., which generates corresponding sales revenues in these other sectors.

Although, **from 2013 onwards, PV installations in Germany have decreased significantly** compared to previous years (refer to Figure 3.4), the **economic benefits yielded from plant operation have remained steady**. Between 2014 and 2016, the total economic stimuli derived from the German solar PV sector remained virtually at the same level of the investments in the construction of plants hinting at the rentability of the investments. The sector received approx. **€13.3 bn in economic benefits between 2000 and 2018**. Also, in this period, the German solar PV sector has created nearly **1.1 million jobs**³. In 2018, the German PV industry employed 24,000 people⁴ in sectors such as the manufacture of materials, manufacture of intermediate and final products including modules, cables and inverters, mechanical engineering for cell and module production and installation [56].

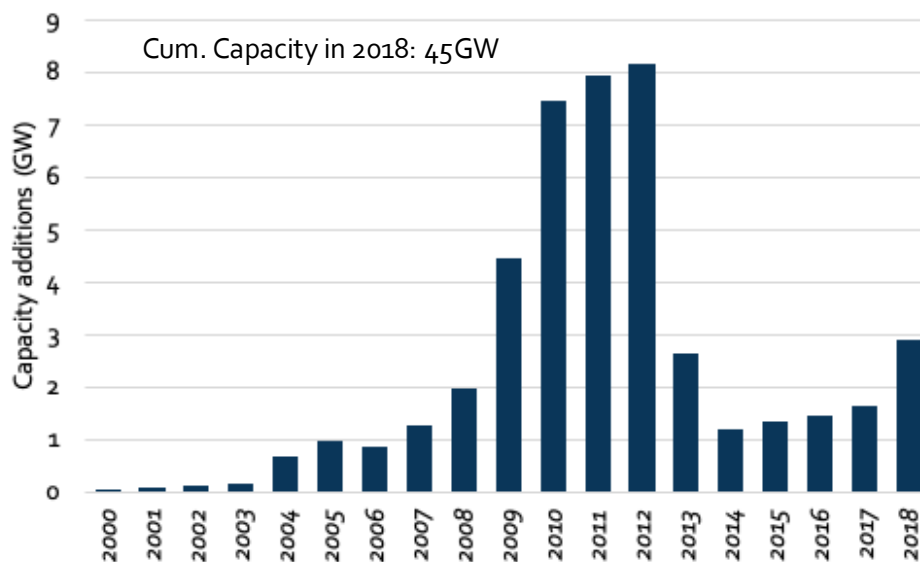


FIGURE 3.4: ANNUAL SOLAR PV CAPACITY ADDITIONS IN GERMANY BETWEEN 2000 AND 2018

The metrics presented in Table 3.6 seek to gauge the effectiveness of the support mechanisms implemented by the federal government in the solar PV sector. Overall, this energy sector has created approx. **3.8 direct jobs per GWh produced** and perceived an **economic benefit of €43.4 per MWh between 2000 and 2018**. In this period, Germany has perceived a **return of 14% on its investment in TP and MP support** mechanisms for the solar PV sector. It can also be said that approx. 12 new jobs were created between 2000 and 2018 for every million Euro invested in these support mechanisms. The investments in TP and MP are equivalent to €0.64 and €60.1 per capita per year, respectively. It is worth highlighting that the sector has **invested over 93 times more in MP mechanisms than in TP**.

³ This figure refers to gross employment in the German solar PV sector between 2000 and 2018.

⁴ This figure refers to net employment in the German solar PV sector in 2018.

TABLE 3.6: SUMMARY OF METRICS ANALYSING THE COST-BENEFITS OF THE GERMAN SOLAR PV SECTOR

Metrics	German Solar PV
Employment to Generation (Jobs/GWh)	3.79
Turnover to Generation (€/MWh)	43.40
Market-pull to Technology-push	93
Technology-Push to Generation (€/MWh)	3.33
Market-pull to Generation (€/MWh)	310.64
Spend to Generation (€/MWh)	313.97
Turnover to Spend* (~ROI)	0.14
Jobs to Spend* (Jobs/€m)	12.1
Average Technology-Push investment per capita per year (€/capita-year)	0.6
Average Market-pull investment per capita per year (€/capita-year)	60.1
LCOE reduction between 2010 and 2018 (%)	-67.6
Learning rate between 2010 and 2018 (%)	16%
2018 Penetration level in national electricity mix (%)	7.7

*Spend is defined as the sum of the investment in both TP and MP support

Despite these benefits, **the German solar PV sector collapsed in 2012 and 2013** [58]. The sector has lost many jobs over the last few years due to **company closures and insolvency** that affected cell and module manufacturers, the mechanical engineering industry, and installers [56]. Initially, TP support mechanisms such as investment grants and research support positioned the sector as an international leader in production volume. However, **the aggressive industrial policy in Asia (China and Japan in particular) and their large investments in production capacity significantly decreased the market share of German manufacturers**. It is estimated that nearly 30% of the German FiT goes to Asia for imported modules [56]. To Germany's advantage, an important part of the value chain for PV power plants remains in the country and a share of all Asian PV products use German manufacturing equipment for their production. **In recent years, the German PV industry has started to regain strength**. The constantly falling costs of PV module manufacturing, the increasing freight costs and long delivery times for Asian PV modules could improve the competitiveness of German manufacturers in the long term.

3.2 CASE STUDY 2: JAPANESE SOLAR PV

Japan's combinations of TP and MP policies have been highly significant in establishing itself as a world leader in the solar PV sector. Consistent TP in the form of RD&D under the first '1974 Sunshine Program' is one of the main success factors that laid the foundation of the solar PV sector. With a mix of RD&D and investment subsidy programmes, the Japanese PV sector first developed in the residential rooftop market. But it was the FiT programme introduced after the 2011 Fukushima disaster (responsible for the phase-out of all nuclear power plants) that remains the main driver for commercial-scale PV development in Japan. In building the Japanese solar PV case study, most of the data was sourced from research papers and government reports. This section reviews the evolution of this energy sector and presents a detailed breakdown of the various indicators, their sources,



assumptions, and the existing gaps under this case study. A discussion section analysing the effect of technology-push and market-pull support mechanisms on the development of the sector and the benefits derived from the investment and operation of solar PV plants in Japan is also included. No significant gaps exist under this case study except an incomplete set of LCOE numbers (available from 2011-2018 only), but we have highlighted some questions towards the end of this case study.

3.2.1 TECHNICAL INDICATORS

The technical indicators used in our analysis include annual deployment capacity, cumulative capacity, generation, LCOE, and estimated capacity factor and are summarised in Table 3.7 below.

The figures corresponding to installed capacity (both annual and cumulative MW installed) were obtained from the report “Trends in Photovoltaic Applications - Report IEA PVPS T1-36” published by the IEA [59]. The figures for electricity generation (GWh) were taken from the IRENA database for data and statistics [60]. For both metrics, the data is directly available for the years 2000–2018 and, thus, no assumptions or calculations were necessary.

The data for LCOE in €/kWh was procured from the 2019 IRENA Report “Renewable Power Generation Costs” [50] for the years 2010–2018. An exchange rate of EUR 0.85 to USD 1.00 was assumed. There is a gap of 10 years (2000–2009) for this metric as the values are only available from 2010 onwards.

Lastly, the average annual capacity factors were estimated based on the generation and cumulative capacity previously described as per Equation (3.1) between 2000 and 2018.

TABLE 3.7: DESCRIPTION OF TECHNICAL INDICATORS AND SOURCES FOR THE JAPANESE SOLAR PV SECTOR

	Capacity	Generation	LCOE	CF
Year	2000-2018	2000-2018	2010-2018	2010-2018
Units	MW	MWh	€/kWh	%
Data Source	IEA Trends in Photovoltaic Applications Report [59]	IRENA database for data and statistics [60]	IRENA Report [50]	Estimated as per Equation (3.1)
Conversion Factor	None	None	EUR 0.85 = USD 1	None
Calculations	None	None	None	Equation (3.1)
Assumptions	None	None	None	None
Gaps	None	None	2000-2009; 10 yrs.	None

3.2.2 FINANCIAL INDICATORS

Under the Japanese solar PV case study, RD&D funds (€m) is the main TP funding mechanism whereas investment subsidy programme and FiT (€m) are the most prominent and relevant MP funding mechanism.

The data for funding under the RD&D programmes has been procured from the annual “National Survey Report of PV Power Application in Japan” put together by the IEA Technology Network [61] and is also supported by the research paper [58]. No assumptions were made nor were any conversion factors used. The available data is complete.

Data for the subsidy programme and FiT spent have been procured from a research paper [58] and the Renewable Energy Institute [62] and does not involve any assumptions or exchange rates. The available data is complete. A summary of these indicators is presented below in Table 3.8.

TABLE 3.8: DESCRIPTION OF FINANCIAL INDICATORS AND SOURCES FOR THE JAPANESE SOLAR PV SECTOR

	RD&D	FiT and Subsidy Spent
Year	2000-2018	2000-2018
Units	€m	€m
Data Source	Annual National Survey Report of PV Power Application in Japan and Research paper [61, 58].	Research paper [58] and Renewable Energy Institute website [62]
Conversion Factor	None	None
Calculations	JPY ⁵ 1 = EUR 0.0079	JPY 1 = EUR 0.0079
Assumptions	None	None
Gaps	None	None

3.2.3 ECONOMIC INDICATORS

The economic indicators reviewed under the Japanese solar sector include business value (€m) and jobs created and are presented in Table 3.9 below. Business value is a representation of the Capital Expenditure (CAPEX) or the investments made along with the turnover from the import of PV modules. The data has been procured from the annual reports put together by the IEA Energy Technology Network [61] and does not involve any assumptions or calculations. No conversion factor has been used and the available data is for the complete set of years.

Jobs created is used as a representation of the number of net jobs generated under this sector and has also been taken from the IEA annual reports [61]. No assumptions or calculations were made, and the data set is complete.

⁵ JPY is Japanese Yen



TABLE 3.9: DESCRIPTION OF ECONOMIC INDICATORS AND SOURCES FOR THE JAPANESE SOLAR PV SECTOR

	Business Value	Jobs Created
Year	2000-2018	2000-2018
Units	€m	—
Data Source	IEA Energy Technology Network Report [61]	IEA Energy Technology Network Report and Research paper [61, 58]
Conversion Factor	None	None
Calculations	JPY 1 = EUR 0.0079	None
Assumptions	None	None
Gaps	None	None

3.2.4 DISCUSSION

Japan holds the third position in the global PV market with **approx. 56.2 GW of cumulative installed PV capacity by 2018** [63]. The Japanese solar PV sector generated **approx. 67.7 TWh of electricity in 2018**, accounting for **6.5% of the gross electricity consumed that year** [64]. As seen from the available information between 2000–2018, this growth has been possible because of the government's consistent commitment to PV development and its strategic policy mix of TP and MP policies, which has enabled the country to develop its solar PV market over the last 20+ years. The Japanese solar PV sector first developed its footprint in the residential sector in the early 2000s and it was only after 2012 that it went on to establish itself commercially.

Key Findings: Japan Solar PV

- ▶ Owing to the scarcity of local fossil fuel reserves, renewable energy deployment has always been one of the key focus of the Japanese government.
- ▶ Combination of TP and MP measures along with government commitment have been key to establishing Japan as a market leader in the solar PV sector.
- ▶ Approx. 56 GW of solar PV have been installed until 2018 in Japan, producing 267 TWh of electricity.
- ▶ The LCOE has dropped from 0.60 €/kWh in 2010 to 0.15 €/kWh in 2018.
- ▶ €1.5 bn have been allocated to RD&D TP support mechanisms between 2000 and 2018, equivalent to 5.56 €/MWh or 11.75 €/capita invested between 2000 and 2018.
- ▶ €69 bn have been invested in MP support mechanisms such as FiT and subsidies between 2000 and 2018. This is equivalent to 259.1 €/GWh of energy produced or 548 €/capita, i.e. over 46 times more in MP mechanisms than in TP.
- ▶ Approx. €71 bn have been invested as total TP and MP measures from 2000–2018. Total spend in technology-push and market-pull support between 2000 and 2018 is equivalent to 560 €/capita
- ▶ Between this period, the sector has a valuation of approx. €122 bn, inclusive of imports.
- ▶ 3.4 total jobs have been created per GWh of electricity generated between 2000 and 2018 from solar PV.

- ▶ Since 2015, with decreasing FiT tariffs along with interconnection and land availability issues, Japan's global market share has started to decline.
- ▶ Changes in the FiT mechanism has driven many solar companies to bankruptcy. In 2018 alone, almost 95 solar companies went bankrupt [65].

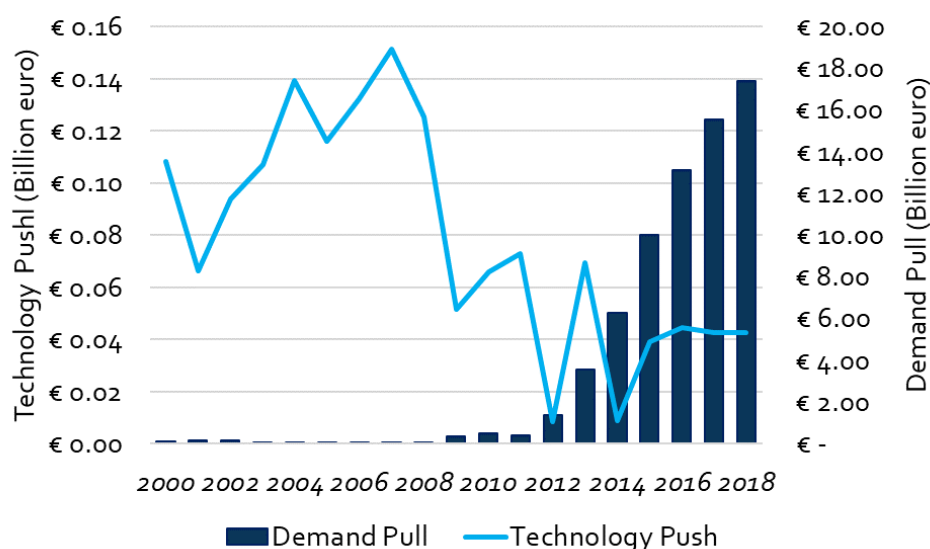


FIGURE 3.5: FUNDING AVAILABLE TO THE JAPAN SOLAR PV SECTOR THROUGH MARKET-PULL AND TECHNOLOGY-PUSH SUPPORT MECHANISMS BETWEEN 2000 AND 2018

The Japanese government introduced the first **Sunshine Programme** in 1974 to support R&D for renewable energy technologies and to cope with the scarcity of fossil fuel reserves. Together with the other demonstration programmes, they proved vital to the technological development of Japanese solar PV in the 1990s. At the same time, the set national targets and commitment from the Japanese government to produce a substantial amount of solar power by 2000 provided a stimulus for many private firms to expand their activities in PV development. This instigated private investment, alongside government funding for the sector. Until 2018, the Japanese government invested approx. **€1.5 bn for RD&D** in the solar PV sector with most investment made during the mid-2000s. This long-term RD&D support along with government commitment laid the foundation for the PV industry in Japan, improving efficiency, reducing costs, and assuring a reliable supply of grid-connected PV systems.

Improvement in efficiency and economics further urged the Japanese government to promote grid-connected PV systems. Numerous market deployment policies like simplified administration process, technical standards, net-metering system, investment subsidies and FiT were adopted. The **net metering policy of 1992** was introduced as a voluntary measure to encourage the purchase of electricity from residential PV systems.

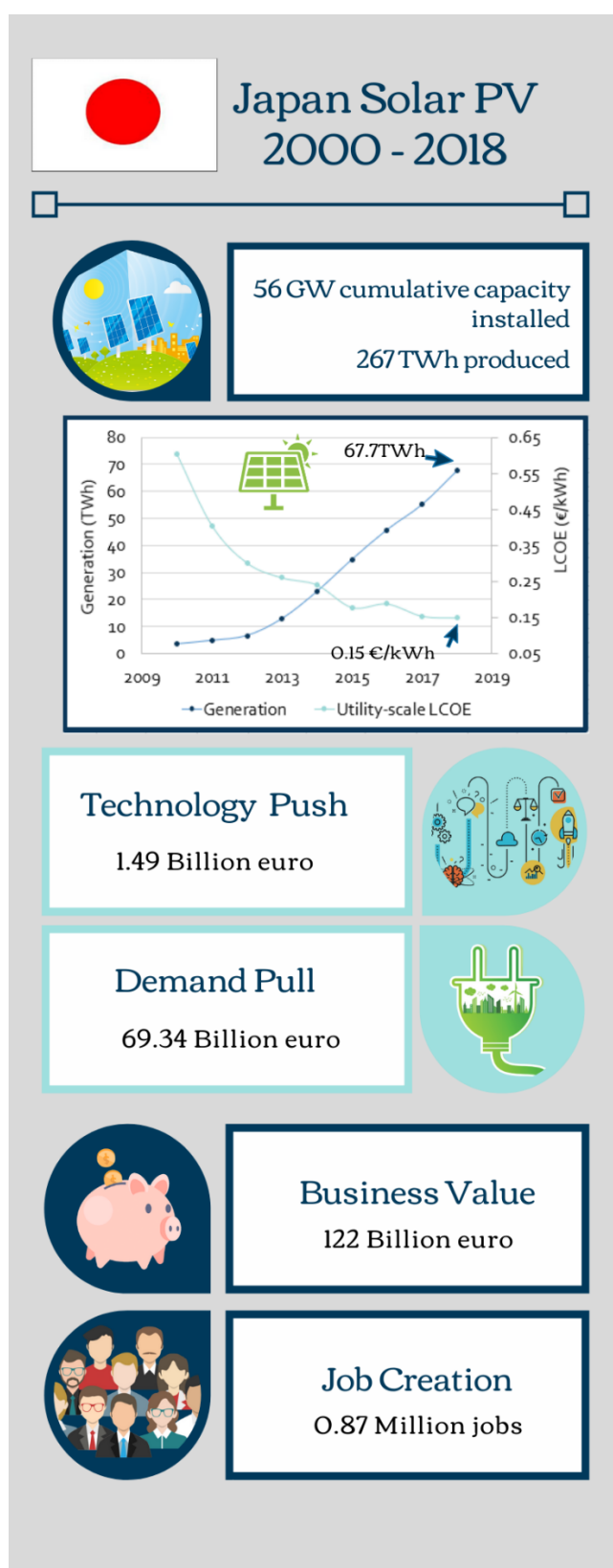


FIGURE 3.6: SUMMARY OF INDICATORS
(ABSOLUTE FIGURES OVER THE 2000–2018 PERIOD)
FOR JAPANESE SOLAR PV

This was followed by the **700 Roofs Subsidy Programme of 1993** to incentivise the installation of residential PV systems in the early 1990s [66]. The program ended in 2005 to stimulate cost reduction and establish the PV industry as a self-sustaining industry but with the declining market, it was restarted again in 2009. Until 2013, approx. **€3 bn were spent under this investment subsidy program**. The subsidy program was quite influential in establishing Japan as a market leader in the 2000s. In fact, by the early 2000s, Japan was responsible for half of the global cumulative installed capacity and produced half the global supply [67]. However, despite being a global leader and achieving significant cost reduction, the Japanese solar PV sector soon ran into fierce global competition. Furthermore, technical, and institutional barriers until 2012 made it difficult for foreign competitors to enter the Japanese solar PV sector, which in turn made its modules and systems more expensive compared to German and Chinese components [58].

In 2012, **following the Fukushima disaster, the FiT program was introduced** to expand the Japanese solar PV sector beyond the residential market and increase the contribution of renewable energy in the energy mix. The program remains one of the main drivers for establishing the industrial and utility-scale PV systems in Japan [59]. Around **€66 bn** were spent under this programme from 2012–2018. A major spike in installations was seen post-2012 (refer to Figure 3.7 below) that once again established Japan as one of the top countries in the global PV market. **Japan's installation peaked, representing 18% of the world's installation growth in 2013 while in 2015 it saw its highest annual installed capacity with approx. 11 GW of solar PV installed** [58]. During this period, the

LCOE decreased by 75% from 0.60 €/kWh in 2010 to 0.15 €/kWh in 2018 [50]. However, despite the massive deployment that took place during this period, the cost reductions under the Japanese solar PV have been quite modest. This could be because the installation costs and installation time are on a higher scale for the Japanese PV sector, comparatively higher than German Solar PV [68].

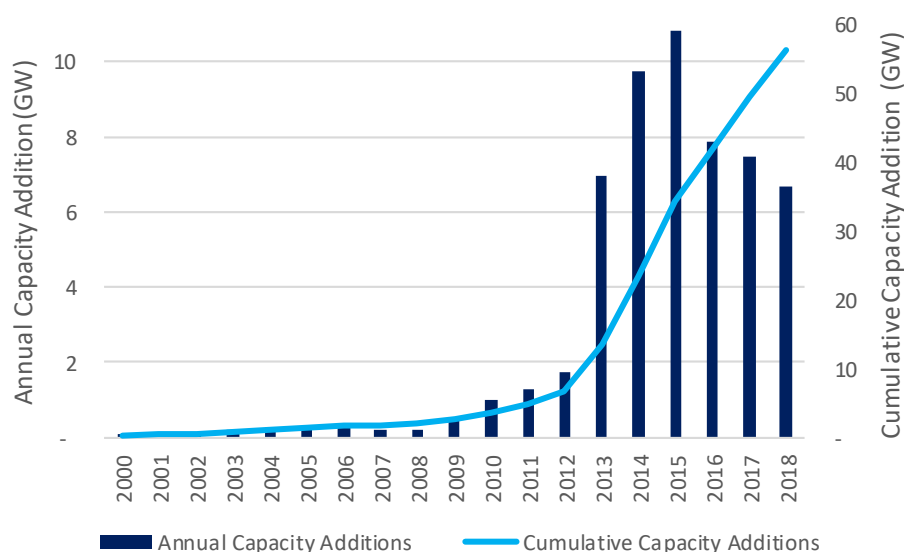


FIGURE 3.7: ANNUAL AND CUMULATIVE SOLAR PV CAPACITY ADDITIONS IN JAPAN BETWEEN 2000 AND 2018

However, **decreasing FiT rates for smaller systems dampened expectations and the annual solar PV installations started to reduce from 2015**. This was further impacted by interconnection and citing issues for large systems and fierce global competition, which drove its steady decline. Japan's global market shares fell from **50% in 2004 to 3% in 2016** [67]. Towards the end of 2017, a tendering scheme was introduced under the FiT scheme. However, with land availability and grid connection concerns becoming serious issues, most of these auctions have so far been undersubscribed and have failed to garner the intended support. Instead, the changes under the FiT mechanism (FiT rates cuts and auction procurement system) have **driven many solar companies to bankruptcy**, and it is expected to intensify further. In 2018 alone, around 95 solar companies went bankrupt. [65] At the same time, with solar prices in Japan still higher than average and an opportunity to show high-efficiency products, this could prove to be an opportunity for international companies to enter the Japanese solar PV market.

With declining annual solar PV installation, the **economic benefits perceived from PV plant installation also continued to fall**. As seen in Figure 3.8, from 2012–2015, the business value of the solar PV sector along with the number of jobs created reached its highest maximum and then declined slowly. From 2000–2018, the Japanese solar PV sector was **worth €122 bn with a total spend of approx. €71 bn**. Within this same period, the sector also created approx. **0.9 million jobs**.

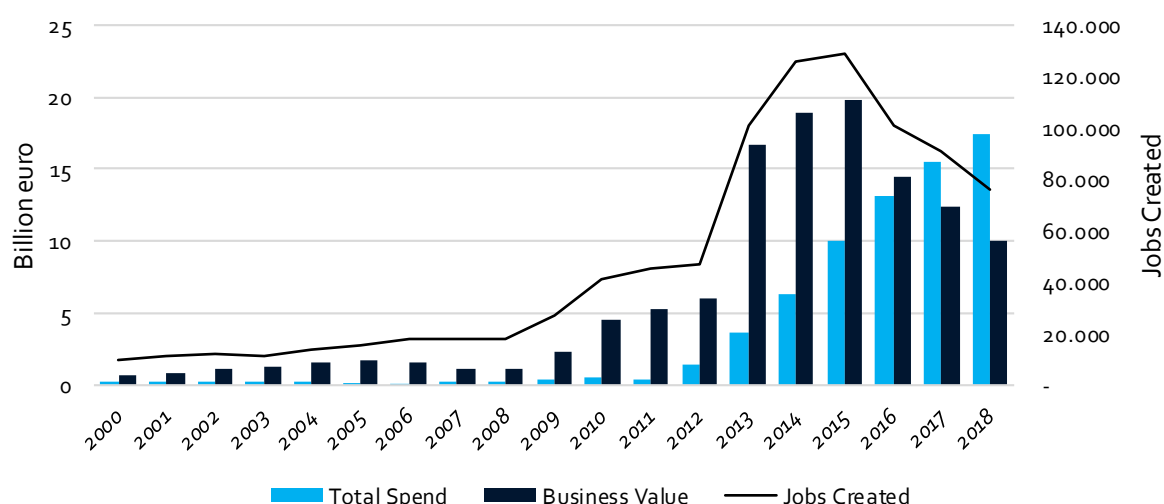


FIGURE 3.8: TOTAL SPEND, BUSINESS VALUE AND JOBS CREATED IN JAPAN SOLAR PV BETWEEN 2000 AND 2018

To understand the effectiveness of the support mechanisms implemented by the Japanese government in the solar PV sector, Table 3.10 presents a summary of the ratios. As seen, this energy sector has created approx. **3.4 jobs per GWh produced** with business value to generation ratio of nearly **454.22 €/MWh between 2000 and 2018**. It can also be said that approx. **12 new jobs were created between 2000 and 2018 for every €m invested** in these support mechanisms. The investments in TP and MP are equivalent to €11.75 and €548.14 per capita respectively. It is worth highlighting that the sector has **invested over 46.6 times more in MP mechanisms than in TP**. In 2018, the solar PV sector also achieved a **penetration level of 6.5%** in the overall energy mix.

TABLE 3.10: SUMMARY OF METRICS ANALYSING THE COST-BENEFITS OF THE JAPANESE SOLAR PV SECTOR

Metrics	Japanese solar PV
Employment to Generation (Jobs/GWh)	3.3
Turnover to Generation (€/MWh)	454.2
Market-pull to Technology-Push	46.62
Technology-Push to Generation (€/MWh)	5.56
Market-pull to Generation (€/MWh)	259.14
Spend to Generation (€/MWh)	264.70
Turnover to Spend* (~ROI)	1.72
Jobs to Spend* (Jobs/€ M)	12.28
Technology-Push per capita (€/capita)	11.75
Market-pull per capita (€/capita)	548.14
LCOE reduction between 2010 and 2018 (%)	-75%
Learning rate between 2010 and 2018 (%)	15%
2018 Penetration level in national electricity mix (%)	6.5

*Spend is defined as the sum of the investment in both TP and MP support

3.3 CASE STUDY 3: GERMAN ONSHORE WIND

Onshore wind has become the main renewable source of electricity generation in Germany [69]. This generating technology experienced rapid growth in the country due to both TP and MP support mechanisms. This section presents a review of the evolution of the German onshore wind sector like that of the German solar PV sector in section 3.1. First, different indicators are collated to review the technical, financial, and economic performance of the German onshore wind sector. This section describes the main sources of information and outlines any assumptions or calculations required for our analysis. Later, a discussion section analyses the efficacy of the support mechanisms and their effect on the development of the sector and the German economy. No data gaps exist under this case study.

3.3.1 TECHNICAL INDICATORS

Table 3.11 summarises the technical indicators used in the analysis. These include (annual and cumulative) installed capacity, generation, LCOE and capacity factor.

TABLE 3.11: DESCRIPTION OF TECHNICAL INDICATORS AND SOURCES FOR THE GERMAN ONSHORE WIND SECTOR

	Capacity	Generation	LCOE	CF
Year	2000-2018	2000-2018	2000-2018	2000-2018
Units	MW	GWh	€/kWh	%
Data Source	Working Group on Renewable Energy Statistics Report [49]	Working Group on Renewable Energy Statistics Report [49]	IRENA Report [50]	IRENA Report [50]
Conversion Factor	None	None	None	None
Calculations	None	None	EUR 0.85 = USD 1.00	None
Assumptions	None	None	Weighted Average LCOE	Weighted Average CF
Gaps	None	None	None	None

As in the case of German solar PV, the figures corresponding to installed capacity (MW) and electricity generation (GWh) were obtained from the report “Time series for the development of renewable energy sources in Germany” published by the Working Group on Renewable Energy Statistics [49]. Because the numbers were directly available, no assumptions or calculations were necessary nor were any conversion factors required. The data was available for the period 2000–2018.

The data for LCOE in €/kWh were procured from the 2019 IRENA Report [50] for the years 2000–2018 and converted to euro at an exchange rate of EUR 0.85 to USD 1.00. No gaps exist under this indicator. The capacity factors have also been sourced from the 2019 IRENA Report [50] for the years 2000–2018. No calculations or conversions were involved nor does any gap exist under this indicator.

3.3.2 FINANCIAL INDICATORS

The financial indicators and their sources are summarised in Table 3.12 below. The financial support offered by the German government for onshore wind is quite similar to that available to the solar PV sector and reviewed in section 3.1.2. Therefore, the financial indicators used in our analysis include federal energy research funding (€m), total annual subsidies and premiums spend (€bn) and total annual capital expenditure for the construction of the wind parks (€bn). The federal energy research programmes (€m) have been the main technology-push funding mechanism and the FIT scheme (€bn) has been the most prominent market-pull funding mechanism.

TABLE 3.12: DESCRIPTION OF FINANCIAL INDICATORS AND SOURCES FOR THE GERMAN ONSHORE WIND SECTOR

	Investment	Federal Energy Research Funding	Annual FIT Spend
Year	2000–2018	2000–2018	2000–2018
Units	€bn	€m	€m
Data Source	Working Group on Renewable Energy Statistics Report [49]	Evaluation of Energy Research Programme Renewable Energies Reports and Federal Ministry for Economic Affairs and Energy Report [51, 52, 53]	Federal Ministry for Economic Affairs and Energy Report [54]
Conversion Factor	None	None	None
Assumptions	None	None	None
Gaps	None	None	None

The data for federal energy research funding has been procured from reports put together by the German government and is also supported by scientific literature evaluating the federal research programmes [51, 52, 53]. No assumptions were made nor were any conversion factors required. The available data is complete for the period 2000–2018.

The data for the annual investment and the annual subsidies and premiums spend has also been procured from reports put together by the German government [54] and it does not involve any assumptions or conversion factor. The available data is complete for the period 2000–2018.

3.3.3 ECONOMIC INDICATORS

The economic indicators used in the analysis of the German onshore wind sector are summarised in Table 3.13 and include economic stimuli from the operation of onshore wind farms and gross employment created by the German onshore wind sector.

TABLE 3.13: DESCRIPTION OF ECONOMIC INDICATORS AND SOURCES FOR THE GERMAN ONSHORE WIND SECTOR

	Economic stimuli	Gross employment
Year	2000–2019	2000–2018
Units	€bn	—
Data Source	Working Group on Renewable Energy Statistics [49]	Federal Ministry for Economic Affairs and Energy Report [55]
Conversion Factor	None	None
Assumptions	None	None
Gaps	None	None

Economic stimulus (€bn) is a representation of the economic benefit generated by the German onshore wind sector through the demand of services and products from other economic sectors. This indicator includes, for example, the revenue from operation and maintenance services, fuel demand, and auxiliary services, among others. The data has been procured from a report published by the German government [69] and it does not involve any assumptions or calculations. No conversion factor has been necessary, and the available data is for the complete set of years.

Gross employment is used as a representation of the gross number of jobs generated under this sector and have also been collated from an official Federal report [55]. No assumptions were involved nor were any calculations necessary. The time series is complete for the period 2000–2018.



3.3.4 DISCUSSION

Key Findings: German Onshore Wind

- ▶ The German onshore wind market is the largest in Europe and one of the top five markets in the world.
- ▶ Wind energy has become Germany's main renewable energy generating technology with its cumulative capacity exceeding 52 GW in 2018.
- ▶ FiTs are funded through consumer prices setting the financial burden of the German energy transition on the shoulders of small energy consumers.
- ▶ Between 2000 and 2018, the FiTs and premiums for the German onshore wind sector totalled €74.5 bn; this is equivalent to 89.97 €/MWh of energy produced or 47.2 €/capita per year.
- ▶ In contrast, the investment on technology-push for the German onshore wind sector has been more modest, totalling €634 m between 2000 and 2018. This is equivalent to 0.766 €/MWh or €0.40 per capita per year invested between 2000 and 2018, i.e. over 117 times more investment in market-pull mechanisms than in technology-push.
- ▶ The German onshore wind sector has created €19.2 bn between 2000 and 2018 in economic benefits as well as 1.7 million jobs.
- ▶ Important R&D activities and innovations have happened at the company level and in response to market-pull support.
- ▶ The LCOE has decreased from 0.13 €/kWh in 2000 to 0.06 €/kWh in 2018.
- ▶ Research suggests that the German onshore wind has reached a lock-in state.
- ▶ Installations have started to decline since 2018.

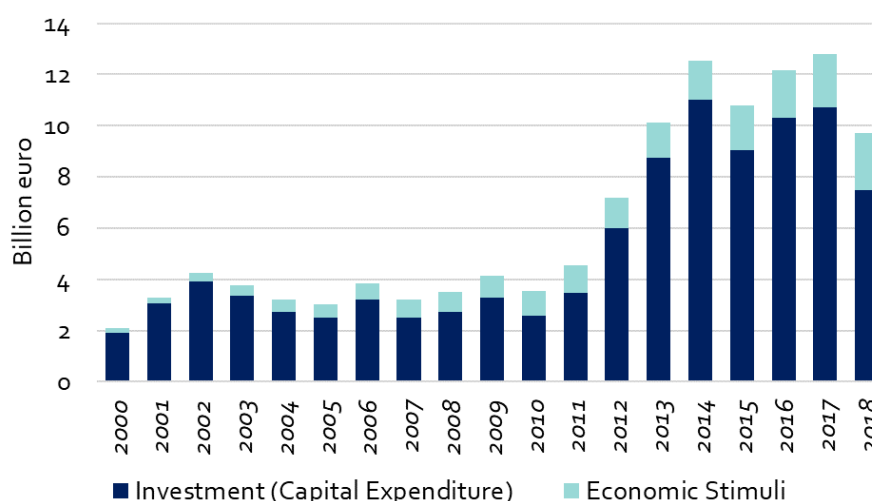


FIGURE 3.9: INVESTMENT AND ECONOMIC BENEFIT UNDER THE GERMAN ONSHORE WIND SECTOR BETWEEN 2000 AND 2018

Currently, the **German onshore wind market is the largest in Europe and one of the top five markets in the world** [70]. The share of wind energy has increased rapidly over the last few decades from nearly 2% of the gross energy consumed in 2000 to approx. 15% in 2018 [71]. This energy source has become **Germany's main renewable energy generating technology with a cumulative capacity exceeding 52 GW in 2018** [49]. Germany plans to generate 60% of its electricity from renewable energy sources by 2035 and wind energy is expected to be the leading generating technology [72]. Figure 3.10 shows that, contrary to the solar PV sector (c.f Figure 3.4), the onshore wind sector grew at historically higher rates between 2014 and 2017.

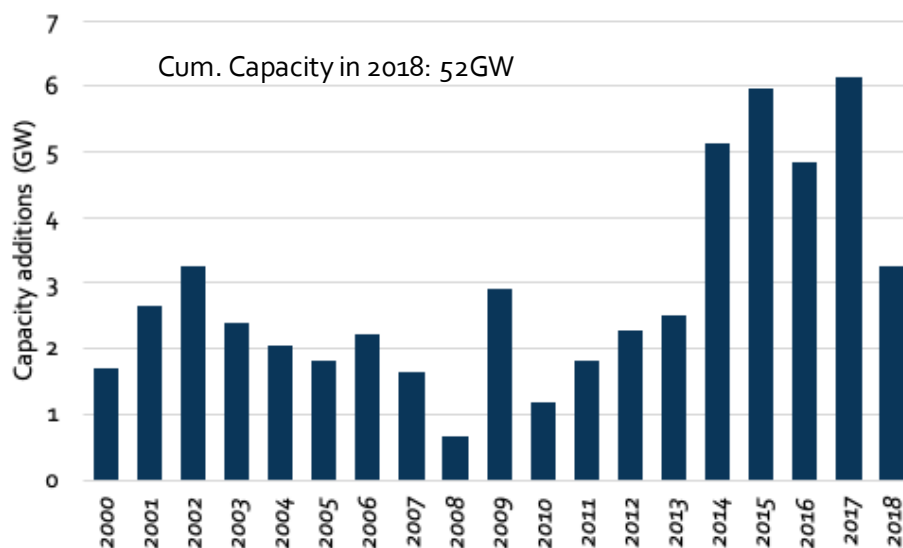


FIGURE 3.10: ANNUAL ONSHORE WIND CAPACITY ADDITIONS IN GERMANY BETWEEN 2000 AND 2018

The rapid growth of the German onshore market is partly due to supporting policies and instruments such as the Renewable Energy Act and the "Energiewende". It is after the introduction of these frameworks that both the solar PV and onshore wind sectors experienced a swift development in the country. On the one hand, these frameworks have enabled **market-pull mechanisms that have been the cornerstone driving the fast expansion of the onshore wind installed capacity** in Germany and strengthen its key role in the "Energiewende". On the other hand, the **Federal energy research programme has supported the German wind energy innovation path**.

Feed-in-tariffs, Germany's most prominent market-pull mechanism, are funded through consumer prices and the so-called Renewable Energy Act (EEG) levy. However, energy-intensive industries such as the car industry are virtually exempt of this contribution paying only 0.05 €/kWh to the EEG levy and setting the financial burden of the German energy transition on the shoulders of small energy consumers that paid 0.68 €/kWh in 2018 to the EEG levy [73]. Between 2000 and 2018, the feed-in-tariffs and premiums for the German onshore wind sector totalled €74.5bn, this is equivalent to 89.97 €/MWh of energy produced or 47.20 €/capita per year (Table 3.14). It can be said that the increasing market-pull funding, seen in Figure 3.11, mirrors the increasing energy costs of the German energy transition.

TABLE 3.14: SUMMARY OF METRICS ANALYSING THE COST-BENEFITS OF THE GERMAN ONSHORE WIND SECTOR

Metrics	German Onshore Wind
Employment to Generation (Jobs/GWh)	2.1
Turnover to Generation (€/MWh)	23.17
Market-pull to Technology-push	117
Technology-Push to Generation (€/MWh)	0.77
Market-pull to Generation (€/MWh)	89.97
Spend to Generation (€/MWh)	90.74
Turnover to Spend* (~ROI)	0.26
Jobs to Spend* (Jobs/€m)	23.4
Average Technology-Push investment per capita per year (€/capita per year)	0.4
Average Market-pull investment per capita per year (€/capita per year)	47.2
LCOE reduction between 2000 and 2018 (%)	-52.6
Learning rate between 2000 and 2018 (%)	36
2018 Penetration level in national electricity mix (%)	15.4

*Spend is defined as the sum of the investment in both TP and MP support

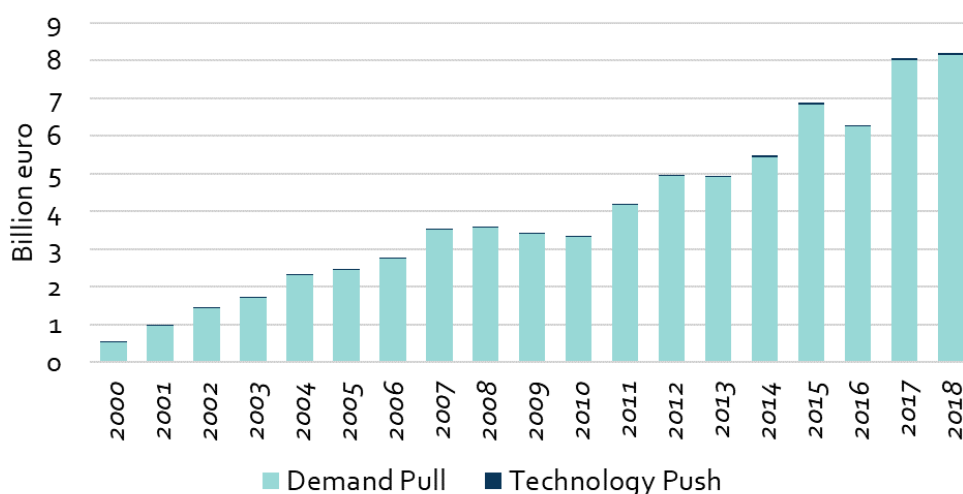
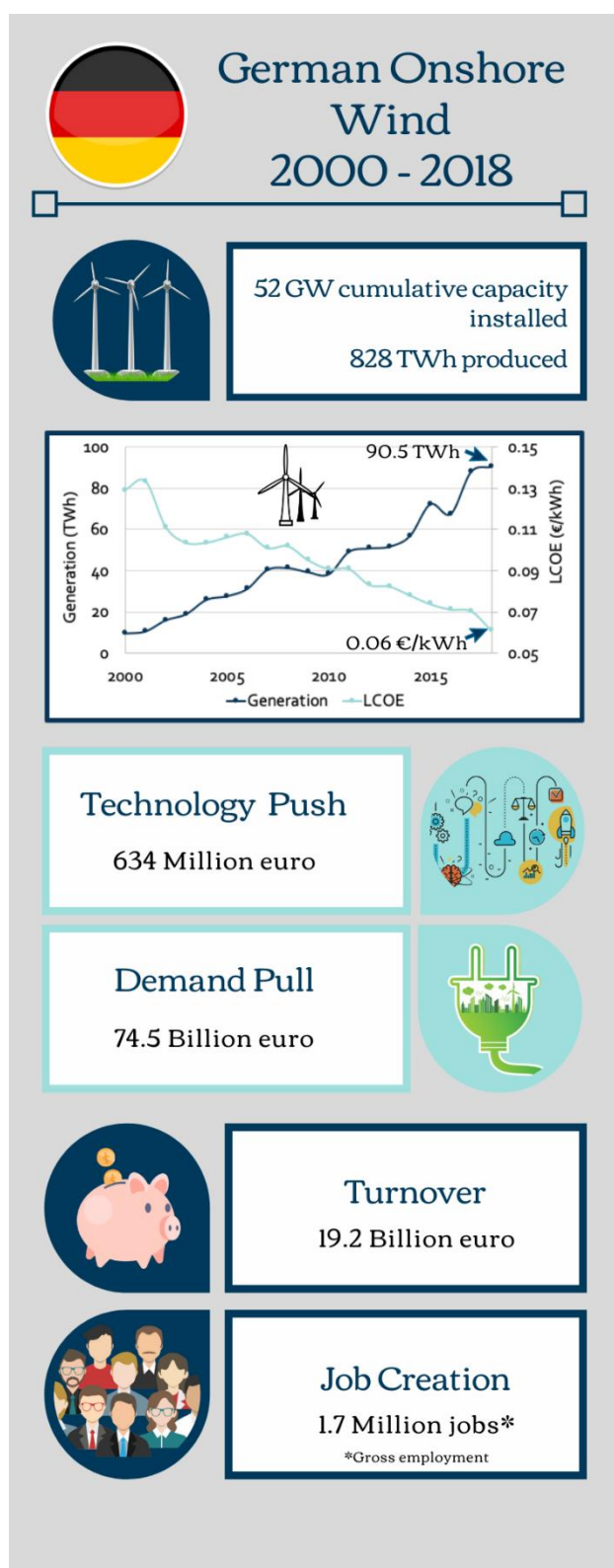


FIGURE 3.11: FUNDING AVAILABLE TO THE GERMAN ONSHORE WIND SECTOR THROUGH MARKET-PULL AND TECHNOLOGY-PUSH SUPPORT MECHANISMS BETWEEN 2000 AND 2018

Also, although the higher levels of wind energy (and, in general, renewable energy) generation have lowered the electricity purchase prices on the spot and futures markets, these reductions have mostly benefited large corporate customers and energy providers, not individual customers that do not purchase electricity on the stock market but from supply contracts and according to fixed prices [74]. This situation has led to critique and questions regarding the merit and financial sustainability of the feed-in-tariffs and the “Energiewende” in Germany.

Only a modest 0.77 €/MWh produced or 0.4 €/capita per year have been invested in technology-push for the German onshore wind sector between 2000 and 2018. Germany has invested over 117 times more in market-pull mechanisms for the onshore wind sector than in technology-push. The



feed-in-tariff scheme has indirectly promoted up-scaling of turbines and/or re-powering and nearly neglected the need to develop the network infrastructure connecting the many wind farms in the north of the country and the energy-intensive manufacturing industries in the south of the country. The large financial burden of the FiT scheme has limited the funding available for wind-related innovations such as low-wind speed area turbines or super-grids and has stimulated offshore developments in recent years. **Important R&D activities and innovations have happened at the company level and in response to market-pull support.** For example, the German manufacturer Enercon developed the Direct-Drive to improve efficiency and reliability in onshore wind turbines [74]. The weighted average **LCOE** of German onshore wind farms **has fallen from 0.13 €/kWh in 2000 to 0.06 €/kWh in 2018**, a decrease of over 52%.

As seen in Figure 3.13, the Danish manufacturer Vestas and the German manufacturer Enercon have been the main suppliers of turbines in the country [74] [75]. However, other important suppliers include German Senvion and Nordex, German-Spanish Siemens Gamesa, American GE Electric and Chinese Vensys (partly owned by Goldwind). The involvement of various German manufacturers and the booming onshore wind capacity in Germany, as well as the world, have brought along benefits to the German economy and society. The German onshore wind sector has created **€19.2bn between 2000 and 2018 in economic benefits** as well as **1.7 million jobs⁶** in the same period. Comparing the total funding for technology-push and market-pull mechanisms targeting the German onshore wind sector to the economic benefits received

FIGURE 3.12: SUMMARY OF INDICATORS (ABSOLUTE FIGURES OVER THE 2000–2018 PERIOD) FOR GERMAN ONSHORE WIND

⁶ This figure refers to gross employment in the German onshore wind sector between 2000 and 2018.

from the operation and maintenance of German onshore wind farms between 2000 and 2018, the return of investment is nearly 26%.

Research suggests that the German onshore wind has reached a lock-in state with technological innovations focusing on turbine size and up-scaling generation [74] [76]. Installations have started to decline since 2018 due to lengthy permitting processes, NIMBY-ism⁷ and lack of land, increasing climate change scepticism, among other challenges [74] [76]. To meet the targets of the “Energiewende” and continue promoting growth in the German onshore wind sector, Germany might have to consider alternatives such as smart grids, local smart energy systems or electro-mobility and balance the output-focused incentives with investment in R&D.

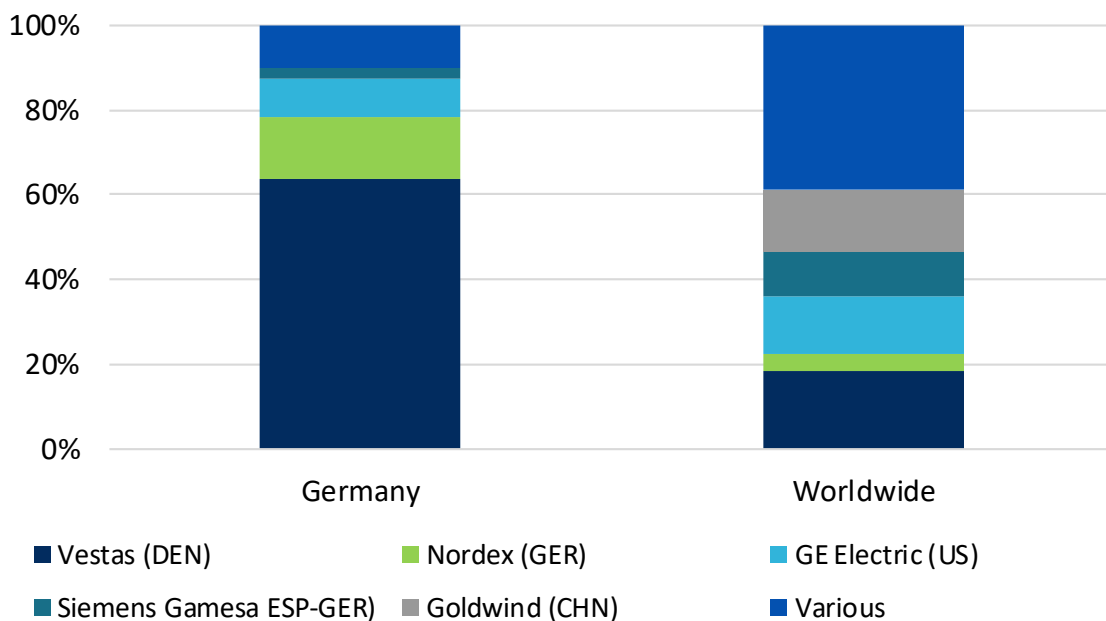


FIGURE 3.13: MARKET SHARE BY NEWLY INSTALLED ONSHORE WIND CAPACITY IN GERMANY AND THE WORLD IN 2019. SOURCE: [75]

3.4 CASE STUDY 4: DANISH (ONSHORE AND OFFSHORE) WIND

Wind energy has long been part of the Danish energy mix. Denmark is the pioneer of wind energy development in Europe. The first energy plans — suggested by independent energy experts after the oil crises in 1973 and 1979 — proposed wind power as one of the key alternatives to the unpopular nuclear power proposal put forth by the Danish parliament [77, 78]. By the early 1980s, several manufacturers were producing wind turbines in Denmark. The high costs of these turbines were

⁷ NIMBY stands for “Not In My Back-Yard” and refers to the opposition of local citizens to the installation of wind farms in their local area https://onlinelibrary.wiley.com/doi/epdf/10.1002/wcc.250?saml_referrer

prohibitive for individual owners, and the concept of local wind cooperatives arose. Coupled with tax incentives offered to energy-generating communities, community-owned wind turbines expanded swiftly throughout the country [19]. Additionally, the Danish government set ambitious targets for utilities to install wind power and provided capital grants and subsidies fostering new wind installations [79]. Some of the subsidies introduced continued to be available through research funds into the mid-2000s. In the early 1990s, a fixed feed-in-tariff was introduced for Danish wind projects along with a refund from the Danish carbon tax and a partial refund on the energy tax.

These incentives enabled cooperatives supporting wind power in Denmark and nearly 100,000 households to have installed 86% of all turbines in the country by 2001 [19]. The turn of the century saw the liberalisation of the Danish electricity market. With this, Denmark decided to abandon its FIT scheme and support renewable energy through a renewable portfolio standard (RPS) mechanism and a system of tradable green certificates. By 2003, all wind generators were connected to the grid under the new RPS.

Later, in 2008, the Danish government committed to making improvements in energy efficiency, promoting renewable energy and technological development. Funding for research, development, and demonstration (RD&D) was made available to help meet these targets. This coincided with many of the wind turbines installed in the 1980s and 1990s reaching the end of their lifetime and the need for repowering. Therefore, as part of Denmark's Energy Strategy 2050 [80] introduced in 2011, the Danish government committed to:

- ▶ 100% renewable energy system by 2050,
- ▶ 100% renewable electricity and heat by 2035 and
- ▶ Supplying half of the traditional electricity consumption through wind energy by 2020.

With these targets and the financial support for technology-push and market-pull mechanisms, the Danish wind sector is expected to expand and be the backbone of the Danish energy transition. This expansion will be accompanied by the expansion of the electricity network and financed through a Public Service Obligation (PSO) scheme via the energy bill.

The wind industry has become a fundamental part of both the Danish economy and the energy transition. It is one of the most significant exporting industries with some world-leading manufacturers such as Vestas and Siemens-Gamesa based in the country. Furthermore, Denmark was the first European country to introduce the FiT system and significant subsidies for R&D [19]. The country is also a pioneer in smart energy systems and decarbonisation of energy sectors heavily reliant on fossil fuels such as heating and transport [81].

Therefore, the case of Denmark can provide relevant lessons learned for the promotion of renewable energy and the efficacy of technology-push and market-pull mechanisms to support the commercialisation of these technologies. This section reviews the technical, financial, and economic performance of the Danish wind energy sector between 2000 and 2018. First, the indicators used to build this case study are presented and, later, an analysis is carried out seeking to assess the



development of the Danish wind energy sector. No gaps exist under this case study, but we have highlighted some questions towards the end of this case study.

3.4.1 TECHNICAL INDICATORS

The indicators used to describe the technical development of the Danish wind energy sector include annual installed capacity, annual generation, LCOE and capacity factor (CF), summarised in Table 3.15 below. The data corresponding to capacity and generation has been procured from the Danish Energy Agency [82] whilst the data corresponding to LCOE and CFs has been retrieved from IRENA's Renewable Power Generation Costs report [50]. It is worth highlighting that the LCOE figures refer to the weighted average LCOE for onshore wind projects and do not include offshore wind energy. Also, the costs were converted to euro using an exchange rate of EUR 0.85 to USD 1.00. The CFs refer solely to onshore wind. In 2018, onshore wind accounted for 49.5% of the total installed capacity in Denmark, whilst offshore wind accounted for 18.9% [83]. These technologies generated 44.6% and 22.3% of the country's total electricity generation in 2018 respectively [83]. The time series are complete for the period 2000–2018. No calculations or conversion factors were necessary.

TABLE 3.15: DESCRIPTION OF TECHNICAL INDICATORS AND SOURCES FOR THE DANISH WIND SECTOR

	Capacity	Generation	LCOE	CF
Year	2000–2018	2000–2018	2000–2018	2000–2018
Units	MW	GWh	2018 \$/kWh	%
Data Source	Danish Energy Agency [82]	Danish Energy Agency [82]	IRENA Report [50]	IRENA Report [50]
Conversion Factor	None	None	None	None
Calculations	None	None	None	None
Assumptions	None	None	Onshore, Weighted Average LCOE	Onshore, Weighted Average CF
Gaps	None	None	None	None

3.4.2 FINANCIAL INDICATORS

Under financial indicators, we have R&D funding as the main technology-push funding mechanism and total annual FIT spend as the market-pull funding mechanism, summarised in Table 3.16.

Denmark has numerous government-funded energy programmes, the details of which are publicly available [84]. The details of all Danish allocated energy research, development, and demonstration projects, funded to date by these programmes were downloaded and collated in order to estimate the amount of technology-push funding made available to the Danish wind sector. No assumptions were made, and the amounts were converted from Danish krone (DKK) to euro using an exchange rate of DKK 1.00 to EUR 0.13. The data is available for the period 2000–2018, i.e. there are no gaps in the time series.



Wind energy support in Denmark is mainly funded through the Public Service Obligation (PSO) scheme, which is paid by all consumers as part of their electricity bill [85]. Thus, the total yearly expenses for the PSO are used as the data for market-pull funding available for the Danish wind sector [86, 87]. The available data is complete for the period 2000–2018 and does not include any assumptions. However, since the information was available in Danish Krone, the amounts were converted to euro using the same exchange rate as in the case of technology-push funding.

TABLE 3.16: DESCRIPTION OF FINANCIAL INDICATORS AND SOURCES FOR THE DANISH WIND SECTOR

	R&D Funding	PSO Expenses
Year	2000-2018	2000-2018
Units	€m	€m
Data Source	Energiforskning.dk [84]	Danish Energy Agency and CEPOS Report [86, 87]
Conversion Factor	DKK 0.13 = EUR 1.00	DKK 0.13 = EUR 1.00
Assumptions	None	None
Gaps	None	None

3.4.3 ECONOMIC INDICATORS

The economic indicators used in this case study include annual turnover and jobs created under the Danish wind sector summarised below in Table 3.17. The figures for both annual turnover and jobs created have been procured from the report published by Wind Denmark [88]. The available data is complete and does not include any assumptions. However, because the data for annual turnover was available in Danish Krone (DKK), the figures were converted to euro using an exchange rate of DKK 1.00 to EUR 0.13.

TABLE 3.17: DESCRIPTION OF ECONOMIC INDICATORS AND SOURCES FOR THE DANISH WIND SECTOR

	Annual Turnover	Jobs Created
Year	2000-2018	2000-2018
Units	€bn	—
Data Source	Wind Denmark Report [88]	Wind Denmark Report [88]
Conversion Factor	0.13 DKK = 1.00 EUR	None
Assumptions	None	None
Gaps	None	None

3.4.4 DISCUSSION

Key Findings: Danish Wind

- ▶ Denmark is the country with the largest share of wind energy in its electricity mix. Wind energy source supplied approx. 40% of the country's electricity in 2018.
- ▶ Wind energy is Denmark's main renewable energy generating technology with a cumulative capacity exceeding 6 GW in 2018.
- ▶ Denmark was the first country to introduce a feed-in-tariff and significant subsidies for RD&D in the wind energy sector.
- ▶ Between 2000 and 2018, the market-pull funding for the Danish onshore wind sector totalled €5 bn, this is equivalent to 32 €/MWh of energy produced or 48.8 €/capita per year.
- ▶ Conversely, €217 m have been invested in technology-push for the Danish wind sector between 2000 and 2018, i.e. 1.3 €/GWh produced or €2 per capita per year.
- ▶ Denmark has invested over 24 times more in market-pull mechanisms than in technology-push.
- ▶ The LCOE has decreased by approx. 96% from 0.11 €/kWh in 2000 to 0.04 €/kWh in 2018.
- ▶ The Danish wind sector is thriving, generating €181 bn between 2000 and 2018 in turnover as well as 509,587 jobs.

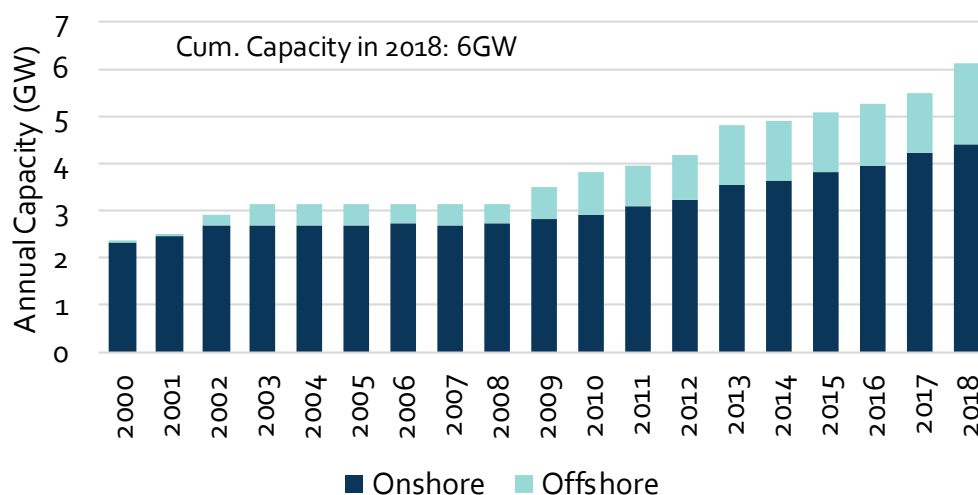


FIGURE 3.14: ANNUAL CUMULATIVE INSTALLED CAPACITY UNDER THE DANISH ONSHORE AND OFFSHORE WIND SECTORS BETWEEN 2000 AND 2018

The Danish wind energy sector is thriving. This sector has become an important source of revenue and employment in the country. Denmark is the largest global exporter of wind turbines with Vestas supplying approx. one-fifth of the global market in 2019 (c.f. Figure 3.13). However, Denmark also exploits its wind energy potential locally. In 2018, wind power production accounted for **40.2% of the domestic electricity supply** in Denmark [87]. Of this share, approx. two-thirds were produced from onshore wind farms [82]. The country's cumulative **wind capacity exceeded 6 GW in 2018**.



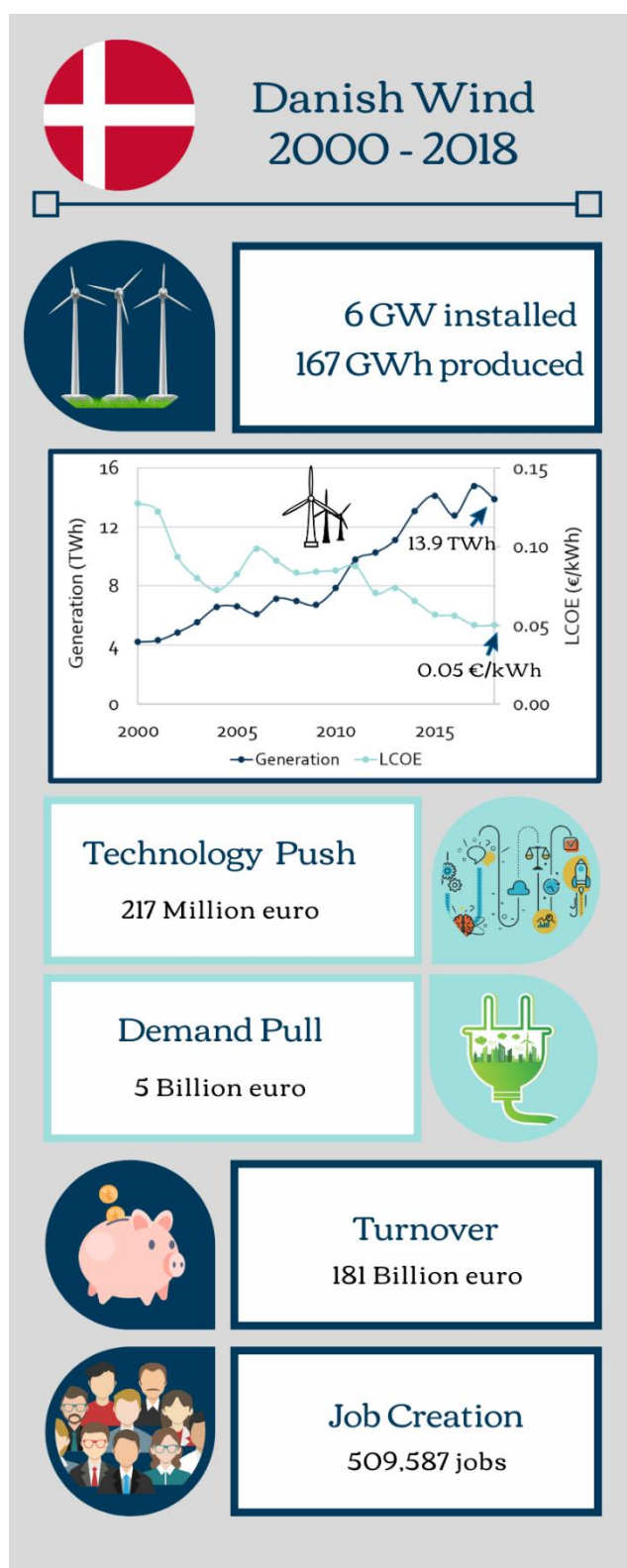


FIGURE 3.15: SUMMARY OF INDICATORS
(ABSOLUTE FIGURES OVER THE 2000–2018 PERIOD)
FOR THE DANISH WIND SECTOR

Denmark has been a pioneer promoting wind energy since the mid-1970s. Investment subsidies and (partial) refunds of taxes in the 1980s were essential for the rapid development of the installed capacity. These financial incentives have been accompanied by national targets and enabling policies resulting in a dynamic and continuously expanding domestic market. The country has also supported RD&D programmes for wind energy since the mid-1970s, which has strengthened its wind turbines manufacturing industry. The balance between RD&D expenditures, investment incentives, tax refunds and other financial instruments have supported both innovation and expansion of wind energy in Denmark.

Our analysis shows that, on the one hand, Denmark has invested **over €5 bn for market-pull mechanisms** targeting the wind energy sector between 2000 and 2018, this is **equivalent to 32 €/GWh** produced in that same period **or 48.8 €/capita annually** (see Table 3.18). On the other hand, the country has invested **€217 m in RD&D programmes** for the wind sector between 2000 and 2018. This is **equivalent to 1.3 €/GWh or 2 €/capita per year**. Denmark has invested 24.6 times more in market-pull mechanisms than in technology-push over the 2000–2018 period as seen in Figure 3.16.

This support has enabled **a reduction of approx. 96% of the levelised cost of energy** from wind in Denmark between 2000 and 2018. The LCOE has decreased from **0.11 €/kWh in 2000 to 0.04 €/kWh in 2018**.

The Danish wind sector has generated **nearly €181 bn in revenue between 2000 and 2018** and created **509,587 full-time jobs**. With ambitious decarbonisation targets, enabling policies and a liberalised electricity market,

Denmark is set to seize the advantages and benefits of wind energy and transition to a 100% renewable energy system and a thriving green economy with wind energy as the backbone of the country's energy system.

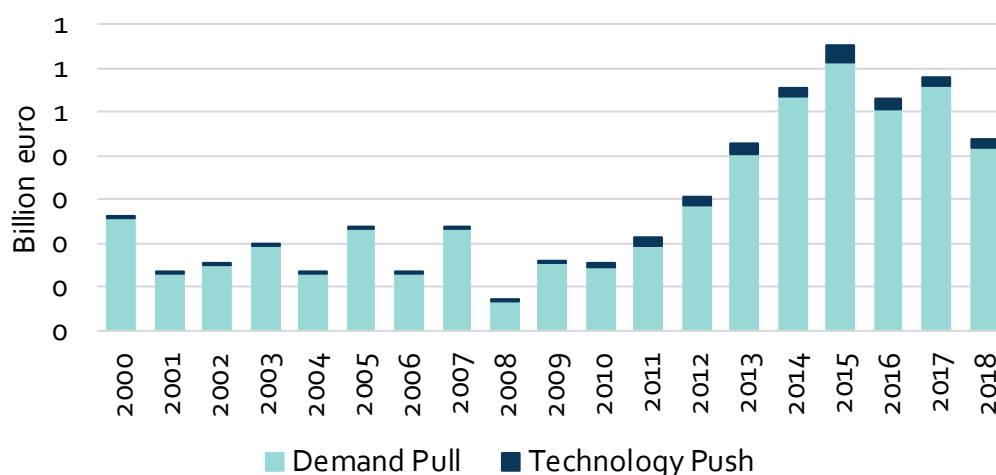


FIGURE 3.16: FUNDING AVAILABLE TO THE DANISH WIND SECTOR THROUGH MARKET-PULL AND TECHNOLOGY-PUSH MECHANISMS BETWEEN 2000 AND 2018

TABLE 3.18: SUMMARY OF METRICS ANALYSING THE COST-BENEFITS OF THE DANISH WIND SECTOR

Metrics	Danish Wind
Employment to Generation (Jobs/GWh)	3.1
Turnover to Generation (€/MWh)	1,084.92
Market-pull to Technology-push	24.6
Technology-Push to Generation (€/MWh)	1.3
Market-pull to Generation (€/MWh)	32
Spend to Generation (€/MWh)	33.3
Turnover to Spend* (~ROI)	35.4
Jobs to Technology-Push (Jobs/€m)	2,352.6
Average Technology-Push investment per capita per year (€/capita-year)	2.0
Market-pull investment per capita per year (€/capita-year)	48.8
LCOE reduction between 2000 and 2018 (%)	-95.7
Learning rate between 2000 and 2018 (%)	23
2018 Penetration level in national electricity mix (%)	40.2

*Spend is defined as the sum of the investment in both TP and MP support

4. QUANTIFYING THE COSTS OF COMMERCIALISING OCEAN ENERGY DEPLOYMENTS

4.1 OVERVIEW OF THE COST MODELLING METHODOLOGY

In terms of the overall cost-benefit analysis, the costs are taken as the **public investment required to reduce the LCOE of ocean energy**. This considers:

1. **Incremental cost reduction** through subsidising deployment.
2. **Step-change cost reduction** resulting from radical innovations.

The former will be largely a result of market pull (or demand pull) funding mechanisms, with the latter primarily achieved through technology push. However, it is important to note that both types of funding are required together for efficient innovation. Previous studies have often differentiated between learning by doing and learning by research, but this distinction is not made in the current analysis.

The modelling presents a range of possible scenarios, combining different mixes of step-change and incremental cost reductions. These are illustrated in terms of three pathways:

- 1) Incremental cost reduction driven through commercial deployment only.
- 2) Step-change cost reduction (through step-change innovation), where either:
 - a) deployment is delayed until a step-change cost reduction has been completed, or
 - b) deployment and step-change cost reductions happen in parallel.

These explore the amount of revenue support expenditure avoided during the technology's deployment phase, when greater investment and time are spent on early-stage step-change cost reduction. Essentially, this can explore the 'value' of early step-change innovation in achieving cost reduction in ocean energy. For pathway 2a) it is assumed that the step-changes in LCOE are achieved prior to significant subsidised deployment, following the approach of technology performance before technology readiness presented by Weber [89].

Due to the uncertainties around this kind of analysis, various scenarios and parameter ranges are included. The impact of the key parameters on overall investment are explored, with sensitivity analyses on other inputs. Round numbers have been used for clarity and to reflect the lack of certainty with which these inputs can be specified in this type of study.

The geographical scope of this modelling must be global. There are many companies around the world currently developing wave and tidal energy technologies, and this is expected to continue. The LCOE used in the modelling is a sectorial average as noted in section 2.3. Companies will also look to deploy technology globally, where the resource and economics are best suited to their projects.



4.2 INCREMENTAL COST-REDUCTION VIA SUBSIDISED DEPLOYMENT

4.2.1 MODEL APPROACH AND KEY ASSUMPTIONS

The incremental cost reduction model is based on the experience curve effect. Combined with a deployment trajectory, this creates LCOE-deployment and deployment-time relationships. These relationships are combined to give an LCOE varying with both deployment and time.

The calculation of total investment is a function of time, cumulative capacity deployed, and the LCOE when the technology was deployed, as shown in Figure 4.1. The model considers these three linked parameters, which have units of years (converted to hours by an annual capacity factor), MW, and €/MWh. Multiplying these gives the total learning investment in €, which is the purple shaded volume in Figure 4.1. It is also necessary to consider the lifetime of the subsidy when calculating the total subsidised energy generated by the required capacity deployed to achieve the desired cost reduction.

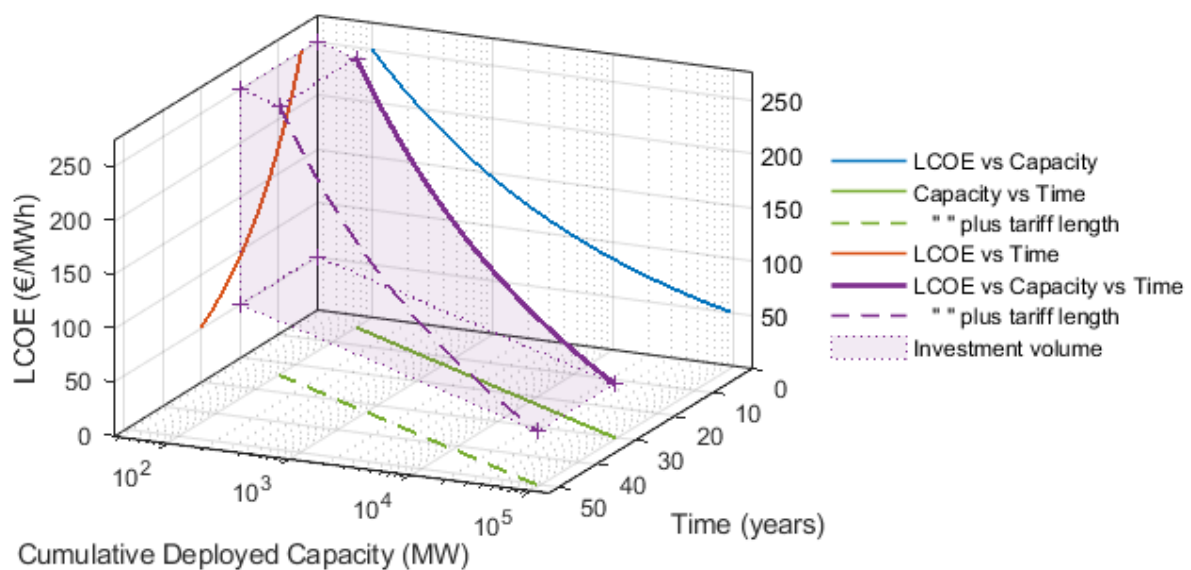


FIGURE 4.1: GRAPHICAL REPRESENTATION THREE AXES USED

As the LCOE of early-stage technologies is uncertain, as discussed in section 2.3, the base point of the experience curve is taken as first commercial arrays. The level of global cumulative deployment CDC_c for both wave and tidal sector commercialisation is taken to be 100 MW. The associated $LCOE_c$ is based on estimates discussed in section 2.3. The LCOE target was taken to reflect a long-term European wholesale market price (of around €/50/MWh); therefore, the modelling considers the required learning investment to meet present day cost competitiveness.

The LCOE learning rate LR of 15% is within the range of estimates presented in ocean energy sector reports [36]. This is slightly higher than typical CAPEX based learning rates used for wave energy sector economic modelling, as more sources of learning are included in an LCOE based learning curve [90], as discussed in section 2.2. As the LR values from marine renewable energy roadmaps are probably based on historical values from other sectors, the baseline rate of incremental cost reduction

used in this study may be optimistic, but this does not affect the key trends presented in the results section.

The base assumptions for the other model parameters are shown in Table 4.1. These were taken as round numbers for clarity, and sensitivity to these parameters is considered in the modelling.

TABLE 4.1: VARIABLES AND BASE CASE VALUES USED FOR INCREMENTAL DEPLOYMENT MODEL

Variable	Symbol	Base Case	Unit	Description
Learning Rate	LR	15	%	LCOE reduction per doubling of capacity [36, 91]
Initial cumulative deployed capacity	CDC_0	25 (wave) 40 (tidal)	MW	Cumulative global deployment ⁸ at $t = 0$ [45, 92]
Capacity at base point	CDC_c	100	MW	Cumulative deployed capacity at experience curve base point in model, corresponding to early commercial arrays
LCOE at base point	$LCOE_c$	350 (wave) 200 (tidal)	€/MWh	LCOE at experience curve base point in model, see section 2.3
LCOE target	$LCOE_{target}$	50	€/MWh	LCOE when calculation stops
Wholesale Market Price	WMP	50	€/MWh	Approximate long-term average European wholesale electricity price
Support Period	T_{sp}	20	Years	Revenue support mechanism duration
Rate of capacity Increase	R_{CI}	30 (base) 60 (faster)	%/year	Increase in cumulative deployed capacity per year (based on REN21 [93])
Capacity factor	cf	35	%	Device average power/rated power
Discount rate ⁹	DR	3.5	%	Social discount rate [94]

Several assumptions are made in the incremental cost reduction model:

- Capacity additions occur in monthly time steps following an exponential growth in cumulative deployed capacity until the LCOE reaches the target LCOE. Capacity additions after this point are considered un-subsidised and are excluded from the learning investment calculation.
 - Deployment in the model is insensitive to the technology's LCOE.
 - Due to data availability, the deployment trajectory is based on trends seen in the wind and PV sectors after >5 GW of deployed capacity [93]. Different deployment trajectory could be expected during early stages of deployment.
- Capacity factor variation is not included in the modelling. Trends from other sectors have shown this may increase over time, but its variation is considered too uncertain to include for a nascent RET.
- The revenue support level perfectly follows the sector experience curve. In reality, this would change in steps, where the support level remained at a set level for durations of time even as

⁸ This is the cumulative global wave/tidal energy capacity deployed from 2001 until the end of 2020.

⁹ The discount rate only affects the present value of the learning investment. This is because we are considering the present value of future government investments. The discount rate for individual projects will fall over time; however, this is included in the LCOE reductions, which the learning rate describes.

the sector's LCOE was reducing, leading to higher overall costs. Therefore, the learning investment presented in this study is an 'optimal level'.

4. The average WMP remains constant. In reality, this fluctuates both spatially and temporally due to factors including supply and demand, weather, changes in the energy mix, economic factors, etc. However, forecasting of and generic trends for future energy prices are outside the scope of this study.
5. The target LCOE is set as the WMP. Specific benefits could apply to individual technologies that increase their value (in terms of portfolio variety etc.) and variations in wholesale capture price may also shift the target LCOE. The target LCOE is, therefore, RET specific and could be varied for different technologies, but this has been excluded from the analysis.
6. The experience curve is smooth and continuous. Some historical experience curves have shown s-shapes [95] where slower learning happens at the beginning and at the end of a technology's deployment. However, as there is little consensus on how to deal with these in long-term extrapolations. Therefore, the s-shaped effect has not been considered.
7. Early commercial renewable energy technology projects (including wave energy) will likely rely on a mix of private finance and either government loans, grants, or investment subsidies etc. alongside revenue support [96, 5]. This was not modelled, and in theory, it should not affect the overall learning investment, but the structure of these financial instruments would be an important consideration for policymakers.

4.2.2 CALCULATION STEPS

As noted above, the calculation of total investment is a function of time, cumulative capacity deployed, and the LCOE when the technology was deployed. The cumulative deployed capacity CDC can either be interpolated from a matrix of future deployment targets per year, or it can be modelled as an exponential increase based on the existing capacity CDC_0 , the rate of capacity increase per year R_{CI} , and the fractional year t as (4.1). The LCOE is then defined using an experience curve (4.2), based on the CDC and $LCOE_c$ at the base point of the model, taken as first commercial arrays with deployed capacity CDC_c .

$$CDC = CDC_0 (1 + R_{CI})^t \quad (4.1)$$

$$LCOE_i = \begin{cases} LCOE_c & \text{if } CDC < CDC_c \\ LCOE_c \left(\frac{CDC}{CDC_c} \right)^{-b} & \text{otherwise} \end{cases} \quad \text{where } b = -\frac{\log(1-LR)}{\log(2)} \quad (4.2)$$

The model calculates outputs at discrete time steps. For the modelling presented in this study monthly time steps $\Delta t = 1/12$ were chosen to reflect a reasonable level of granularity considering sector-wide deployment. As the deployments have staggered start times and each one receives revenue support for a fixed duration $T_{support}$, a band matrix of subsidised generation hours is created for each individual deployment at each time step, noting that subsidy is paid for the energy generated not capacity deployed. In the generation matrix $Gen_{i,j}$, subscript i refers to a specific timestep and j to a specific deployment. The generation per step is a function of deployed capacity in that step dep_i and time step Δt multiplied by the capacity factor cf and average number of hours per year (8766) as equation (4.3). Conditional clauses 1&2 in equation (4.3) account for the lack of subsidised generation before the time of deployment ($i < j$) or after the length of the tariff $T_{support}$.



$$Gen_{i,j} = \begin{cases} 0 & \text{if } j < i & \text{(before deployment)} \\ 0 & \text{if } j \geq i + \frac{T_{support}}{\Delta t} & \text{(after tariff ends)} \\ dep_j \cdot cf \cdot \Delta t \cdot 8766 & \text{otherwise} & \text{(subsidised deployment)} \end{cases} \quad (4.3)$$

$$\text{where } dep_i = CDC_i - CDC_{i-1}$$

The investment for each cell in the generation matrix is then calculated by multiplying the generation matrix $Gen_{i,j}$ by the differential cost (difference between the LCOE and WMP) for each capacity step. Note that LCOE varies with the cumulative deployed capacity, and it is assumed that LCOE reductions will happen following each deployment. In the modelling, the LCOE does not continue to decrease once the target $LCOE_{target}$ is reached, although in reality this is likely.

$$Inv_{i,j} = Gen_{i,j} \cdot (LCOE_j - WMP) \quad (4.4)$$

To calculate the cumulative investment $CumInv_i$ at time t_i the columns of the investment matrix are summed (4.5). The total investment $CumInv_{total}$ is calculated by summing the entire investment matrix (4.6). The present value of these of these investments can also be calculated, discounted at rate DR .

$$CumInv_i = \sum_j Inv_{i,j} \quad (4.5)$$

$$CumInv_{total} = \sum_i \sum_j Inv_{i,j} \quad (4.6)$$

The main outputs from the model are the total deployment in GW at which the LCOE target is met, the time this takes in years, time series of the investment, and the total investment required to subsidise this deployment, both discounted and undiscounted.

4.3 STEP-CHANGE COST REDUCTIONS FROM RADICAL INNOVATION

4.3.1 APPROACH AND KEY ASSUMPTIONS

The approach to step-change cost reductions is based on a competitive stage-gate innovation programme, similar to the Wave Energy Scotland procurement programme.

It is postulated in this work that novel subsystem(s) with lower capital costs (CAPEX), operational costs (OPEX), increased annual energy production, or some combination thereof can be implemented within an existing ocean energy device. This results in a step-change reduction in LCOE. Implementing these would require development, integration, and demonstration, which can be split into two overall stages:



1. Novel subsystems are developed in a competitive staged approach, with stages corresponding to those developed by IEA OES task 12, aligned to IEC specifications¹⁰ and other guidance, linked to the TRL scale as shown in Table 4.2. Stage 0 refers to concept creation, which would happen before a structured programme, and stage 5 refers to the first commercial arrays that would likely be funded through a market pull subsidy. Concepts would either enter at Stage 1 or enter at a later stage by incorporating technology transfer from other sectors and applications. Multiple concepts are funded at the early stages, resulting in a reduced number of successful subsystems at Stage 4 (around TRL8).
2. The successfully developed subsystem(s) are then integrated within an existing device and demonstrated at (close to) full scale to validate the reduction in LCOE.

All these activities have associated time and cost, which are offset against the reduction in LCOE. The total investment required includes the cost of developing all concepts through all stages required (whether successful or not), plus the integration and demonstration costs. The minimum time required to carry out this type of step-change cost reduction is the sum of the maximum time taken at each stage of the development programme plus the total time for both integration and demonstration. Lessons are learnt from the development of unsuccessful concepts, and these lessons can be used to further develop the sector, but this is not explicitly considered in the modelling. The approach is summarised in Figure 4.2.

TABLE 4.2: STAGES OF DEVELOPMENT, FOR OCEAN ENERGY DEVICES

Stage	TRL	Nominal test scale
0) Concept creation	1	–
1) Concept development	1–3	Small scale (c. 1:100-1:25)
2) Design optimisation	3–5	Larger scale (c. 1:25-1:10)
3) Scaled demonstration	5–6	Sub-prototype size (c. 1:4)
4) Commercial-scale single device demonstration	7–8	Approaching full size (c. 1:1)
5) Commercial-scale array demonstration	9	Full size, small arrays

¹⁰ IEC TS 62600-103 Marine energy - Wave, tidal and other water current converters - Part 103: Guidelines for the early-stage development of wave energy converters - Best practices and recommended procedures for the testing of pre-prototype devices
IEC TS 62600-202 Marine energy - Wave, tidal and other water current converters - Part 202: Scale testing of tidal stream energy systems

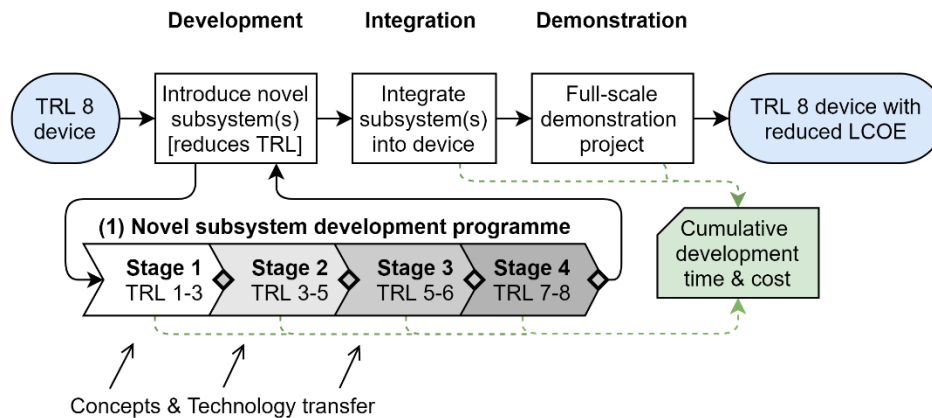


FIGURE 4.2: OVERALL APPROACH OF STAGED SUBSYSTEM DEVELOPMENT, INTEGRATION AND DEMONSTRATION. 'FEEDSTOCK' OF NOVEL CONCEPTS SHOWN IN BOTTOM LEFT OF FIGURE.

It is important to highlight that some aspects of the 'innovation chain' shown in Figure 2.1 are not captured by this approach. Only the costs and time associated with experimental development through to demonstration of technology subsystems are considered. This assumes sufficient basic and applied research is being carried out, which supplies early-stage concepts as a 'feedstock' for the novel subsystem development programme (see Figure 4.2). For countries that invest heavily in earlier stages of R&D, there are likely ample concepts available for development through an innovation programme. However, this is an important contextual factor when considering the applicability of a stage-gate style innovation programme to a specific country.

Two other key assumptions are considered for the step-change cost-reduction process:

- ▶ The process starts with a device concept at a pre-commercial level (around TRL 7-8). The step-change in LCOE is not derived from developing a novel device from an early TRL concept.
- ▶ The step reductions in LCOE are the result of using a structured and staged innovation programme. They are not the result of developers refining/improving designs, which is included in the incremental innovation model.

While the midline scenario in the modelling (shown bold in Table 4.5) considers novel subsystems (as there is a level of data availability for this), it is possible that more radical approaches from entirely novel concepts could reduce the sector's LCOE by a larger proportion. Sensitivity around the baseline LCOE in the results section explores this further.

To illustrate the impact of a step-change cost reduction on the total investment, a series of what-if scenarios are used. A range of values have been considered for the total investment, time, and change in LCOE resulting from step-change cost reductions, summarised in Table 4.5. These values have been selected, as discussed below, using published guidance on developing ocean energy technologies [97, 98, 91] experience from the Wave Energy Scotland development programmes [99] and values quoted in the Community Research and Development Information Service (CORDIS) database [100] of EU-funded projects. Metrics from relevant ocean energy subsystem development and demonstration projects from [100] are given in Table 11.1 in Annex I.

Investment and time required

As noted above, the total investment required includes the cost of developing all concepts through all stages required (whether successful or not), plus the integration and demonstration costs. The minimum time required to carry out this type of step-change cost reduction is the sum of the maximum time taken at each stage of the development programme plus the total time for both integration and demonstration.

For reference, the number of participants and direct entrants to each stage of the WES programmes is shown in Table 4.3. For each stage, the total investment per concept, assumed number of concepts, and maximum duration is given in Table 4.4, using the WES programme estimates for stages 1–3 and estimates from the CORDIS database for stage 4.

Using this data provides an estimate of total investment of around €4.4 m to €50 m to develop, integrate, and demonstrate a single novel subsystem. It is noted that many of the projects listed in Table 11.1 in Annex I include multiple subsystems, particularly those that claim a more significant cost reduction. Developing multiple subsystems would proportionately increase the costs. It is also noted the costs associated with the agency running the development programme are not included within these estimates. Therefore, the upper bound of €50 m has been used for the base case with a wide sensitivity range.

Similarly, the total duration of stages 1–4 ranges from 3 years to just over 10 years, and this does not account for any delay between stages, or project over-runs. However, there is ongoing innovation at present, such as the Wave Energy Scotland and H2020 programmes. Therefore, both 5 years and 10 years are considered in the analysis. It is likely that the shorter projects might result in a lesser reduction in LCOE, but there is insufficient data to assess this fully.

TABLE 4.3: NUMBER OF PARTICIPANTS AND ENTRANTS IN EACH STAGE OF THE WES PROGRAMMES

Programme	Number of Participants (of which direct entrants)		
	Stage 1	Stage 2	Stage 3
NWEC	8	4	2
Power Take-Off	10	10 (6)	5 (1)
Structural Materials and Manufacturing Processes	10	3	2
Control Systems	13	3	2
Quick Connection Systems	7	4	–
Total	48	24 (6)	11 (1)
Average	10	5	3

TABLE 4.4: ESTIMATES OF INVESTMENT AND DURATION FOR INNOVATION PROGRAMME

Stage	Investment per concept (€k)	Number of concepts	Total investment (€m)	Duration (months)
1) Concept development	62–333	10	0.62–3.33	3–12
2) Design optimisation	250–810	5	1.25–4.05	9–16
3) Scaled demonstration	633–4429	3	1.90–13.3	12–24
4) Commercial-scale single device demonstration	300–15000	2	0.60–29.8	12–60
Total for single subsystem	–	–	4.4–50.5	36–122

Reduction in LCOE expected from innovation programmes

As noted in section 4.3, the reduction in LCOE could be achieved through a reduction in CAPEX and/or OPEX, and/or an increase in AEP. Table 11.1 in Annex I shows a range of estimates for improvement in LCOE, AEP, CAPEX and OPEX for various projects in the CORDIS database. Due to a lack of data covering different subsystems, it is not possible to accurately estimate values for specific subsystems, and thus a general estimate must be used in the modelling.

These estimates are subject to several important caveats, including:

- ▶ The CAPEX and/or OPEX reductions quoted are assumed to only refer to the CAPEX and/or OPEX of the particular subsystem(s) considered, rather than to the device or project as a whole, and as such would have a smaller corresponding impact on overall LCOE.
- ▶ These improvements claimed in these projects may be optimistic estimates since they may be used to justify funding and/or may not yet be fully substantiated.
- ▶ Only a small subset of the projects specifically quotes the projected improvement in LCOE, CAPEX, OPEX, and/or AEP, and some give a range; consequently, it is not possible to provide useful statistics.

Due to significant variation of resource in different sites, ocean energy (particularly wave energy) may not converge on one successful device concept. Developing and implementing a novel subsystem for a leading device will reduce the LCOE of that device, but it may not reduce the LCOE of the whole sector. On the other hand, one technology innovation (such as a grid connection system) may easily diffuse through the entire sector. It may, therefore, be necessary to develop several implementations of a novel subsystem to reduce the LCOE of the entire sector. We can reasonably assume that this happens in parallel, so this does not affect the timing. However, it directly multiplies the cost of step-change innovation. Similarly, multiple countries may fund innovation programmes in parallel. The sensitivity analysis in section 5.2 on the cost of step-change innovation addresses this matter.



4.3.2 SCENARIOS TO ILLUSTRATE IMPACT OF STEP-CHANGE INNOVATION

The base case step-change innovation scenario is an investment of €50 m in funding over 5–10 years, which results in an LCOE reduction of 25% (i.e. a relative LCOE of 75%). Higher and lower estimates are used to illustrate the impact of these parameters on the overall time and investment required to reach the target LCOE. While these parameters are independent in the model, both time and expense are more likely to result in (1) a higher probability of both achieving step-change cost reductions and (2) these cost reductions being larger (as the development of a greater variety of promising novel concepts can be funded).

**TABLE 4.5: PARAMETERS AND VALUES USED IN WHAT-IF SCENARIOS
TO ILLUSTRATE IMPACT OF STEP-CHANGE INNOVATION**

Parameter	Values used (base case in bold)
Investment in each step-change innovation programme	€25 m, €50 m , €100 m, €200 m, €400 m, or €800 m
Time taken to develop step-change innovation	5 years , 10 years , or 15 years (noting 5 years is very ambitious, but innovation programmes are ongoing)
LCOE reduction resulting from step-change innovation (relative LCOE remaining shown in parentheses)	50%, 25% , or 10% (50%, 75% , or 90%)
Deployment occurs in parallel with technology development	yes , no
Transition time to adopt innovation across the sector	Immediately, 5 years , 10 years, or 15 years

4.3.3 INTEGRATION INTO THE MODELLING

To assess the impact of step-change cost reductions, they were integrated into the incremental cost-reduction modelling as follows:

1. The total investment is increased by the total investment required for the programme(s) to develop and demonstrate the step-change innovation(s). This includes investment in unsuccessful subsystem innovations required to obtain those that were successful.
2. No benefit is observed from the step-change cost-reduction until this is complete, i.e. demonstrated at close to full scale. Two options have been considered for how this is then implemented across the sector:
 - a. The whole deployment time series is delayed by total duration of the step-change development and demonstration activities. In this case, it is assumed deployment is not subsidised until an acceptably low starting LCOE has been achieved.
 - b. Deployment continues in parallel with the novel technology development, with the assumption that one country delaying their subsidy programme would not stop subsidised deployment in other countries. Once the novel technology is developed, several time scales have been considered for the transition period as the technology is adopted throughout the sector.
3. The LCOE is reduced by the factor resulting from the step-change innovation(s). It is assumed that during the transition period the novel variant can accumulate the experience gained from

deploying the previous variant [31]. This experience may not be fully transferable in practice; however, it is considered as such for the purposes of this study.

4. The reduction in LCOE plus required investment and time for the step-change cost-reduction are accounted for as one block. In reality, this may occur in a series of smaller steps, but this does not change the overall results.

As noted above, one of the key underpinning assumptions in this process is that experience accrued by the incumbent technologies can be transferred to the novel technology variant [31]. This means the switch of technology variants can be modelled at any point in the deployment trajectory as a transition between similar experience curves with different starting LCOE (see Figure 2.6). An alternative approach would be assuming none of the experience is transferred and the learning essentially 'starts from scratch' when the novel technology variant is introduced. However, this would suggest an unrealistic absence of knowledge transfer between technology variants; therefore, the former approach was adopted. In reality, a middle ground between these assumptions is likely, but this was not included in this study.



5. COST MODELLING RESULTS

As noted in section 4.1, three pathways are used in the modelling:

- 1) Incremental cost reduction driven through commercial deployment only.
- 2) Step-change cost reduction (through step-change innovation), where either:
 - a. deployment is delayed until a step-change cost reduction has been completed or
 - b. deployment and step-change cost reductions happen in parallel.

This section first presents results for pathway 1, exclusively deployment-based incremental cost reductions, in section 5.1. Followed in section 5.2 by a comparison of pathway 1 with pathways 2a and 2b, integrating the step-change cost reduction. Finally, section 5.3 considers a set of scenarios that aim to illustrate the balance of different funding policies.

5.1 INCREMENTAL COST REDUCTION THROUGH SUBSIDISED DEPLOYMENT ONLY

The following section presents results for purely deployment-based incremental cost reductions (pathway 1 scenarios). If not stated otherwise, the assumptions shown in Table 4.1 were used for the analysis in this section. These are a 15% LR , $LCOE_{target}$ of the WMP at 50 €/MWh, a fixed 35% capacity factor, 20-year project length and support period, and an exponential deployment at 30%/year increase. For the tidal scenarios current cumulative deployed capacity $CD C_0$ is 40 MW, with the LCOE at commercialisation $LCOE_c = 200$ €/MWh. For the wave scenarios, $CD C_0$ is 25 MW and $LCOE_c = 350$ €/MWh.

Figure 5.1 shows relationship between total learning investment and $LCOE_c$ and LR , with dashed lines showing the base case $LCOE_c$, LR and corresponding investment. The present value figures are calculated following the approach taken by the marine Technology Innovation Needs Assessment (TINA) [101] using the UK Treasury social discount rate of 3.5% [94]. This reflects the social time preference of public investments and is not representative of private sector discount rates.

It can be seen in Figure 5.1 that $LCOE_c$ and the learning rate have a nonlinear relationship with the total learning investment and are coupled (a change in one variables' effect on learning investment is dependent on the value of the other). Total learning investment is highly sensitive to learning rate, especially at lower values (increasing the learning rate from 10 to 11% learning reduces the learning investment by a factor of >2.5).



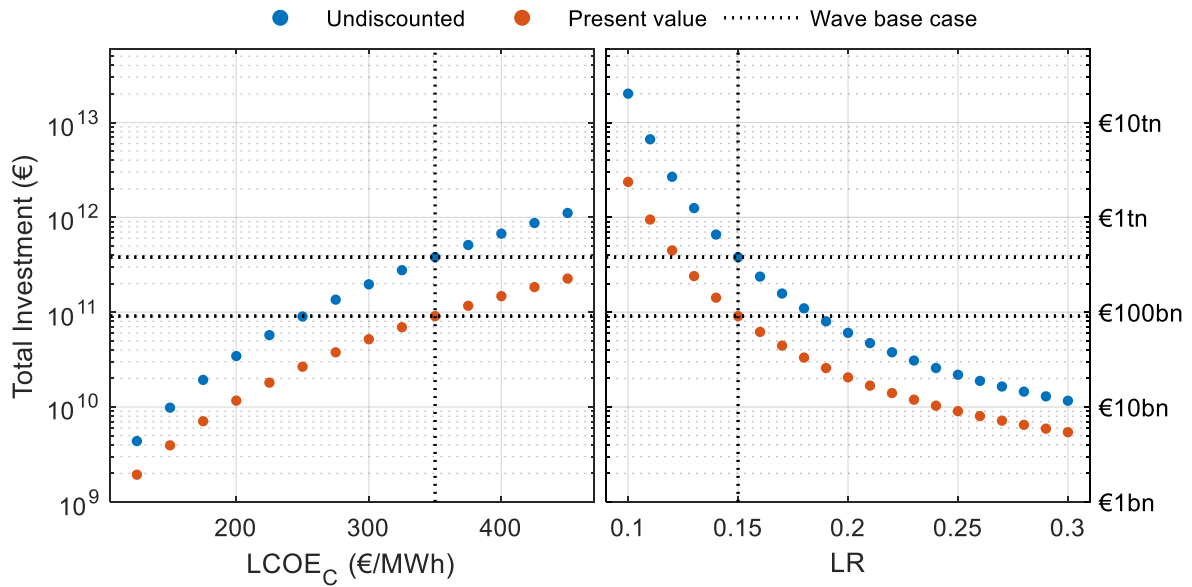


FIGURE 5.1: SENSITIVITY OF TOTAL LEARNING INVESTMENT TO MAIN INPUTS, $LCOE_c$ AND LR . WAVE BASE CASE (SEE TABLE 4.1) USED FOR OTHER PARAMETERS. VALUES SHOWN AS UNDISCOUNTED AND PRESENT VALUE.

The total learning investment from combinations of $LCOE_c$ and LR values at a given CDC_c is shown in Figure 5.2. This can be used to understand the requirements to achieve 'attractive scenarios' for ocean energy development. The wave base case scenario ($LCOE_c = 350$ €/MWh, $LR = 15\%$) is highlighted in Figure 5.2, and results in a total learning investment of €380 bn. Figure 5.2 illustrates how relatively small changes to $LCOE_c$ (shifting downwards) and the LR (shifting to the right) can result in large changes in the total learning investment.

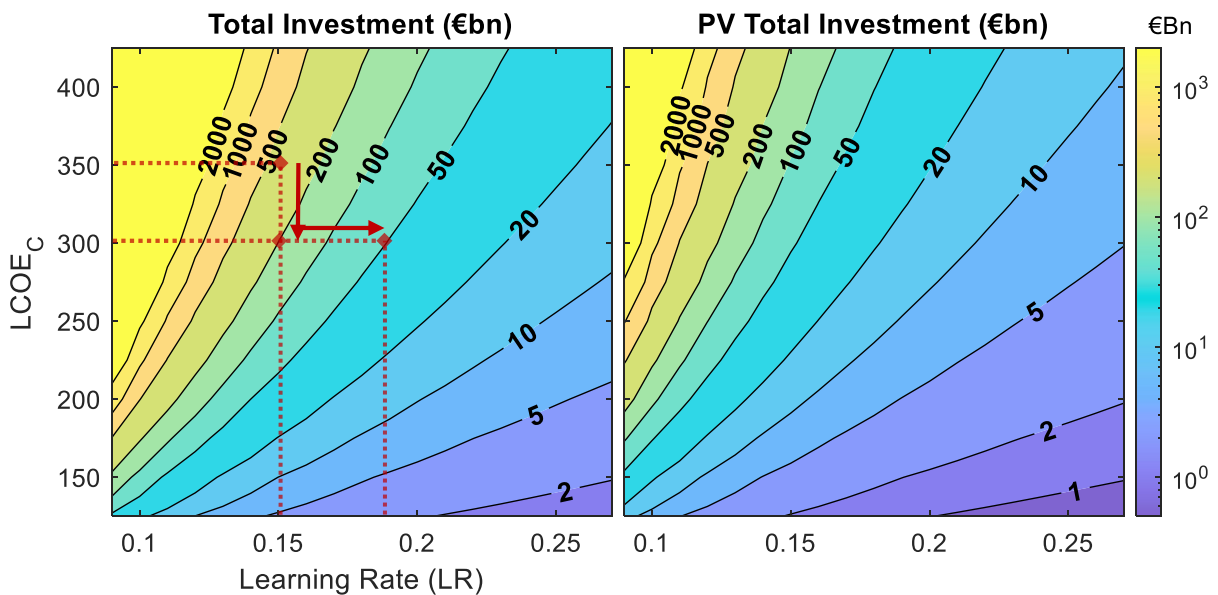


FIGURE 5.2: CONTOURS OF TOTAL INVESTMENT (UNDISCOUNTED AND DISCOUNTED) FOR VARYING STARTING $LCOE$ AND LEARNING RATE, HIGHLIGHTING IMPACT OF REDUCED STARTING $LCOE$ ↓ AND INCREASED LEARNING RATE →.

It is evident that there are low levels of compensation between these parameters. There is only a small range of scenarios in which a very high $LCOE_c$ or low LR can result in a feasible level of learning investment. This shows that achieving moderate to strong performance in each of these parameters is a necessity for economically viable cost reduction in the ocean energy sector.

While not presented here, the support period length and capacity factor have no effect on the total cumulative deployment capacity at which the LCOE target is met, nor the time taken to get there. However, both parameters are directly proportional to the level of subsidised generation, and therefore, to the learning investment. Changing the rate of deployment effects how the learning investment is distributed over time, but it results in the same total subsidised generation (and therefore learning investment) for each scenario.

Figure 5.3 below shows how the annual investment varies with time for different starting $LCOE_c$ values. The faster rate of deployment (shown dotted) results in the same learning investment for each $LCOE_c$ just distributed over a shorter period with correspondingly higher peak annual investment. The investment in these scenarios is highly back loaded. In the base case scenario (dark blue line in Figure 5.3) where $LCOE_c = 350$ €/MWh, the peak annual investment of around €17.9 bn is met 37 years after the initial subsidised deployments. For the faster deployment of 60%/year, the peak is €19.2 bn/year in year 22.

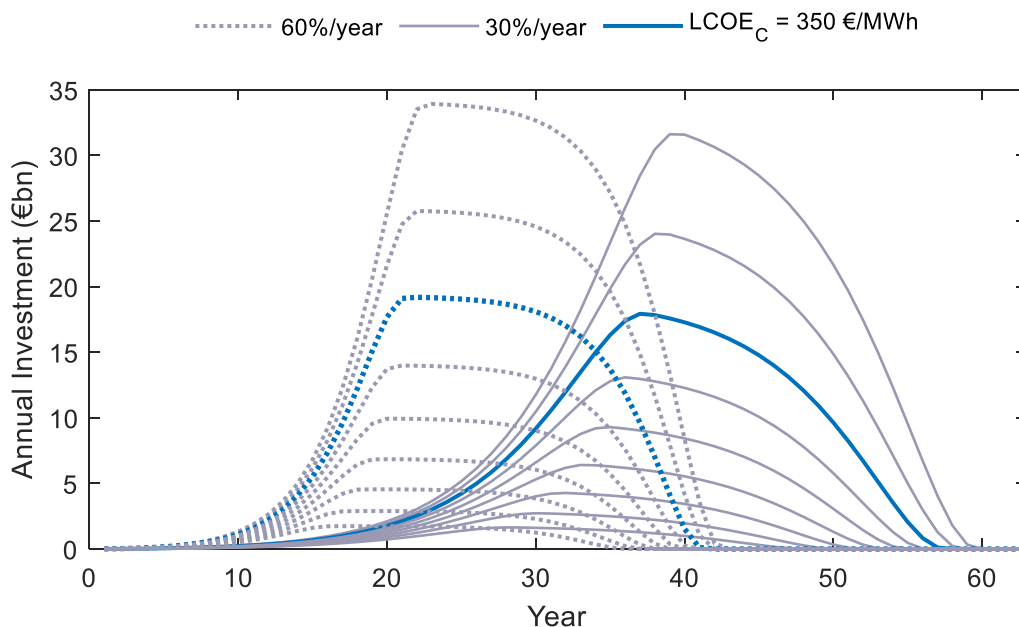


FIGURE 5.3: ANNUAL INVESTMENT PER YEAR FOR A RANGE OF $LCOE_c$ VALUES
 $LCOE_c$ INCREMENTS OF 25 €/MWH BETWEEN 200 €/MWH AND 400 €/MWH.
 DOTTED LINES SHOW ALTERNATIVE FASTER DEPLOYMENT TRAJECTORY THAT RESULTS IN A
 HIGHER AND EARLIER PEAK ANNUAL INVESTMENT, BUT THE SAME OVERALL TOTAL INVESTMENT.
 ALL OTHER INPUT PARAMETERS KEPT CONSTANT.

5.2 INCLUDING STEP-CHANGE COST REDUCTIONS

The following results include the impact of running a focused innovation programme resulting in a sector wide step-change cost reduction, as described in section 4.3. The pathway 1 experience curve (cost reduction exclusively through deployment) uses the same base assumptions as above (see Table 4.1). The base case used for the step-change cost reduction considers an investment of €50 m in funding over 10 years, which results in a step-change LCOE reduction of 25% and a transition period of 5 years for sector diffusion of the new technology (as shown in Table 4.5).

5.2.1 SENSITIVITY OF TOTAL LEARNING INVESTMENT TO MODEL PARAMETERS

The total learning investment in all scenarios is highly sensitive to the level of step-change cost reduction. Figure 5.4 shows that even a 10% step-change cost reduction can reduce the total learning investment required by over a third, and a 50% step-change can reduce this by around 90%. The total investment for pathway 2a (delaying deployment until after innovation) is marginally less than pathway 2b, deploying in parallel. For scenarios on pathway 2b, higher rates of deployment increase the learning investment as more deployed capacity is subsidised before the step-change cost-reduction transition period. Additionally, in scenarios on pathway 2b, the transition period duration and the time taken for the innovation programme also affect the total investment, although to a lesser degree. This is discussed further below.

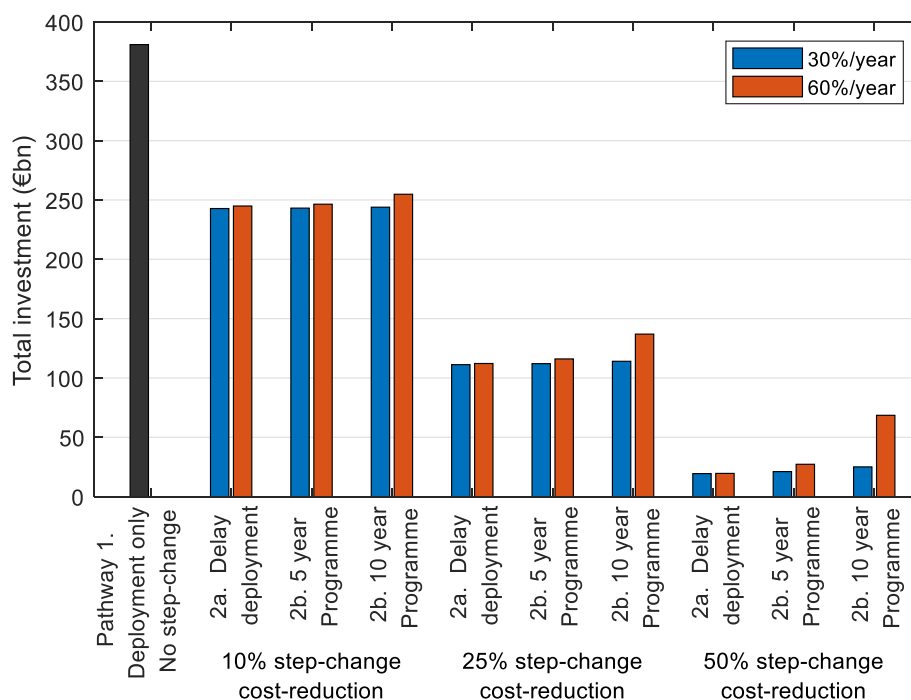


FIGURE 5.4: TOTAL LEARNING INVESTMENT REQUIRED FOR DIFFERING SCENARIOS OF STEP-CHANGE COST REDUCTION BEFORE SUBSIDISED DEPLOYMENT AND EXPONENTIAL DEPLOYMENT RATE.

In most scenarios, the relative difference in total learning investment between pathways 2a and 2b is limited. However, if accumulated learning is not fully transferable between technology variants (which is probable in reality), the relative benefits of delaying deployment (pathway 2a) compared to parallel deployment (pathway 2b) on learning investment would be increased and the relative penalty on timescale would be reduced.

Figure 5.5 shows the sensitivity of the overall investment (revenue support plus innovation programmes) to the other parameters in pathway 2b scenarios. Within our sensitivity range, the time taken to run the step-change innovation programme (5–15 years) and transition period (0–15 years) to the new technology have the greatest relative impact on overall investment, especially in the larger step-change or faster deployment scenarios. Within the sensitivity range (€25–800 m), the amount spent on innovation programme(s) has a limited impact on the overall investment. Effectively the cost of successful innovation programmes (within the sensitivity range) is minimal compared to the offset revenue support.

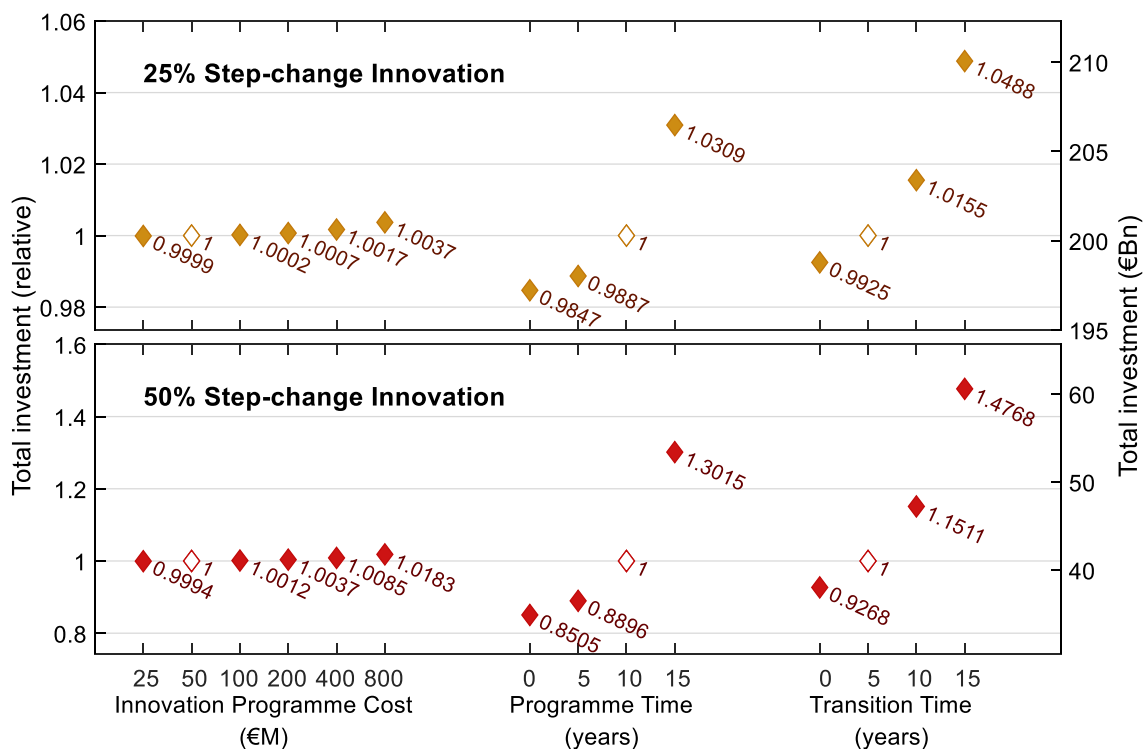


FIGURE 5.5: SENSITIVITY OF THE TOTAL INVESTMENT REQUIRED OF THE TOTAL COST OF RUNNING THE INNOVATION PROGRAMME(S), THE TIME TAKEN, AND THE TRANSITION TIME FOR ADOPTION. TOTAL INVESTMENT WHEN DELAYING DEPLOYMENT IS INDEPENDENT OF PROGRAMME TIME, EQUAL TO 0 YEARS. SUB-PLOTS SHOW DIFFERING AMOUNTS OF STEP-CHANGE INNOVATION (25% & 50%), NOTING THE Y-AXIS SCALES ARE DIFFERENT.

To illustrate the benefit of step-change cost reduction, the total investment required to subsidise sufficient deployment to achieve a 10%, 25%, or 50% cost reduction through incremental cost reduction alone can be calculated. The total investment is a function of the LCOE at commercialisation, as shown in Figure 5.6. For $LCOE_c$ of 250 €/MWh and 15% LR, approximately €3.2 bn would need to be spent on subsidised deployment to achieve a 25% cost reduction. It must be stressed, however, that due to the overall additional deployment required, the investment to reach the target LCOE will be significantly greater, as shown in Figure 5.4.

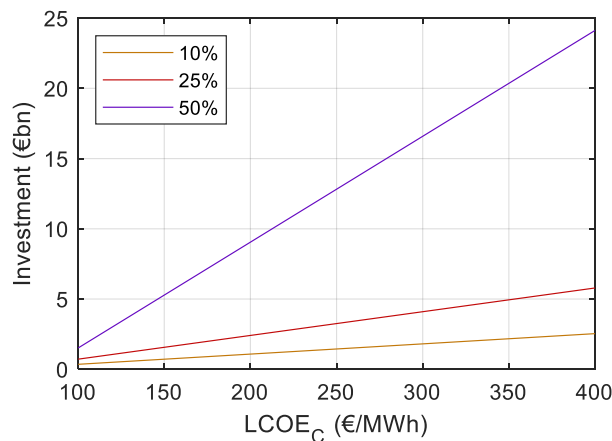


FIGURE 5.6: INVESTMENT REQUIRED TO ACHIEVE PERCENTAGE COST REDUCTION THROUGH SUBSIDISED DEPLOYMENT ALONE

5.2.2 ILLUSTRATING DIFFERENT COST-REDUCTION TRAJECTORIES

Figure 5.7 presents several cost reduction scenarios for the wave energy sector following pathways 1, 2a and 2b. Pathway 1 shown as black dashed line, with 2a and 2b shown coloured in these pathways illustrate both the base case (30%/year) and aggressive (60%/year) increase in cumulative deployed capacity. In all cases, the experience curve is only extrapolated after CDC_c is met (100 MW). For comparison, the European Commission's SET plan targets [102] are shown as blue crosses. As seen in Figure 5.7, the pathway 2a scenarios take longer to reach cost parity than pathway 1 unless there is a significant step-change cost reduction in a short time scale. In pathway 2a scenarios, the required capacity of subsidised deployment reduces with increasing step-change cost reduction, but it is independent of deployment rate. Subsidising deployment in parallel with running the innovation programme (pathway 2b) reduces the overall time taken to reach cost parity, provided accumulated experience is transferred from the incumbent to the novel technology. Using these input values, the SET plan target is only met in the 30%/year deployment scenario where a 50% step-change cost reduction is achieved in 5 years in parallel with deployment (pathway 2b). In the 60%/year deployment scenarios, the SET plan target is met with either a 25% or 50% step-change cost reduction (achieved in 5 years) in parallel with deployment (pathway 2b).

Similar cost reduction scenarios for the tidal energy sector are shown in Figure 5.8, starting from a lower $LCOE_c$ and higher deployed capacity at present.

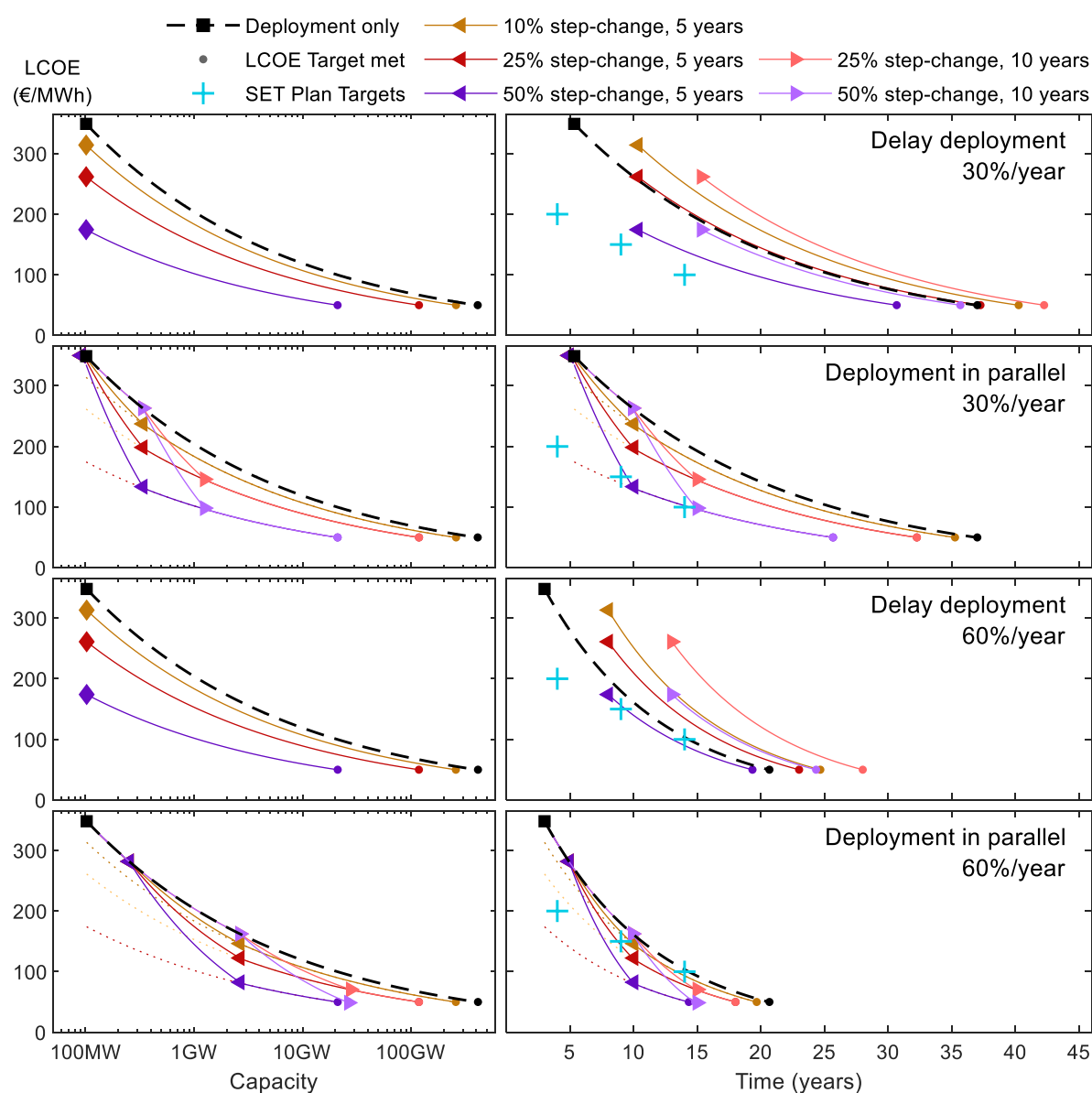


FIGURE 5.7: ILLUSTRATIVE TRAJECTORIES OF LCOE VS TIME & CUMULATIVE DEPLOYED CAPACITY FOR THE WAVE ENERGY SECTOR .

DOTTED LINES SHOW THE LOWER EXPERIENCE CURVE FOR DIFFERENT TECHNOLOGY VARIANTS RESULTING FROM INNOVATION PROGRAMMES, EXTRAPOLATED BEFORE THEIR ADOPTION.

DIAMOND SYMBOLS ♦ USED WHERE STEP-CHANGE TIMESCALE NOT A FACTOR.

THE PERCENTAGE STEP-CHANGE IS THE LCOE REDUCTION COMPARED TO THE DEPLOYMENT ONLY EXPERIENCE CURVE ONCE THE NOVEL TECHNOLOGY HAS BEEN ADOPTED. THE TRANSITION PERIOD BETWEEN TECHNOLOGY VARIANTS IS 5 YEARS IN ALL CASES SHOWN.

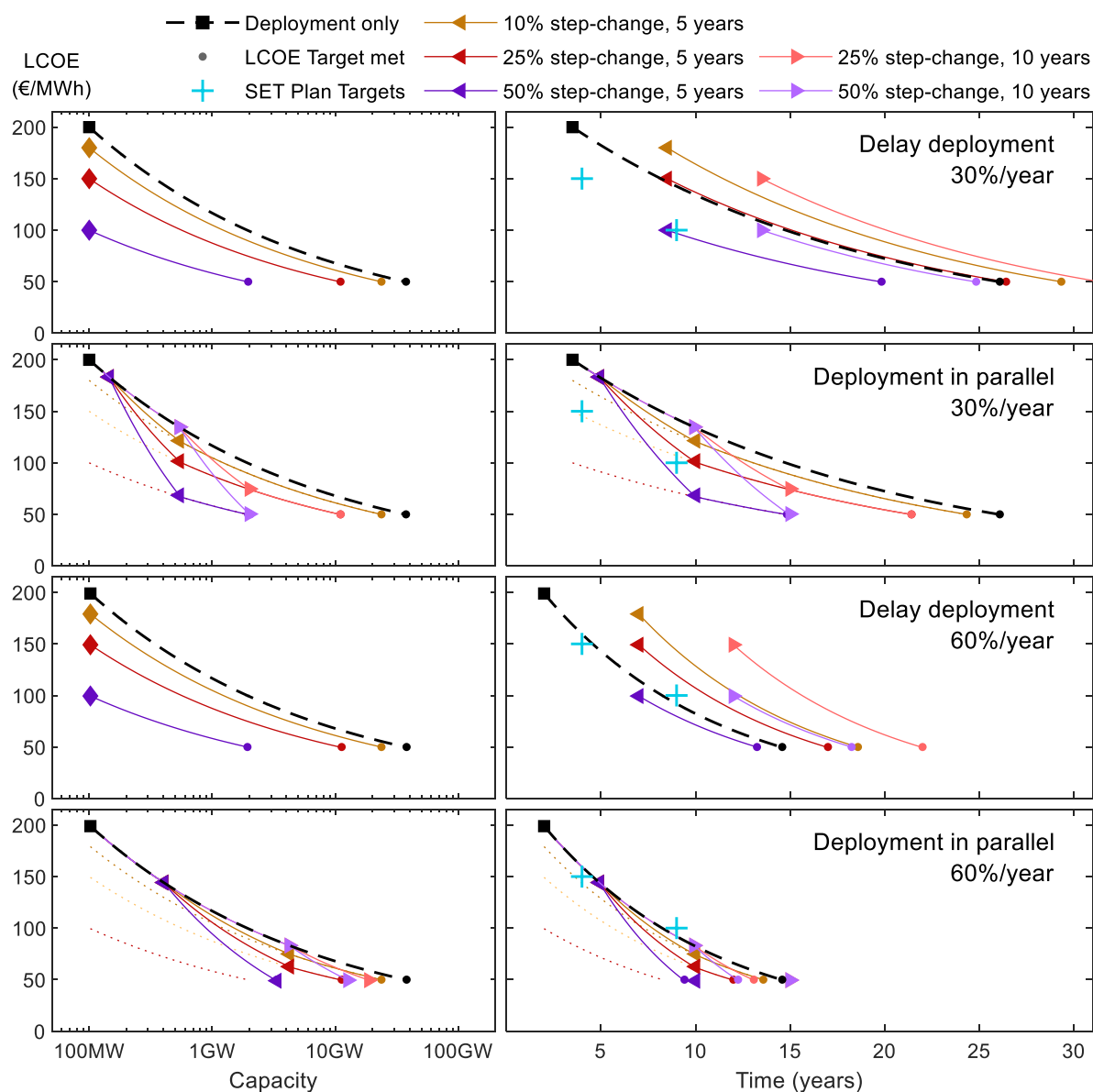


FIGURE 5.8: ILLUSTRATIVE TRAJECTORIES OF LCOE VS TIME & CUMULATIVE DEPLOYED CAPACITY FOR THE TIDAL ENERGY SECTOR.

DOTTED LINES SHOW THE LOWER EXPERIENCE CURVE FOR DIFFERENT TECHNOLOGY VARIANTS RESULTING FROM INNOVATION PROGRAMMES, EXTRAPOLATED BEFORE THEIR ADOPTION.

DIAMOND SYMBOLS ♦ USED WHERE STEP-CHANGE TIMESCALE NOT A FACTOR.

THE PERCENTAGE STEP-CHANGE IS THE LCOE REDUCTION COMPARED TO THE DEPLOYMENT ONLY EXPERIENCE CURVE ONCE THE NOVEL TECHNOLOGY HAS BEEN ADOPTED. THE TRANSITION PERIOD BETWEEN TECHNOLOGY VARIANTS IS 5 YEARS IN ALL CASES SHOWN.

5.3 SCENARIOS TO ILLUSTRATE BALANCE BETWEEN DIFFERENT FUNDING POLICIES

To illustrate the balance between TP and MP funding mechanisms, the following balances between funding policies are considered:

- Funding structured stage-gated innovation programme(s) via TP (as described in 4.3) over a defined period to achieve a step-change cost reduction. It is assumed there are ten programmes running worldwide at a cost of €50 m each, resulting in 25% reduction in the LCOE of the sector. A 50% cost reduction is also shown for wave energy, currently a less mature sector with higher LCOE.
- Funding other policy interventions to promote higher and sustained learning during the subsidised roll-out of technology. These policy interventions include ongoing public R&D, knowledge transfer programmes, etc. The base case LR of 15% assumes this is funded, and without it is postulated that the LR might fall by 2 percentage points to 13%. A ballpark estimate of €100 m annual worldwide has been used to illustrate this, noting again it would be split between multiple countries.
- Subsidising deployment of technology, via a feed-in tariff or similar MP mechanism, supporting the difference between the sector's LCOE and the wholesale market price. This may be delayed until after the step-change cost reduction is demonstrated or may run from the start in parallel to the innovation programme.

This results in the scenarios shown in Table 5.1, which can be related back to the pathways used previously in the cost modelling. These scenarios were analysed for wave and tidal technologies separately in a global context, using the same base case assumptions as before. The baseline exponential deployment rate of 30%/year increase has been used for all, with the faster deployment of 60%/year also considered for wave energy to illustrate the impact of this. Additionally, a larger 50% step-change cost reduction is also modelled for wave energy, as this sector has less design consensus. As noted in section 2.4, the first year of the exponential deployment trajectories is taken to be 2022.

TABLE 5.1: SCENARIOS TO ILLUSTRATE BALANCE OF TECHNOLOGY PUSH/MARKET PULL FUNDING

Scenario	Technology Push				Market Pull			Cost model pathway
	Structured step-change innovation programme & LCOE Reduction		Policies to facilitate enhanced learning & corresponding LR		Timeline for FIT or similar subsidy cf. innovation prog.	LCOE at start of subsidy (€/MWh)		
						Wave	Tidal	
(1)	No	—	No	13%	Deployment only, from start	350.00	250.00	—
(2)	No	—	Yes	15%	Deployment only, from start	350.00	250.00	1
(3)	Yes	25%	No	13%	Deployment in parallel from start	350.00	250.00	—
(4)	Yes	25%	Yes	15%	Deployment in parallel from start	350.00	250.00	2a
(5)	Yes	25%	No	13%	Delay deployment after step-change	262.50	187.50	—
(6)	Yes	25%	Yes	15%	Delay deployment after step-change	262.50	187.50	2b
(7)	Yes	50%	Yes	15%	Delay deployment after step-change	175.00	—	—



5.3.1 COMPARISON OF SCENARIOS BY FUNDING REQUIRED, TIME TO REACH COST PARITY, CAPACITY DEPLOYED, AND LCOE AT 100GW

The relative merit of each of these scenarios is illustrated in Figure 5.9 and Figure 5.10. The left plots show the total funding required to get to cost parity ($LCOE_{\text{target}} = 50 \text{ €/MWh}$) and the year this could be expected. The right plots show the total funding required to deploy 100 GW of devices and the corresponding LCOE after this. The more attractive scenarios are located towards the lower left corner of these plots, with the same trend seen in both technologies. These results are tabulated in Annex II.

For the tidal base-case scenario in Figure 5.9, the total funding required is between €13 bn and €77 bn. As all scenarios achieve cost parity with $\leq 100 \text{ GW}$ deployed, there is no extra subsidy required to deploy 100 GW. Assuming 30%/year exponential deployment, to get to 100 GW CDC takes 30 years (until 2051) for scenarios (1)–(4), and an extra 5 years for (5)–(6) where the FIT is delayed until the step-change innovation cost-reduction has occurred.

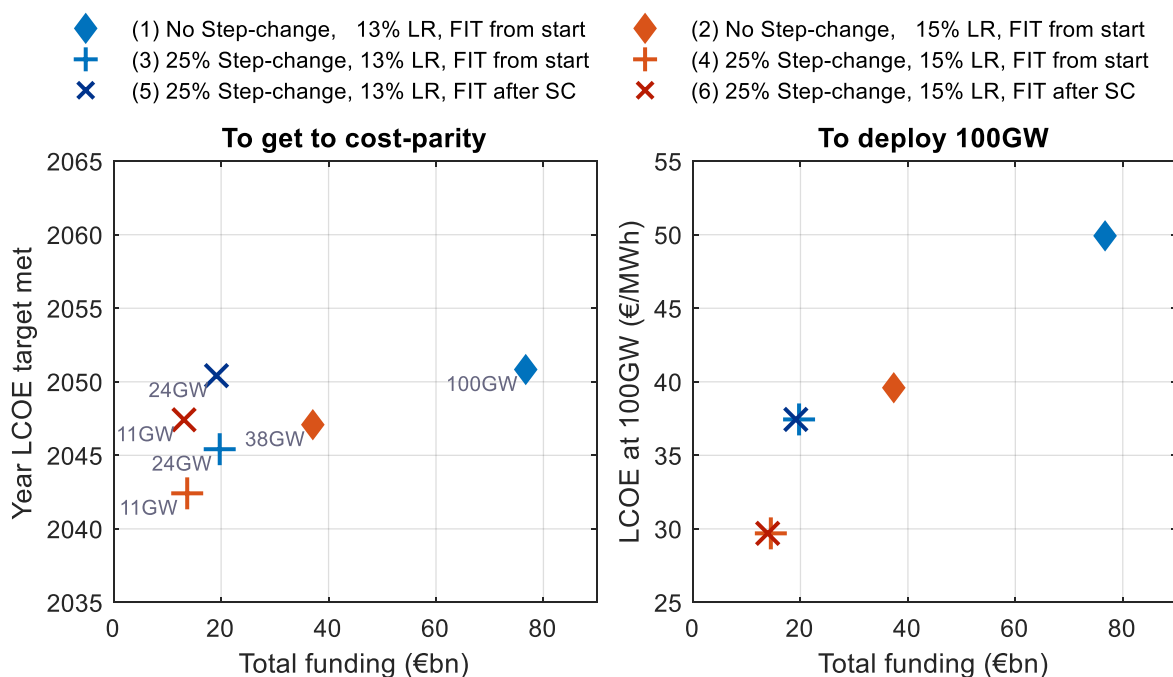


FIGURE 5.9: SCENARIOS TO ILLUSTRATE DIFFERENT POLICY MIXES FOR TIDAL
($CDC_0=40 \text{ MW}$, $LCOE_C=200 \text{ €/MWh}$, $RCI=30\%/YEAR$).

NOTE THAT SCENARIOS (3)&(5) AND (4)&(6) OVERLAP ON THE RIGHT PLOT

With a higher $LCOE_C$ and lower CDC at present, Figure 5.10 shows a slightly different picture for the wave scenarios. Reaching cost-parity requires $>100 \text{ GW}$ deployment for all scenarios considered except the 50% step-change cost reduction (Table 5.1). For scenario (1), this requires significantly more than 1000 GW to be deployed, which could be more than the global wave resource and very expensive to subsidise this much deployment (therefore, it is not shown). Assuming the 30%/year exponential deployment, it takes 32 years (until 2053) to deploy 100 GW for scenarios (1)–(4)&(7), and

an extra 5 years for (5)–(6) where the FIT is delayed until the step-change cost-reduction has occurred. Cost parity would be met between 2053 and 2063 for scenarios (2)–(6) and 2047 for scenario (7) with the larger step-change cost reduction. To illustrate the impact of faster deployment, a 60%/year case is also shown on Figure 5.10, which is 11–16 year faster, but costs marginally more and requires increased deployment because of subsidising more deployment at higher costs in the early years.

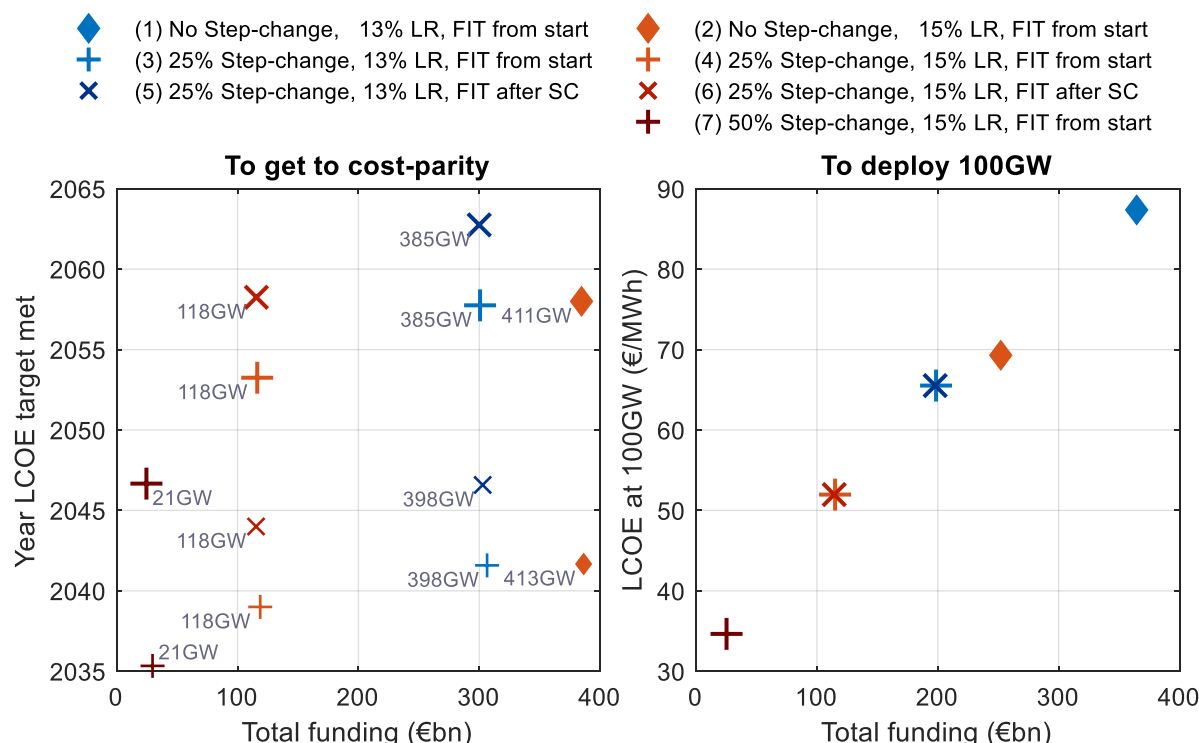


FIGURE 5.10: SCENARIOS TO ILLUSTRATE DIFFERENT POLICY MIXES FOR WAVE
($CDC_0=25\text{MW}$, $LCOEC=350\text{€/MWh}$, $RCI=30\%/YEAR$, $RCI=60\%/YEAR$ FOR SMALLER LOWER MARKERS ON LEFT PLOT). NOTE THAT SCENARIOS (3)&(5) AND (4)&(6) OVERLAP ON THE RIGHT PLOT

While the exact figures for $LCOEC$, LR, the amount of step-change cost reduction possible, and the trajectory of deployment cannot be known, the trends between the two examples shown in Figure 5.9 and Figure 5.10 are the same. Scenarios with a lower LR (blue symbols) cost more and take longer than those with a higher LR (red symbols). Scenarios with subsidised deployment from the start in parallel with the step-change innovation programmes (+ symbols), reach cost parity 5 years earlier than the corresponding ones without (x symbols). This follows the assumption that the learning is fully transferable.

From this, scenarios (4) and (6) are the most attractive, as they deliver the largest cost-reduction with the lowest funding and reach cost parity the earliest. These scenarios are, therefore, considered further in the benefits analysis in section 6.2.

5.3.2 SPLIT BETWEEN FUNDING SOURCES

The split between the different sources of funding is shown in Figure 5.11 and Figure 5.12 for each of the scenarios in Table 5.1. These are compared with the case studies in the discussion section 7.2.

The total public funding comprises MP and optionally TP policies. This is split into: (a) step-change innovation programmes (i.e. TP), (b) policies to support enhanced learning (i.e. TP), and (c) subsidised deployment through a FIT (i.e. MP), which gives (d) the total TP+MP policies (i.e. $d = a + b + c$), which is the learning investment described earlier. The percentage split between these is also shown, with MP comprising between 79% and 100%.

In addition to this, the project developers also receive (e) the wholesale market price (WMP) of all the electricity generated over each project's lifetime, at an assumed 50 €/MWh. The overall total (f) is then the sum of TP+MP policies plus the WMP (i.e. $f = a + b + c + e$). The percentage split between the public funding through TP+MP policies and the total WMP is also shown, with the public funding through TP+MP comprising between 20% and 29% of the total.

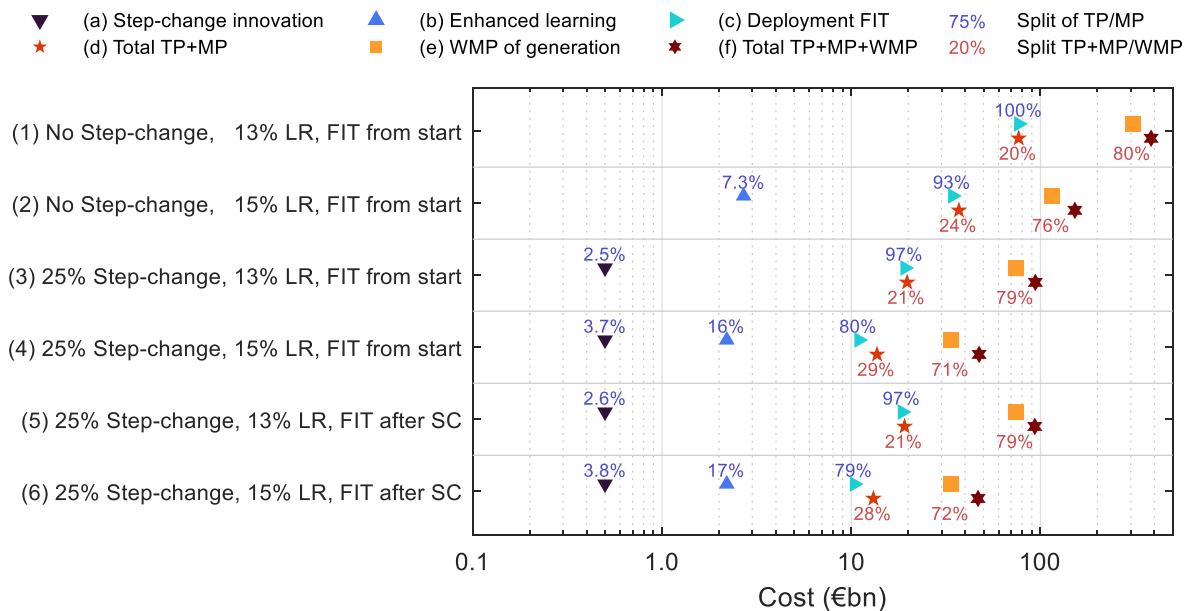


FIGURE 5.11: COSTS FOR SCENARIOS TO ILLUSTRATE DIFFERENT POLICY MIXES FOR TIDAL (COST TO REACH MARKET PARITY, $CDC_0=40$ MW, $LCOEC=200$ €/MWh, $RCI=30\%$ /YEAR)

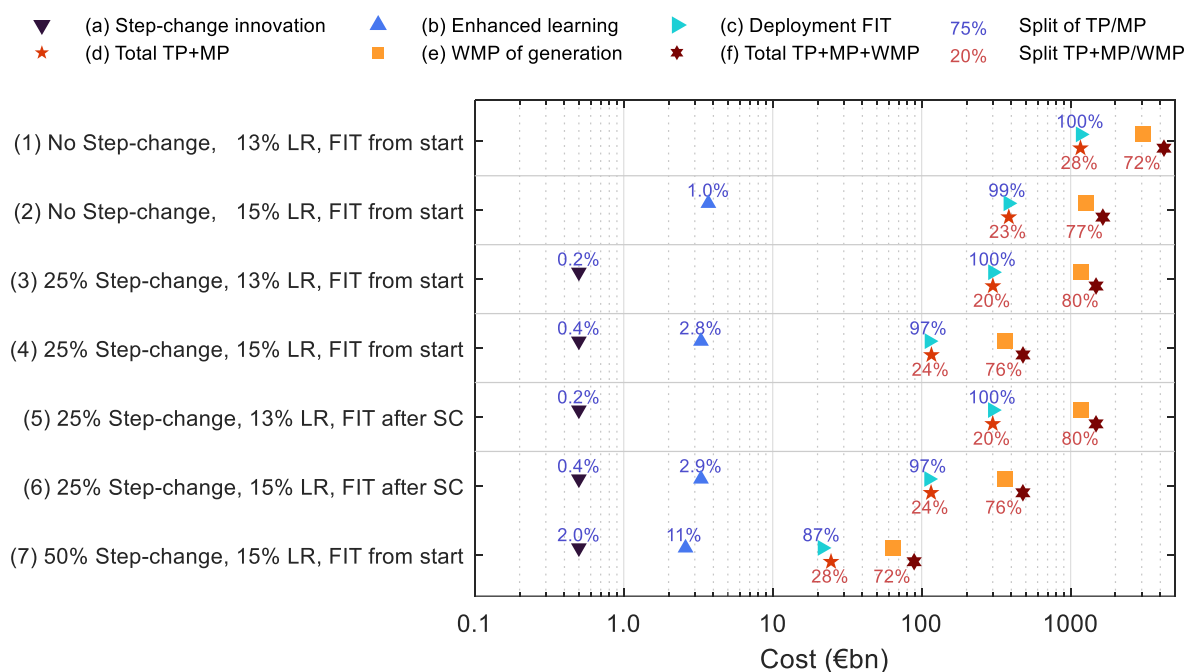


**FIGURE 5.12: COSTS FOR SCENARIOS TO ILLUSTRATE DIFFERENT POLICY MIXES FOR WAVE
(COST TO REACH MARKET PARITY, $CDC_0=25\text{MW}$, $LCOE_c=350\text{€}/\text{MWH}$, $R_{CI}=30\%/ \text{YEAR}$)**

Figure 5.12 shows that the costs of subsidising cost reductions in wave could be quite significant without a large step-change cost reduction. For the base case assumptions used previously (scenario 2), the MP subsidy would be €380 bn with a further €3.7 bn on policies to increase the LR. Without these (1), the subsidy would be over €1.1 trillion, require over 1 TW of subsidised deployment, and still not quite meet cost parity.

As seen in Figure 5.11 and Figure 5.12, the costs of TP policies are significantly lower than costs of MP subsidy (with TP comprising between 0.2% and 21% of the total). To further illustrate the benefit of these policies, the saving in MP subsidy relative to scenario (1) can be calculated. Firstly, the cost of policies to facilitate enhanced LR (2) alone. Secondly, without the policies to increase LR, comparing the costs of the step-change innovation programme either with subsidised deployment in parallel from the start (3) or delayed until afterwards (5). Finally, combining both TP funding policies together (4 & 6). As shown in Figure 5.13 and Figure 5.14, the savings in MP subsidy relative to the base scenario could be very significant — tens of billion euro for the tidal case and many hundreds of billion euro for wave.

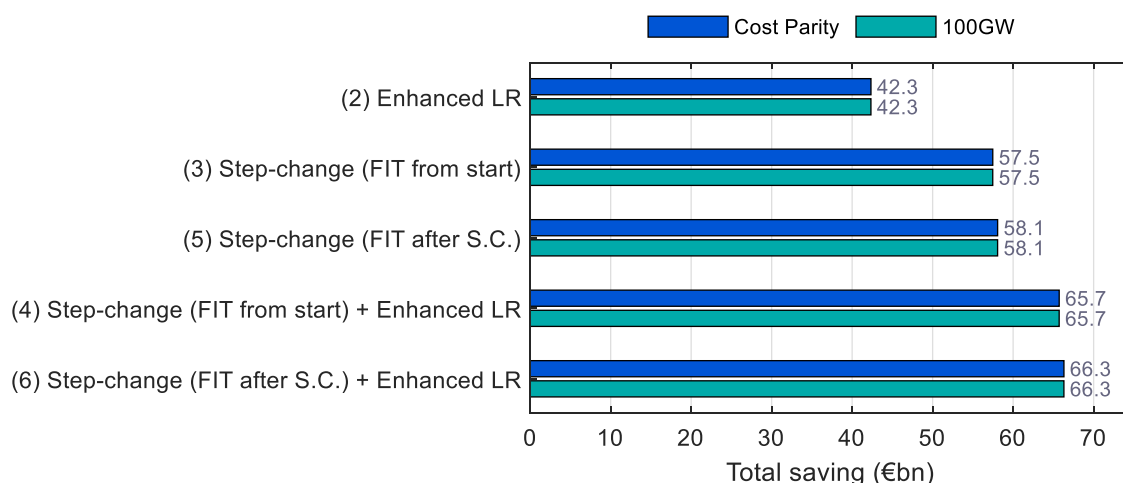


FIGURE 5.13: SAVING IN MP SUBSIDY BY SPENDING ON TP POLICIES FORTIDAL
ALL SHOWN RELATIVE TO SCENARIO (1) NO-STEP-CHANGE OR POLICIES TO ENHANCE LEARNING
($CDC_0=40\text{MW}$, $LCOE_c=200\text{€}/\text{MWH}$, $R_{CI}=30\%/ \text{YEAR}$)

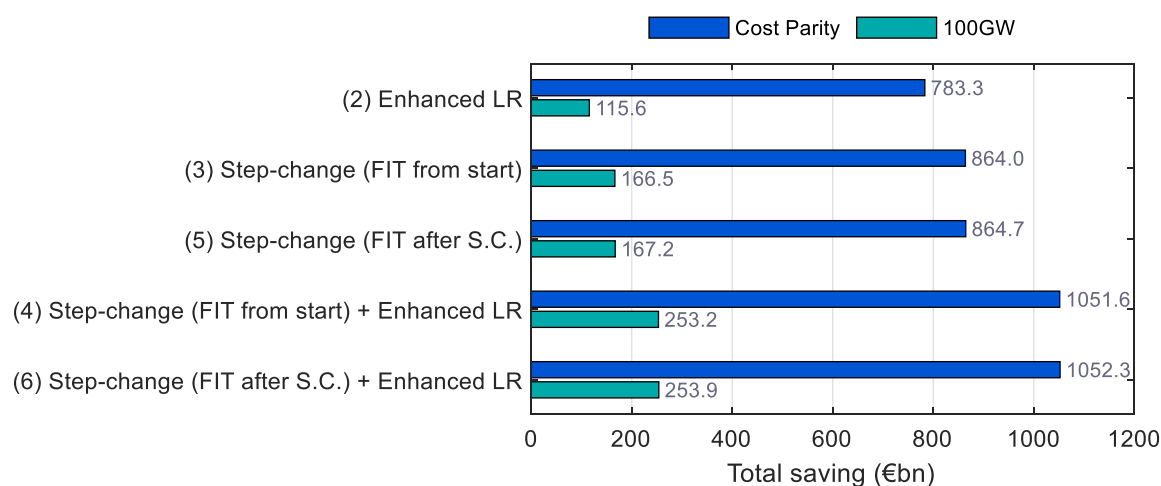


FIGURE 5.14 SAVING IN MP SUBSIDY BY SPENDING ON TP POLICIES FOR WAVE
ALL SHOWN RELATIVE TO SCENARIO (1) NO-STEP-CHANGE OR POLICIES TO ENHANCE LEARNING
($CDC_0=25\text{MW}$, $LCOE_c=350\text{€}/\text{MWH}$, $R_{CI}=30\%/ \text{YEAR}$)

6. ASSESSING THE BENEFITS OF OCEAN ENERGY

While there are significant costs of developing and subsidising deployment of ocean energy technologies as presented in section 5; these can be more than offset by the benefits to the wider economy combined with a range of socio-environmental benefits including low carbon renewable electricity.

The benefits of ocean energy have been assessed firstly in terms of Gross Value Added (GVA) to the economy, and secondly in terms of other non-monetary social and environmental benefits. GVA benefits can be assessed across a range of scenarios; however, not all scenarios from the cost model minimise the cost incurred to the public. Thus, for this study, only a selected few options that optimise the balance between TP and MP funding options have been considered.

6.1 METHODOLOGY FOR ASSESSING BENEFITS IN TERMS OF GROSS VALUE ADDED

GVA is used as an indicator of the increase in economic activity in a region that a business or project generates. It is a popular metric and is usually defined as the difference between output and intermediate consumption for a given sector or firm. As stated in the Scottish Government's Input-Output Methodology Guide, "broadly speaking, it is simply the sum of each company's outputs (sales) less inputs (purchases)" [103]. More simply, it is made up of the difference between the value of goods and services produced and the cost of the raw materials and other inputs, which are used up in the production process [104]. GVA is linked with Gross Domestic Product (GDP) according to Equation (6.1):

$$GVA = GDP + \text{subsidies on products} - \text{taxes on products} \quad (6.1)$$

A GVA model uses an input-output (IO) framework to account for the interdependence of industries within the economy. This analytical framework includes region-specific Industry by Industry (I×I) IO tables to describe the sale and purchase relationships between producers and consumers within an economy [105]. These tables are used in the calculation of effects and multipliers, which relate the invested project spend to the GVA generated.

The GVA analysis is conducted to understand the economic benefits derived from the global deployment of ocean energy projects across a range of scenarios used to illustrate the costs of developing this technology in section 5. The study analyses the economic benefits from the net spend invested in wave and tidal projects and their associated activities (involving development, manufacture, installation, operation & maintenance, and decommissioning) over the project lifetime, globally. The main inputs and assumptions towards the model are discussed in section 6.1.1, while a description of the adopted methodology in general is explained in section 6.1.2. The results obtained from this analysis are discussed in section 6.2.

In sections 6.1 and 6.2, the costs in terms of TP and MP funding are referred to as 'spend', which should be differentiated from total expense of deploying a technology, split into capital and operational expenditure (i.e. CAPEX and OPEX).



6.1.1 INPUTS AND ASSUMPTIONS

A summary of the inputs, and assumptions that goes into the model, are given below and are further discussed in detail thereafter. Key limitations associated with the model are discussed separately in section o.

- ▶ Scope and deployment scenarios.
- ▶ Annual CAPEX and OPEX made throughout the project.
- ▶ Sectorial breakdown, to identify the industrial sectors that would be impacted by the investments made under this project.
- ▶ Project timeline, to understand how long the project and its related activities are expected to last.
- ▶ Industry-by-industry IO tables.

Scope and Deployment scenarios

As with the cost modelling, the scope of the study is global. We are trying to assess the GVA benefits derived from the global development and deployment of ocean energy technologies and projects.

Within the GVA analysis, 12 deployment scenarios have been taken into consideration for wave and tidal technologies, as shown in Table 6.1. These are scenarios (4) and (6) in section 5.3 Table 5.1, with a 25% step-change cost reduction a 15% LR, and a FIT or similar subsidy, either from the start in parallel with the innovation programme (4) or delaying the deployment until after the step-change cost-reduction has been demonstrated (6). These use the baseline 30%/year exponential deployment trajectory. Additionally, the faster deployment of 60%/year is also considered for wave. GVA has been calculated both for the deployment required to reach market parity (reducing LCOE to 50 €/MWh) and for deploying 100 GW of each technology.

TABLE 6.1 DEPLOYMENT SCENARIOS USED FOR GVA ANALYSIS

Technology	Exponential deployment growth rate	Deployment amount	Scenario in section 5.3 and Timeline for FIT or similar subsidy
Tidal stream	30%/year	To meet cost-parity	(4) Deployment in parallel from start
			(6) Delay deployment after step-change
		100GW	(4) Deployment in parallel from start
			(6) Delay deployment after step-change
Wave	30%/year	To meet cost-parity	(4) Deployment in parallel from start
			(6) Delay deployment after step-change
		100GW	(4) Deployment in parallel from start
			(6) Delay deployment after step-change
Wave	60%/year	To meet cost-parity	(4) Deployment in parallel from start
			(6) Delay deployment after step-change
		100GW	(4) Deployment in parallel from start
			(6) Delay deployment after step-change



Annual CAPEX and OPEX investment

Annual expenditure has been calculated, in terms of CAPEX and OPEX, for each of the deployment scenarios considered. For simplicity, this calculation is made for each year of deployment, lumping together all deployment in that year. The cost modelling (sections 4 and 5) only considers reduction in LCOE but not the underlying CAPEX and OPEX required for the GVA calculation. The calculation behind this derivation is discussed below. Note that almost all parameters could have quite different values given the maturity and diversity of the ocean energy sector. A comprehensive sensitivity analysis of these is outside of the scope of this task, and reasonable values have been used to provide an indication of the GVA for different policy mechanisms to illustrate their relative merits.

As noted in section 2.2.1, one of the factors contributing to reduction in LCOE could be reduction in the commercial discount rate DR. This is assumed to reduce in line with the sector maturity, using the cumulative deployed capacity (CDC) as an indicator, as shown in Table 6.2. This is in line with previous studies [36, 38, 91] and experience of the industrial partners within the DTOceanPlus project.

TABLE 6.2 COMMERCIAL DISCOUNT RATE REDUCING IN LINE WITH SECTOR MATURITY IN TERMS OF CUMULATIVE DEPLOYED CAPACITY

CDC	DR
10 MW	14%
100 MW	10%
1 GW	8%
10 GW	7%

For the calculation, all CAPEX is assumed to occur in year 0 with OPEX in years 1-20. Therefore, CAPEX is not discounted. Annual OPEX is assumed to be a fixed percentage oc of total CAPEX, taken as 4% in line with the WES Programme and developer estimates [106]. The OPEX and AEP is taken to be constant throughout the 20-year period of subsidised deployment, which means that the summation of present values in the LCOE calculation can be simplified using a present value factor.

Starting with the LCOE equation and our OPEX assumption (6.2), noting that CAPEX is not discounted, re-arranging and simplifying, we can show an equation for CAPEX (6.6). The total OPEX per year is then calculated as the sum of annual OPEX for all deployments that have occurred over the previous 20 years.

$$LCOE = \frac{\sum_{t=0}^{20} \frac{CAPEX + OPEX}{(1 + DR)^t}}{\sum_{t=1}^{20} \frac{AEP}{(1 + DR)^t}} \quad \text{and} \quad OPEX = oc \times CAPEX \quad (6.2)$$

$$\Rightarrow LCOE \times \sum_{t=1}^{20} \frac{AEP}{(1 + DR)^t} = CAPEX + \sum_{t=1}^{20} \frac{oc \times CAPEX}{(1 + DR)^t} \quad (6.3)$$

$$\sum_{t=1}^{20} \frac{x}{(1 + DR)^t} = x \cdot PVF \quad \text{where} \quad PVF = \sum_{t=1}^{20} \frac{1}{(1 + DR)^t} \quad (6.4)$$

$$\Rightarrow LCOE \times AEP \times PVF = CAPEX + oc \times CAPEX \times PVF \quad (6.5)$$

$$\Rightarrow CAPEX = \frac{LCOE \times AEP \times PVF}{1 + oc \times PVF} \quad (6.6)$$



Sectorial breakdown

Cost components and their cost breakdown available under each technology define their contribution toward CAPEX and OPEX. These cost components along with their cost breakdown are allocated to specific sectors as per the standard industrial classification (SIC) codes¹¹ [107]. This helps identify the most relevant industrial sectors that would be impacted by the investments made under this project. A detailed percentage contribution of various sectors towards CAPEX and OPEX for wave and tidal projects is taken from the value chain study by BVG Associates [108] as also adopted by the European Technology and Innovation Platform for Ocean Energy (ETIP OCEAN 2) study [109].

It is this sectorial contribution towards CAPEX and OPEX with which the expense is finally multiplied in order to split it by the different sectors. Table 6.3 and Table 6.4 below provide a representation of the final proportion of sectorial contribution towards CAPEX and OPEX for tidal and wave deployments, respectively as adopted by the ETIP OCEAN 2 study [109].

TABLE 6.3: COST SECTOR ALLOCATION FOR TIDAL STREAM

SIC Codes	Description	CAPEX	OPEX
C25	Manufacture of fabricated metal products, except machinery and equipment	45.0%	0.0%
C26	Manufacture of computer, electronic and optical products	0.0%	0.0%
C27	Manufacture of electrical equipment	28.0%	0.0%
C33	Repair and installation of machinery and equipment	1.0%	30.0%
H50	Water transport	10.0%	57.0%
K65	Insurance, reinsurance, and pension funding, except compulsory social security	9.0%	0.0%
M69_M70	Legal and accounting activities; activities of head offices; management consultancy activities	7.0%	13.0%
	Total	100.0%	100.0%

TABLE 6.4: COST SECTOR ALLOCATION FOR WAVE

SIC Codes	Description	CAPEX	OPEX
C25	Manufacture of fabricated metal products, except machinery and equipment	57.0%	0.0%
C26	Manufacture of computer, electronic and optical products	3.0%	0.0%
C27	Manufacture of electrical equipment	14.0%	0.0%
C33	Repair and installation of machinery and equipment	1.0%	31.0%
H50	Water transport	11.0%	56.0%
K65	Insurance, reinsurance, and pension funding, except compulsory social security	10.0%	0.0%
M69_M70	Legal and accounting activities; activities of head offices; management consultancy activities	4.0%	13.0%
	Total	100.0%	100.0%

¹¹ SIC = Standard Industrial Classification of economic activities. It consists of an industry classification system to sort data according to the kind of economic activity it is related to.

Project timeline

A project timeline of 21 years is considered for both wave and tidal projects, wherein it is assumed that the CAPEX is invested in the first year while the OPEX is invested equally over the next 20 years. The first year of exponential deployment is taken as 2022, in line with the cost modelling.

Input-output tables

GVA effects, used to estimate GVA benefits from project activities, are calculated from the Leontief Inverse of the combined 2014 industry-by-industry world IO tables. The world IO database provides a range of tables from different time periods that can be used for calculating these effects. In this case, the 2014 tables have been used [110]. Furthermore, type II GVA effects have been considered for our analysis to derive the total GVA generated (direct, indirect, and induced GVA benefits) from the investments made under wave and tidal projects. The process to calculate GVA effects is taken from the publicly available Scottish Government's Input-Output Methodology Guide [103].

6.1.2 GENERAL METHODOLOGY

An in-house GVA model has been used to assess the economic benefits derived from global deployment of wave and tidal energy projects. This has been developed by the Policy & Innovation Group at The University of Edinburgh, building on experience from previous projects like the Open Sea Operating Experience to Reduce Wave Energy Costs (OPERA) project, Tidal turbine Power Take-off Accelerator (TiPA) project etc. [111, 112]. The GVA model uses CAPEX and OPEX spend derived from the cost model and inputs from the value chain study by BVG Associates to define the project spend invested in each of the project activities [108]. The CAPEX and OPEX is the total spend of the technology development and is paid for by the combined costs of TP, MP, and Wholesale Market Price (WMP). The project spends invested in each of the activities is finally combined with the effects generated from the world input-output (IO) tables to estimate the GVA generated [113].

The methodology for conducting the adopted GVA analysis can be broken down into the following steps:

1. The annual CAPEX and OPEX invested globally for wave and tidal projects are calculated over the deployment timeline from the cost model. This expenditure varies accordingly, depending on the deployment timeline and the various deployment scenarios (defined in Table 6.1) taken into consideration for each technology.
2. The annual gross expenditure is multiplied with a leakage ready reckoner. Leakage ready reckoners are an indication of where items are manufactured/sourced from and is dependent on various cost centres. Because a global scope is considered for the deployment, it is assumed that 0% of the spend is leaked or a 100% is retained by the economy. Thus, the spend is multiplied with 100% retention rate as shown in equation (6.7) below.

$$Spend \times LeakageReadyReckoner = Spend \times (1 - 0\%) = Spend \quad (6.7)$$

3. The annual investment is then multiplied with the sectorial contribution towards CAPEX and OPEX for tidal and wave deployments as provided in Table 6.3 and Table 6.4 respectively, adopted from the recent ETIP Ocean 2 Study [109]. This allows us to further split the investments by different sectors for both technologies.



4. The net investment amount distributed by sectors is finally multiplied with the type II GVA effects calculated from the Leontief Inverse of the combined 2014 world IO tables. This gives us the total undiscounted GVA benefits derived from the investments made under the project activities for ocean energy deployments within the global economy.

A schematic representation of the adopted methodology is given in Figure 6.1.

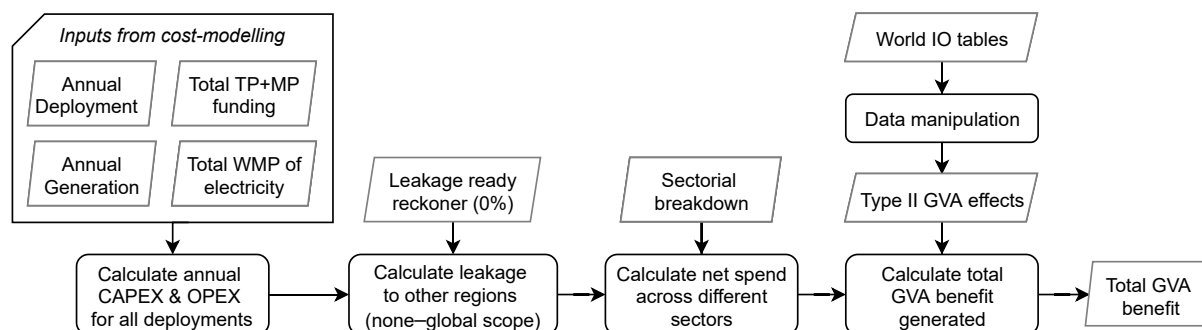


FIGURE 6.1: SCHEMATIC OF GVA METHODOLOGY

6.2 BENEFITS OF OCEAN ENERGY IN TERMS OF GROSS VALUE ADDED

The monetary benefits of ocean energy in terms of GVA generated can be calculated using the methodology above. It is important to note that the total spend of the technology development (i.e. CAPEX + OPEX) is paid for by a combination of subsidy (both TP and MP) and WMP of electricity. The WMP covers the value of the electricity produced and is set by market forces.

The GVA results below are presented in two ways: firstly, the intermediate results of GVA generated from the total CAPEX and OPEX and, secondly, the GVA generated compared to spend on TP and MP funding policies, which is the primary focus.

6.2.1 GVA CALCULATED FROM TOTAL EXPENDITURE

The GVA generated from the total expenditure has a similar ratio to the total expense in all scenarios due to the methodology followed and assumptions made, as discussed section 6.1.

Table 6.5 below gives us a breakdown of the CAPEX and OPEX in each of the deployment scenarios (refer to Table 6.1) for the tidal sector and the associated GVA benefits derived from them. The scenarios to meet cost parity requires a total expense of approx. €31 bn but generates around €36 bn in GVA. As cost parity is met with just 11 GW of deployment, the scenarios to deploy 100 GW are more attractive. A total expense of approx. €160 bn generates over €185 bn in GVA. Delaying the deployment until after the cost reduction is slightly cheaper as seen in section 5.2, but these also generate slightly less GVA.

TABLE 6.5: UNDISCOUNTED EXPENSE AND GVA GENERATED FOR TIDAL SCENARIOS

Scenario & deployment goal		Exponential deployment growth rate	Last Deployment	Total CAPEX (€bn)	Total OPEX (€bn)	Total Expense (€bn)	GVA generated (€bn)
(4) Deployment in parallel from start	cost parity	30%/year	2043	18.7	12.8	31.5	36.2
	100GW		2051	91.9	70.7	162.6	186.0
(6) Delay deployment after step-change	cost parity		2048	18.0	12.7	30.7	35.2
	100GW		2056	91.2	70.6	161.8	185.0

For the wave sector scenarios, the corresponding CAPEX and OPEX breakdown and the associated GVA benefits derived from them can be seen in **¡Error! No se encuentra el origen de la referencia..**. Besides a similar set of assumption used for the tidal scenarios, the wave scenarios have an additional assumption where the deployment growth rate is either 30%/year or 60%/year. The expense and GVA figures are similar for the 30%/year and 60%/year exponential deployments. However, since these deploy the technology at different rates, the overall deployment timescales are very different for these scenarios, and if discounted (present value) GVA would look very different.

All scenarios considered to meet cost parity require a total expense of approx. €320 bn and generate around €365 bn in GVA. The scenarios to deploy 100 GW of wave energy have approx. €280 bn in expense for a GVA of just over €320 bn. Similarly, to the tidal scenarios, delaying deployment requires marginally less expenditure, with a corresponding reduction in GVA generated. In all instances, the faster deployment trajectory of 60%/year costs marginally more than the equivalent 30%/year scenario, with the corresponding increase in GVA generated.

TABLE 6.6: UNDISCOUNTED EXPENSE AND GVA GENERATED FOR WAVE SCENARIOS

Scenario & deployment goal		Exponential deployment growth rate	Last Deployment	Total CAPEX (€bn)	Total OPEX (€bn)	Total Expense (€bn)	GVA generated (€bn)
(4) Deployment in parallel from start	cost parity	30%/year	2054	179.8	140.8	320.5	365.9
	100GW		2053	158.3	123.7	282.0	322.0
(6) Delay deployment after step-change	cost parity		2059	179.0	140.6	319.6	364.8
	100GW		2058	157.60	123.5	281.1	320.9
(4) Deployment in parallel from start	cost parity	60%/year	2039	180.2	142.3	322.5	368.0
	100GW		2039	158.5	124.9	283.4	323.4
(6) Delay deployment after step-change	cost parity		2044	178.5	141.3	319.8	364.9
	100GW		2044	156.7	124.0	280.7	320.3

6.2.2 GVA COMPARED TO SPEND ON FUNDING POLICIES

While the GVA model is based on the total expense of the technology deployment, i.e. CAPEX and OPEX, what we are interested in is the balance of GVA generated to the spend on TP and MP funding policies. Figure 6.2, Figure 6.3, and Figure 6.4 show this breakdown of the spend on TP and MP funding policies (calculated in section 865.3) for tidal and wave scenarios together with the GVA generated. It should be re-iterated that in addition to these funding policies, the deployed



technologies also receive the WMP of the electricity generated (as shown in section 865.3) but this is not included in the figures below.

Under tidal deployment, all scenarios have a TP and MP funding of approx. €3 bn and €10 bn, respectively. The breakdown for spend under funding policies and the GVA generated for both tidal scenarios can be seen in Figure 6.2. The scenarios to meet cost parity generates around €36 bn in GVA, about 2.5 times the funding. The impact of the un-subsidised deployment in the scenarios to reach 100 GW deployment is even more pronounced, with a GVA of over €185 bn, largely funded though the renewable electricity generated (i.e. the WMP).

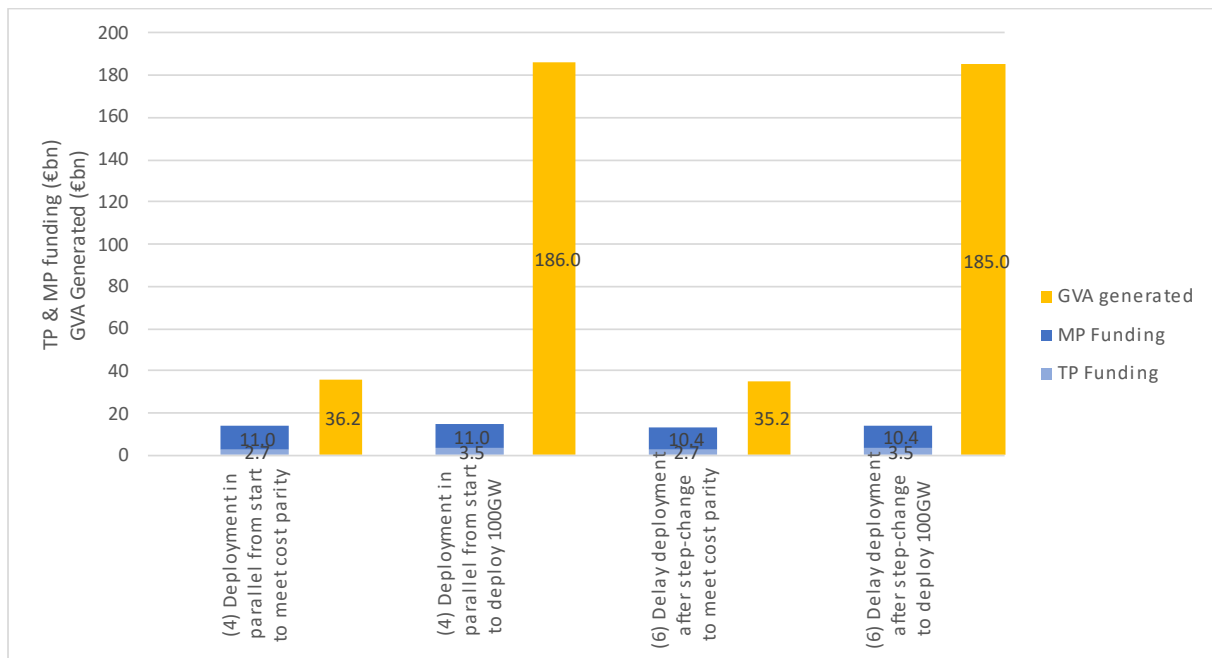


FIGURE 6.2: UNDISCOUNTED SPEND ON FUNDING POLICIES AND GVA GENERATED FOR TIDAL SCENARIOS

As with the tidal scenarios, Figure 6.3 and Figure 6.4 give us the representation of the TP and MP funding policies associated with the spend (calculated in section 865.3) for wave scenarios and the GVA benefits derived from it. In all scenarios, the total funding (TP + MP) is around €115 bn, with GVA of €320–380 bn. The GVA is thus 2.6–3.1 times the spend on funding policies. The total subsidised deployment to meet cost parity in these scenarios is almost 120 GW, resulting in a slightly larger GVA for these scenarios. The faster deployment trajectory (60%/year) requires slightly more funding and generates marginally more GVA than the corresponding baseline trajectory (30%/year).

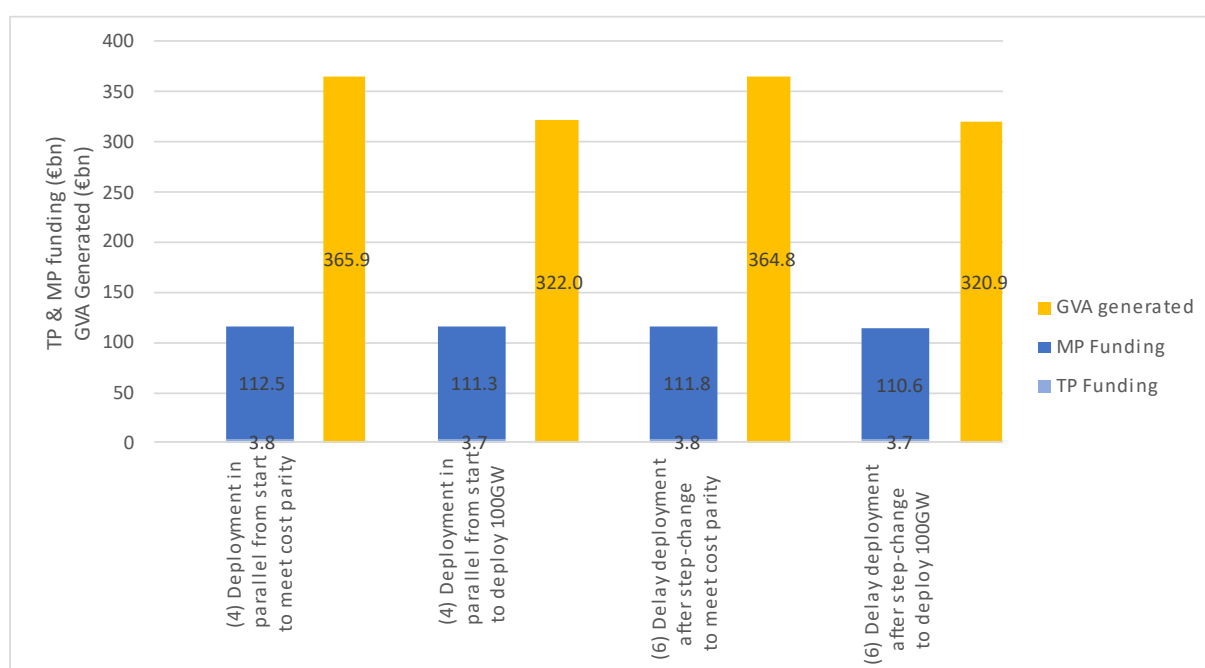


FIGURE 6.3: UNDISCOUNTED SPEND ON FUNDING POLICIES AND GVA GENERATED FOR WAVE SCENARIOS WITH A 30%/YEAR EXPONENTIAL DEPLOYMENT GROWTH RATE

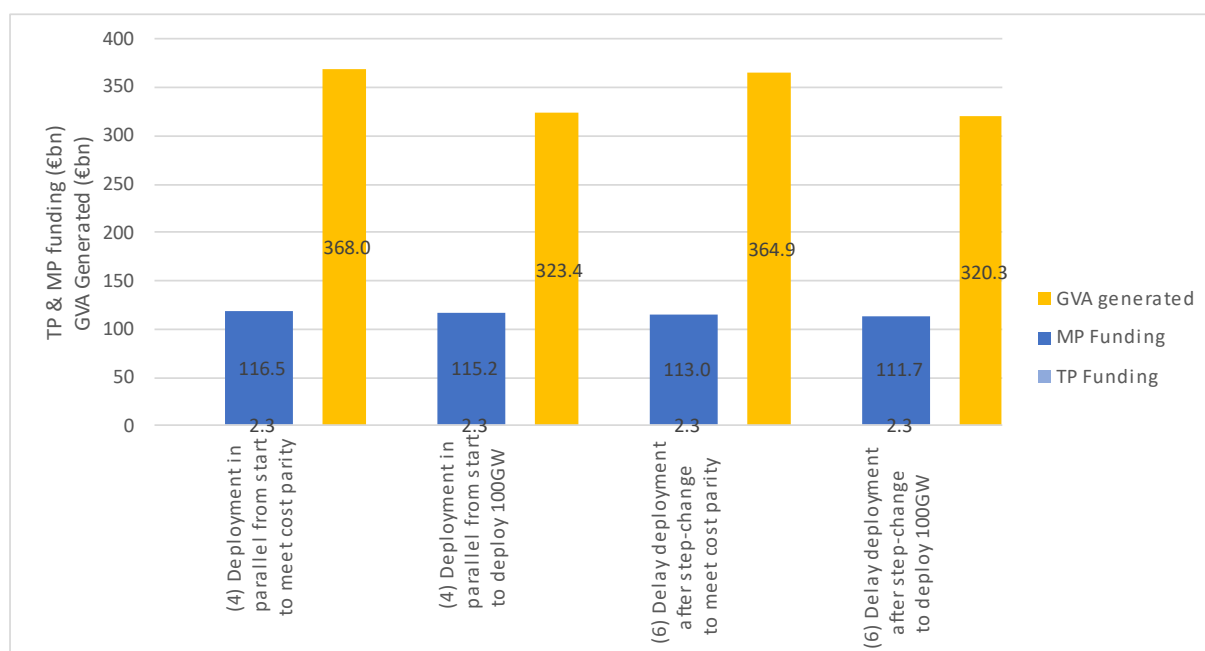


FIGURE 6.4: UNDISCOUNTED SPEND ON FUNDING POLICIES AND GVA GENERATED FOR WAVE SCENARIOS WITH A 60%/YEAR EXPONENTIAL DEPLOYMENT GROWTH RATE

6.3 OTHER SOCIAL AND ENVIRONMENTAL BENEFITS OF OCEAN ENERGY

The rise in public concern on climate change impacts and the cost-competitive nature of renewable technologies compared to conventional fuelled power plants have accelerated the global transition to low-carbon economies with large-scale deployment of renewable energy. Declining technology costs, maturing markets and supporting policies have made the renewable energy industry more attractive. Power generated from new wind and solar PV plants is now becoming increasingly cost-competitive compared to conventional fossil fuel-fired power plants in many places. The 2020 IRENA report [50] states that new solar PV and onshore wind power now costs less than operating coal power plants and that the falling costs of renewables along with stringent market policies can aid towards a green recovery. Countries are increasingly deploying renewable energy to diversify their energy mix, reduce their carbon footprint and demonstrate leadership on broader sustainability commitments.

This section describes the other social and environmental benefits of ocean energy. Together with the economic benefits discussed in section 6.2, they provide a holistic picture of the benefits that can be derived from the global deployment of ocean energy projects.

6.3.1 BENEFITS AND NEGATIVE EXTERNALITIES OF CONVENTIONAL RENEWABLE AND LOW CARBON ENERGY SOURCES

6.3.1.1 BENEFITS

Apart from achieving climate commitments and reductions in costs, renewable energy also offers many economic, social, and environmental benefits. Some common benefits derived from renewable sources are greenhouse gas (GHG) emissions reductions, energy security, low maintenance requirements, lower vulnerability to the volatility of fossil fuel prices, job creation, etc. Numerous studies and research have been conducted to investigate the costs and benefits of conventional renewable energy deployment around the world. Despite having high upfront costs, geographic limitations, and intermittent behaviours, the long-term benefits of renewable energy far outweigh the drawbacks. An overview of some of these studies is discussed in brief below.

Barbose et al. [114] explores the costs, benefits, and other impacts of the 2013 US renewable energy standards (RPS). The analysis found that by increasing RE generation technologies like solar, wind, biomass, geothermal, hydropower and landfill gas, a considerable number of reductions was found in air pollution, greenhouse gas emissions, and water use. Additional benefits were also noted in the form of job additions, wholesale electricity market price suppression, and natural gas price suppression. The analysis found that the GHG and air pollution emissions reduction generated an approximate \$7.4 bn in 2013 while a reduction in wholesale electricity prices and natural gas prices, saved consumers approximately \$1.3–4.9 bn. In addition, water withdrawals and water consumptions worth 830 billion gallons and 27 billion gallons were reduced. Sofia et al [115] developed a cost-benefit analysis of Italy's 2030 decarbonisation scenarios and estimated environmental benefits such as air pollution reduction and social benefits in the form of morbidity and mortality reduction. Overall, they found that the total benefits are higher than the mitigation cost of the strategies to be adopted for decarbonising various sectors. Similar research has also been conducted to assess the benefits and



externalities of other RE technologies. A cost-benefit analysis of solar PV implementation in Kuwait [116] found that the total fuel savings along with the CO₂ emission savings could significantly reduce the true economic cost of LCOE of a PV system. Another study that investigates the social cost and benefits of solar PV deployment in India [117] found that the social benefit is greater than the social cost in the case of solar power in India. The authors found employment generation, global warming reduction, rural electrification and reduction in fossil fuel subsidy as some of the social benefits of solar power projects. On the other hand, high generation costs and health hazards from solar projects were noted as some of the social costs.

Numerous studies also discuss the financial and environmental impacts of wind energy. For example, Baringa [118], in their cost-benefit analysis of wind development in Ireland over the period 2000-2020, reported key financial benefits of wind in the form of wholesale energy cost savings, capacity payment savings and avoided non-compliance costs. Other benefits in the form of reduced exposure to volatile fuel prices and avoided carbon emissions were also noted. Similarly, Sustainable Energy Ireland [119] reviewed the costs and benefits of offshore wind deployment in Ireland and found, apart from aiding in achieving renewable energy targets and emissions savings targets, significant economic returns in the form of avoided fossil fuel imports and royalties earned. The report also mentions other benefits such as industrial development, fuel diversity and sustainability.

6.3.1.2 NEGATIVE EXTERNALITIES

The studies reveal that the transition to renewable energy systems will not only procure economic returns but also promote a sustainable future. However, alongside the benefits derived from these energy sources, many of them have some form of negative externalities or impacts associated which can be again found in the literature. Andrzej et al. [120] discuss some of the most notable externalities of clean electricity production, which are summarised in Table 6.7. For example, production of biomass at a commercial scale for electricity and heat generation not only leads to the increase of food and feed prices but also causes environmental degradation, through consumption of water resources and decrease of biodiversity [121] [122]. Burning of biomass also releases atmospheric emission affecting health and causing pollution [123] [124]. Furthermore, land economics is another challenge for biomass where it has been found that generating a significant amount of energy from biomass would require large amount of land [125] [126]. While the more popular solar PV plants are more environmentally sustainable, they are challenged with the problem of intermittency, recycling, and waste treatment [120]. A significant amount of research and monitoring of the waste treatment problem for solar PV plants is still required. Similarly, technical malfunctions, noise, vibration, flashing glare and space requirements are some of the major challenges in the wind energy sector [120]. Martijn et al. [127] investigate the effect of wind turbines on house prices and find that house prices decrease by 0.7 to 3.1% if located within 2 kms of an operational wind turbine. Unpredictability of wind-based energy generation and limitation of wind harvesting technologies in frigid and north temperate zones are some other drawbacks for wind power plant [120]. Matteo et al. [128] conducted a meta-analysis of hydropower externalities and found evidence on strong public aversion towards deteriorations in landscape, vegetation, and wildlife. The authors also found that welfare losses due to environmental deteriorations outweigh gains of GHG reductions. Furthermore, nuclear energy faces the challenges of radioactive by-product storage and the failures associated with nuclear



energy, even though rare, can be very catastrophic like the 1986 Chernobyl disaster and the 2011 Fukushima disaster [120]. The table below provides a summary of the externalities related to different types of renewable power generation [120].

TABLE 6.7: SUMMARY OF EXTERNALITIES FROM OTHER RENEWABLE AND LOW CARBON POWER SOURCES, ADAPTED FROM [120]

Technology	Effect on human health	Nuisance for humans	Environmental impact	Worst-case disaster scenario
Nuclear	Increased long-term radiation exposure for staff	—	Environmental hazards due to nuclear waste storage	Catastrophic environment pollution and human health hazard
Biomass (thermal)	Not sufficiently investigated, potentially significant due to organic material combustion	—	Significant due to crop fields designated for energetic plants	Local, in case of biogas generator fire
Geothermal (man-made)	Groundwater pollution, air pollution	No information available	Groundwater pollution, air pollution	No information available
Hydropower	—	Deteriorations in landscape, vegetation, and wildlife	Deteriorations in landscape, vegetation, and wildlife	Catastrophic flooding due to dam breach
Solar concentrated	—	Large area needed	Lethal threat to flyby birds	Fire, releasing steam to atmosphere
Solar PV	—	—	Area consuming, potential problems due to modules recycling	—
Wind turbines	—	Noise, vibration, flashing glare, large area needed	Noise, vibration, Collision risks for aviation	Local disruption due to turbine failure

6.3.2 OTHER BENEFITS OF MARINE ENERGY

While there is an extensive amount of literature available on the more generic forms of renewable energy, there is very limited public perception and understanding of the benefits of the ocean energy (OE) sector. More specifically, the awareness of wave and tidal energy in comparison to the more conventional and popular sources of renewable energy is relatively low. This is because, unlike other forms of renewable energy, this sector is comparatively new and still under development with very few projects deployed at a pre-commercial scale. Thus, an understanding of the benefits from the wave and tidal sector reflects the information available from the pilot projects around the world. The quantification of some of these economic benefits is discussed in more detail in the GVA analysis of the wave and tidal sectors presented in section 6.2 of the report. It is understood because it is not

possible to quantify all benefits; a more qualitative review of some benefits around these nascent sectors is presented here.

Most of the benefits from the conventional forms of renewable energy like wind, solar, hydro, nuclear, biomass, among others, also apply to the OE sector [129]. For example, wave and tidal energy production reduces greenhouse gas emissions by displacing fossil fuel-based generation and provides environmentally friendly and easily assimilated grid connection for meeting load requirements. In turn, this reduces dependence on imported energy and risks of fossil fuel price volatility, thereby increasing energy security. At the same time, wave and tidal energy, even though relatively new, can stimulate economic development and output while generating revenue and employment opportunities at different stages of project development [130]. Therefore, construction and operation of wave energy plants along the coastal region can induce significant positive socio-economic benefits to these regions. For example, a study by the Electric Power Research Institute (EPRI) found that operation and maintenance activities alone for a 100 MW wave power deployment would create about 25 direct local jobs [131].

Apart from the generic forms of transferrable and common benefits available across all forms of renewable energy, many of the negative externalities (refer Table 6.7) seen across other renewable resources are absent in the OE sector. This includes challenges like air pollution, exposure to dangerous radiations, environmental hazards, waste storage, need for large areas, catastrophic damages, human health hazards, etc. This makes the OE sector comparatively less risky and far more favourable from the environment and human health perspective. Furthermore, the wave and tidal sectors can also potentially create significant social benefits, including benefits for rural and coastal communities and economies [132, 42].

In common with offshore wind farms, ocean energy arrays may provide additional benefits to the aquatic environment. Research shows that the closing of an offshore area to vessel movements and fishing activities can cause the area to act as a Marine Protected Area (MPA), decreasing fishing pressure and allowing fish to breed naturally [133, 134]. Absence of disturbance helps the area act as a refuge for exploited species and habitats, allowing them to recover and regenerate. This leads to spillover effects benefiting adjacent fisheries by net emigration of fishes across borders, and export of pelagic eggs and larvae [135]. It is also seen that foundation or anchoring components in the form of hard substrate and seabed structures can have artificial reef effects leading to colonisation by benthic organisms, attracting other marine organisms and acting as fish aggregating devices (FAD) [136, 137, 138]. Thus, OE can help restore seabed areas lost through commercial fishing methods [134]. This can also enhance tourism opportunities beyond sightseeing and fishing experiences.

Although wave and tidal energy are intermittent and not 'dispatchable', they offer additional benefit to the grid. Due to the predictable motion of the planets, tidal generation can be forecast even years in advance. Additionally, Lewis et al. found that fine-scale power variability appears low for tidal-stream energy, increasing its value to the grid [139]. Research has also shown that wind and wave resources are not strongly correlated and that co-located farms could have significantly lower costs than standalone [140]. In addition, wave energy has proven more forecastable than wind or solar



[141]. OE devices may also have a lower visual impact than other forms of generation, because they could often be located far offshore with a significant portion or completely under water [131].

Ocean energy can be particularly beneficial to remote islands and coastal areas due to its ability to provide both power and promote economic growth by establishing local supply chain networks, enabling linkages to global supply chains and markets, encouraging local skilled workforce, and enabling social inclusion. In addition, the sector can also support opportunities for co-design and integration with other infrastructure including coastal resilience and disaster recovery [142].

While most of these benefits are discussed concerning the OE sector, a better understanding of the qualitative benefits concerning wave and tidal projects can be made once the technology matures and more devices are deployed commercially. Overtime, most of these benefits might vary depending on location, season, design, and scale of the devices deployed. Multi-disciplinary research with strategic collaboration between developers, academicians, communities, and the public sector will assist in further investigating the benefits of the wave and tidal sector.



7. DISCUSSION

7.1 DISCUSSION OF CASE STUDIES AND RESULTING LESSONS THAT COULD BE APPLIED TO THE OCEAN ENERGY SECTOR

This section will draw lessons learned from the experience of the other energy sectors reviewed in section 3. It is important to note that despite the similarities that might exist, it is not possible to compare like-for-like. Thus, we will not be directly comparing the sectors as the indicators vary among the different countries. However, trends existing between similar sectors (i.e. German vs Japanese solar, German vs Danish wind) shall be explored here. Based on the discussion, suggestions will be drawn for the OE sector. For example, Danish wind has a lot of exports and could be transferring some of its learning to other sectors. Similarly, German solar has significant imports driving domestic deployment but limited local manufacturing. What can ocean energy learn from these two examples?

It is understood that despite the existing trends and relative success of these mature case studies, not all learning might be valid for the OE sector. Within the case studies, only a few possible factors responsible for the growth of these sectors have been explored which might be relevant. This is because these sectors were conceived more than 30 years ago, and we have considered only a fraction of this period in our analysis. Thus, what was applicable back then might not be quite so relevant now. Nevertheless, the lessons learned from other energy sectors can still help shape enabling and supportive legal frameworks to aid the commercialisation of the OE.

While the case studies focus only on the wind and solar PV sector, learnings from other sectors such as aerospace, oil & gas, the automotive industry, among others further explored in DTOceanPlus D8.2 Analysis of the European Supply Chain [106] can also prove to be quite valuable. From the case studies, some common learning can come in the form of target setting, adopting a mix of support mechanisms, investing in local supply chain capabilities, ensuring a competitive environment, etc. Apart from these, OE can build on their existing experience by either making use of some elements in their supply chain, adopting technologies and/or materials from these other sectors. In this way, the OE would benefit from this spillover effect.

Some key indicators and ratios from the case studies are summarised in Table 7.1 más adelante for reference.



TABLE 7.1: SUMMARY OF INDICATORS AND RATIOS FROM CASE STUDIES (2000-2018)

Case study:		German solar PV	Japanese solar PV	German onshore wind	Danish wind (onshore & offshore)
Indicator or ratio					
Cumulative deployment (GW)	in 2000	0.1	0.3	6.1	2.4
	in 2018	45.2	56.1	52.4	6.1
	increase	45.1	55.8	46.4	3.7
Total Generation (TWh)		305.5	267.6	827.9	166.8
Total LCOE reduction		-67.6%	-75.0%	-52.6%	-63.6%
Total TP funding (€bn)		1.02	1.5	0.63	0.22
Total MP funding (€bn)		94.91	69.34	74.5	5.34
MP / TP (-)		93.0	46.6	117	24.6
TP / Deployment (€/MW)		0.023	0.027	0.014	0.058
MP / Deployment (€/MW)		2.106	1.242	1.607	1.433
TP / Generation (€/MWh)		3.33	5.56	0.77	1.3
MP / Generation (€/MWh)		310.6	259.1	89.97	32.0
TP+MP / Generation (€/MWh)		314.0	264.7	90.74	33.3

7.1.1 GERMAN SOLAR

The German Renewable Energy Sources act EEG has been key in the growth of both its solar and wind sector in the country [143]. Germany made funding available towards more competition and cost efficiency in the solar PV sector, via a combination of technology-push and market-pull mechanisms. The country spent an approx. total of €96 bn TP and MP funding support between 2000 and 2018 in the sector, of which almost 99% of the share is taken by MP funding policies.

During this period, the funding support contributed towards cumulative deployment, generation, and improved capacity factors, which led to the decrease in the levelised cost of energy by 67.6%, from 0.28 €/kWh in 2010 to 0.09 €/kWh in 2018. **For the nascent OE sector, this could prove to be a useful learning where strong and consistent investment support policies are seen lacking.** The strong investment support within the German solar sector also triggered economic stimulus in other sectors through personnel demand, auxiliary services, spare parts, fuel, etc., which in turn generated a 14% return on investment (ROI) for the sector based on Germany's TP and MP support. **Similar to the German Solar sector, significant investment in the OE sector (which already shares a great deal of similarity with the more mature renewable energy sectors) could also prompt economic stimulus in these other sectors with which it is associated (e.g. offshore wind, onshore wind etc.).** However, it is to be noted that the economic stimulus (worth €13.26 bn) generated from the operation of the German Solar PV plants is comparatively much lesser than the MP funding support provided (worth €94.91 bn). **This means it will take more than 7 times the turnover to pay back the investment made through the MP policies; something that cannot be easily replicated in the OE sector in the near-term future.**



It is also seen that even though the country invested heavily around cost efficiency, production and deployment, the sector is heavily dependent on imports with limited local manufacturing. It is estimated that nearly 30% of the German FiT is transferred to Asia due to imports of modules. In 2012, the German Solar PV manufacturers lost a significant part of their global and German market share due to the aggressive industrial and investment policies in Asia. **For the emerging OE sector, investing in local manufacturing capabilities from an early stage will allow the sector to be less dependent on foreign sources and retain the investment made within the region itself.**

7.1.2 JAPANESE SOLAR

For the Japanese solar sector, consistent TP funding through the '1974 Sunshine Program' laid the foundation for the development of the sector. The Japanese PV sector first developed in the residential rooftop market with a mix of RD&D and investment subsidy programmes, and it was only after the 2011 Fukushima disaster that the sector reached commercialisation. It is to be noted that commitment from the Japanese government to produce a substantial amount of solar power by 2000, instigated private investment and provided stimulus for many private firms to expand their activities in PV development. **This could be an important lesson for the OE sector where commitment from local governments and the establishment of legally binding targets to incorporate OE into the RE mix is still missing. Dedicated government support along with a target for OE production will instil the required investment support necessary for the commercialisation of the technologies.**

The Japanese PV sector spent approx. €71 bn in TP and MP funding support between 2000 and 2018, of which almost 98% is taken by MP funding policies. The Japanese government spent 46 times more in MP mechanisms than in TP policies whereas the German government spent 93 times more. During this period, the Japanese Solar PV LCOE decreased by approx. 75%, from 0.60 €/kWh in 2010 to 0.15 €/kWh in 2018 and had a sector valuation of approx. €122 bn, inclusive of imports. When compared with the German Solar sector (LCOE of 0.09 €/kWh in 2018), the LCOE for the Japanese PV sector is on a comparatively higher end because of its bigger installation costs and installation time. Furthermore, technical and institutional barriers contributed towards the increase in price for Japanese modules and systems. **This could be a useful lesson for the OE sector where ensuring competition between the manufacturers and developers while providing opportunities for international companies to participate in the local sector will be highly influential in driving down the costs and bringing technological improvements.** It is also important to bear in mind that with a third of the spend for German solar coming from Asia, we can hardly assume that the German and Japanese PV sectors are reducing costs in complete isolation from each other. There will certainly have been some knowledge transfer involved between them.

Despite the strong investment support within the Japanese Solar sector, falling FiT rates towards 2015 led to a decrease in annual installations and drove many solar companies to bankruptcy. This is because the sector was highly dependent on MP funding instruments and not commercially viable by itself. **As a lesson for the OE sector, it should be ensured that the sector is competitive enough to sustain without any form of economic support before drastically readjusting MP funding strategies.**



7.1.3 GERMAN ONSHORE WIND

For the German onshore wind sector, a mix of TP and MP funding strategies have supported this sector's innovation path while driving the fast expansion of the installed capacity. The country spent approx. €75 bn in TP and MP funding support between 2000 and 2018 on the sector, of which almost 99% was MP funding policies. Furthermore, the country invested over 117 times more in MP mechanisms than in TP, comparatively higher than the solar PV sector where it spent 93 times more in MP than TP. The Federal Energy Research Funding and FIT investment strategies have been quite influential in driving R&D activities and innovations within the country besides supporting numerous German and international onshore wind manufactures present within the country. **As seen in previous case studies, consistent investment support from the local governments for the OE sector is pertinent in bringing about innovations and cost reductions within the sector.**

During this period, the LCOE of German onshore wind farms decreased over 52.6%, comparatively lesser than the solar PV sector where it decreased over 67%. However, the ROI within the German onshore wind sector is nearly 26% whereas for the solar PV sector it is only 14%. The higher economic returns could be because of the growing onshore wind capacity within the country and the presence of various German manufacturers that account for 49% of the market within the country. In addition, due to the booming wind sector within the country alongside a strong supply chain, the German wind sector has a higher share in jobs per installed capacity compared with the solar PV sector. **As mentioned earlier, investing in local manufacturing capabilities and establishing a strong supply chain from an early stage for the OE sector will lead to less dependency on foreign sources while bringing along economic benefits for the local economy.**

7.1.4 DANISH WIND

As a pioneer of wind energy development in Europe and one of the most significant exporting industries, Denmark can provide relevant lessons for the promotion of renewable energy and the efficacy of TP and MP mechanisms to support the commercialisation of these RET. The country spent approx. €5.5 bn in TP and MP funding support between 2000 and 2018 on the sector, much less than the total spent by Germany. Denmark invested over 24 times more in MP mechanisms than in TP, comparatively lesser than Germany who spent 117 times more in MP than TP. However, the TP and MP balances are diverse and respond to the realities of the local economies, interest of the local governments, legal frameworks, and the strength of the supply chains, among others. Therefore, a support mechanism that proved successful in one country might not necessarily have the same efficacy in another country.

A key player in the global wind market, the Danish wind sector is an important source of revenue and employment for the country. The €5.5 bn spent in support mechanisms have enabled €181 bn in revenue and 509,587 full-time jobs over the 2000–2018 period. The Danish manufacturer Vestas is the largest wind turbines manufacturer in the world and exports a high share of Danish wind turbines globally. As a forerunner in the wind energy sector, it is quite possible that the global onshore wind sector (including German wind) has experienced cost reductions derived from the learning experienced in the Danish wind sector. **This transferrable learning experience can also prove to be**



quite valuable for the OE sector particularly in terms of supply chain strengthening, taking advantage of spillover learning from associated industrial sectors, export strategies and the establishment of financial support mechanisms.

7.2 COMPARISON OF COST MODELLING WITH CASE STUDIES USING FUNDING RATIOS

In the review of case studies in section 3, several ratios are used to quantify the results found. These ratios can be compared to corresponding ratios calculated for the various scenarios used in the cost modelling in section 5. The ratios used are the balance of funding policies, i.e. MP to TP, and the ratios of spend to deployment and to subsidised generation, namely TP to deployment, TP to generation, MP to deployment, MP to generation, and total TP + MP spend to generation.

Although it is interesting to compare the cost modelling with the real-life case studies of other sectors, these two sets of results represent different technologies at different stages of development, over different periods and with different geographical scope. However, more knowledge transfer may be possible now. These factors should be considered when directly comparing these numbers.

A summary of the results from the case studies is presented on page 112 in Table 7.2, with results from the cost modelling scenarios in Table 7.3 for tidal and Table 7.4 for wave. The two most attractive scenarios from the cost modelling are highlighted in these tables, namely (4) and (6) with higher learning rate and a step-change cost reduction but differing in whether or not the subsidised deployment occurs in parallel with the step-change. The ratios are discussed below in turn.

Market Pull to Technology Push (MP/TP)

The cost modelling shows that increased spending on TP policies that lead to faster/larger cost reductions in the early stages can significantly reduce the overall subsidised deployment required (a MP mechanism). This equates to a lower ratio of MP/TP being potentially more attractive, noting that the balance seen in the development of other renewable energy technologies may have been biased too far in terms of MP subsidies [144, 145, 146]. The case studies range from 25 to 117 on this metric. The largest cost reductions (of 75% in Japanese solar PV) were achieved while spending 46 times more on MP than TP, whereas the lowest reductions (~53% for German wind) had 117 times more on MP.

As there are no TP policies in scenario (1), this ratio does not apply. The tidal scenarios all have MP/TP ratios between 3 and 38, and wave scenarios (4), (6) and (7) are all within the range 5–51. However, some of the wave scenarios have a much higher ratio of MP/TP for the same cost reduction, around 600 for scenarios (3) and (5) and 100–200 for (2). This shows that the LCOE reduction can be achieved more efficiently by spending more on TP policies than these scenarios.

Technology Push to Deployment

The case studies range from €0.023–0.056 million/MW spent on TP policies. Most of the cost modelling scenarios are at the lower end of this range or below. The exception is scenarios (4) and (6) for tidal to meet cost-parity, where the ratio is €0.245 million/MW, but this discrepancy disappears



when considering increased deployment in the 100GW deployment scenarios. The fact that the cost modelling scenarios are mostly lower could suggest more effective funding mechanisms per unit deployment than has occurred historically, resulting from the assumptions used.

Market Pull to Deployment

The case studies range from €1.2–2.1 million/MW spent on MP policies. Most of the cost modelling scenarios lie within this range or just below, with a few notable exceptions. This emphasises that the cost modelling results reflect similar levels of funding for ocean energy that wind and solar have been able to access historically.

As cost parity is met before 100 GW is deployed in most of the tidal scenarios, these have a much lower ratio (as low as €0.1 million/MW) when considering the cost to deploy the 100 GW as much of this is not subsidised. Conversely, wave scenarios (1) and (2) have a higher ratio of €2.5–3.6 million/MW to deploy 100GW as this first 100GW has a relatively high LCOE.

Technology Push to Generation

The case studies range from 0.77–5.56 €/MWh spent on TP policies. This reinforces the hypothesis above that more cost-effective LCOE reduction might be achieved by spending more on TP policies than in scenarios (1), (2), (3), and (5) without a step-change cost reduction or policies to facilitate enhanced learning, as these scenarios are mostly lower (and in some cases significantly so) than has been observed. The exception to this is the tidal scenario (2).

Market Pull to Generation

It should be noted when comparing subsidy to generation that MP subsidies are only a part of the revenue earned by generators in addition to the WMP of electricity. The case studies range from 32–310 €/MWh spent on MP policies for electricity generation over the period 2000–2018; however, this includes subsidy to earlier deployment of more expensive technologies and excludes future years where the LCOE has reduced significantly.

On this metric, all cost modelling scenarios are at the lower end of this range or below. The cost modelling considers the MP support paid over the 20-year project lifetime. Due to the smooth and continuous cost reductions modelled, the scenarios to reach market parity have many deployments with small subsidy, which might skew this metric to be lower than the case studies.

The scenarios with either a lower $LCOE_c$ or that include a step-change cost reduction and/or with a higher LR require a reduced amount of subsidised generation, and thus have the lowest ratios on this metric of around 15–18. The large amount of unsubsidised generation in the 100 GW tidal deployment scenario skews this much lower to just 1.7, but this is not directly comparable to the case studies.

Total Spend (TP+MP) to Generation

The case studies range from 33–314 €/MWh spent on TP+MP policies. Overall, this is very similar to the MP to generation ratio as the amount spent on MP policies is significantly larger than spent on TP, both for the case studies and the scenarios considered in the cost modelling. This re-iterates the fact that subsidising a lot of deployment to get cost reductions is expensive. Step-change reductions in LCOE during the early years are a much more cost-effective method if achievable.



7.2.1 TABULATED RESULTS

TABLE 7.2: RATIOS OF TECHNOLOGY PUSH, MARKET PULL FUNDING AND GENERATION FOR CASE STUDIES (2000–2018)

Case study	Cumulative deployment (GW)			Total TP+MP funding (€bn)	Total LCOE reduction	MP/TP (–)	TP/Deployment (€/MW)	MP/Deployment (€/MW)	TP/Generation (€/MWh)	MP/Generation (€/MWh)	TP+MP / Generation (€/MWh)
	in 2000	in 2018	increase								
German solar PV	0.1	45.2	45.1	95.9	-67.9%	93	0.023	2.106	3.33	310.6	314.0
Japanese solar PV	0.3	56.1	55.8	70.8	-75.0%	46.6	0.027	1.242	5.56	259.1	264.7
German onshore wind	6.1	52.4	46.4	75.1	-52.6%	117	0.014	1.607	0.77	89.97	90.74
Danish wind (onshore & offshore)	2.4	6.1	3.7	5.5	-63.6%	24.6	0.058	1.433	1.30	32.00	33.30

TABLE 7.3: RATIOS OF TECHNOLOGY PUSH, MARKET PULL FUNDING AND GENERATION FOR TIDAL SCENARIOS

Scenario	Technology Push		Market Pull	Total subsidised deployment (GW)	Total TP+MP funding (€bn)	Total LCOE reduction	MP/ TP (–)	TP/ Deployment (€/MW)	MP/ Deployment (€/MW)	TP/ Generation (€/MWh)	MP/ Generation (€/MWh)	TP+MP / Generation (€/MWh)
	Step-change cost-reduction	Policies for enhanced LR	FIT subsidy timescale									
To meet cost-parity (CDC ₀ =40MW, LCOE _C =200€/MWh, R _C =30%/year)												
(1)	None	No	Deployment only, from start	100.3	76.7	-75.0%	–	0.000	0.765	–	12.47	12.47
(2)	None	Yes		37.5	37.1		12.73	0.072	0.916	1.17	14.95	16.13
(3)	25%	No	Deployment in parallel from start	24.2	19.7		38.48	0.021	0.794	0.34	12.97	13.30
(4)	25%	Yes		11.0	13.7		4.07	0.245	0.997	4.01	16.30	20.31
(5)	25%	No	Delay deployment after step-change	24.2	19.1		37.27	0.021	0.769	0.34	12.56	12.90
(6)	25%	Yes		11.0	13.1		3.85	0.245	0.943	4.01	15.43	19.43
To deploy 100GW (CDC ₀ =40MW, LCOE _C =200€/MWh, R _C =30%/year)												
(1)	None	No	Deployment only, from start	100.0	76.7	-75.0%	–	0.000	0.767	–	12.51	12.51
(2)	None	Yes		37.5	37.4	-80.2%	11.46	0.030	0.344	0.49	5.60	6.09
(3)	25%	No	Deployment in parallel from start	24.2	19.7	-81.3%	38.48	0.005	0.192	0.08	3.14	3.22
(4)	25%	Yes		11.0	14.5	-85.2%	3.14	0.035	0.110	0.57	1.79	2.36
(5)	25%	No	Delay deployment after step-change	24.2	19.1	-81.3%	37.27	0.005	0.186	0.08	3.04	3.12
(6)	25%	Yes		11.0	13.9	-85.2%	2.97	0.035	0.104	0.57	1.69	2.27



TABLE 7.4: RATIOS OF TECHNOLOGY PUSH, MARKET PULL FUNDING AND GENERATION FOR WAVE SCENARIOS

Scenario	Technology Push		Market Pull	Total subsidised deployment (GW)	Total TP+MP funding (€bn)	Total LCOE reduction	MP/ TP (–)	TP/ Deployment (€/MW)	MP/ Deployment (€/MW)	TP/ Generation (€/MWh)	MP/ Generation (€/MWh)	TP+MP / Generation (€/MWh)
	Step-change cost-reduction	Policies for enhanced LR	FIT subsidy timescale									
To meet cost-parity (CDC ₀ =25MW, LCOE _C =350€/MWh, R _{CI} =30%/year)												
(1)	None	No	Deployment only, from start	1000†	1164.2	-75.0%	–	0.000	1.164	–	18.97	18.97
(2)	None	Yes		411.0	384.6	-87.5%	102.9	0.009	0.927	0.15	15.10	15.25
(3)	25%	No	Deployment in parallel from start	384.9	300.7		600.3	0.001	0.780	0.02	12.71	12.73
(4)	25%	Yes		118.2	116.3		29.61	0.032	0.952	0.52	15.52	16.04
(5)	25%	No	Delay deployment after step-change	384.9	300.0		598.9	0.001	0.778	0.02	12.68	12.70
(6)	25%	Yes		118.2	115.6		29.43	0.032	0.946	0.52	15.42	15.94
(7)	50%	Yes		21.0	24.6		6.95	0.148	1.025	2.41	16.72	19.13
To deploy 100GW (CDC ₀ =25MW, LCOE _C =350€/MWh, R _{CI} =30%/year)												
(1)	None	No	Deployment only, from start	100.0	364.5	-84.3%	–	0.000	3.645	–	59.42	59.42
(2)	None	Yes			252.1	-80.2%	119.0	0.032	2.489	0.52	40.57	41.09
(3)	25%	No	Deployment in parallel from start		198.6	-81.3%	600.3	0.005	1.981	0.08	32.29	32.37
(4)	25%	Yes			115.0	-85.2%	30.41	0.037	1.113	0.60	18.15	18.75
(5)	25%	No	Delay deployment after step-change		197.9	-81.3%	598.9	0.005	1.974	0.08	32.17	32.25
(6)	25%	Yes			114.3	-85.2%	30.22	0.037	1.106	0.60	18.03	18.64
(7)	50%	Yes			21.0	-90.1%	5.82	0.037	0.215	0.60	3.51	4.11
To meet cost-parity (CDC ₀ =25MW, LCOE _C =350€/MWh, R _{CI} =60%/year)												
(1)	None	No	Deployment only, from start	1000†	1171.5	-75.0%	—	0.000	1.171	0.00	19.09	19.09
(2)	None	Yes		413.4	386.3	-87.5%	183.0	0.005	0.929	0.08	15.15	15.23
(3)	25%	No	Deployment in parallel from start	397.6	306.5		611.9	0.001	0.770	0.02	12.54	12.56
(4)	25%	Yes		118.1	118.8		50.65	0.019	0.987	0.32	16.08	16.40
(5)	25%	No	Delay deployment after step-change	397.6	302.8		604.6	0.001	0.760	0.02	12.39	12.41
(6)	25%	Yes		118.1	115.3		49.15	0.019	0.958	0.32	15.61	15.93
(7)	50%	Yes		21.1	29.7		13.86	0.095	1.315	1.55	21.46	23.01



Scenario	Technology Push		Market Pull	Total subsidised deployment (GW)	Total TP+MP funding (€bn)	Total LCOE reduction	MP/ TP (–)	TP/ Deployment (€/MW)	MP/ Deployment (€/MW)	TP/ Generation (€/MWh)	MP/ Generation (€/MWh)	TP+MP / Generation (€/MWh)
	Step-change cost-reduction	Policies for enhanced LR	FIT subsidy timescale									
To deploy 100GW (CDC ₀ =25MW, LCOE _c =350€/MWh, R _{CI} =60%/year)												
(1)	None	No	Deployment only, from start	100.0	365.7	-84.3%	—	0.000	3.657	0.00	59.61	59.61
(2)	None	Yes			251.8	-80.2%	213.5	0.018	2.500	0.29	40.75	41.05
(3)	25%	No	Deployment in parallel from start		202.6	-81.3%	611.9	0.005	2.021	0.08	32.95	33.03
(4)	25%	Yes			117.5	-85.2%	50.65	0.023	1.152	0.37	18.77	19.15
(5)	25%	No	Delay deployment after step-change		199.0	-81.3%	604.6	0.005	1.985	0.08	32.35	32.44
(6)	25%	Yes			114.0	-85.2%	49.15	0.023	1.117	0.37	18.21	18.59
(7)	50%	Yes		21.1	30.0	-90.1%	12.05	0.023	0.277	0.37	4.52	4.89
† note that scenario (1) does not meet cost-parity but is limited at 1TW deployment.												



7.2.2 OTHER CONSIDERATIONS

It should be noted that the case studies are used as a benchmark of what has been observed before, but they are not a perfect comparison for several reasons.

- ▶ The case studies focus on how a technology has developed in a single country, although this is happening within a global context. The cost modelling has a global scope with the assumption that several countries are concurrently running programmes to commercialise wave and tidal energy.
- ▶ The periods analysed are different, with the case studies considering 2000–2018, whereas the scenarios for ocean energy are of varying length starting now. Energy policy was perhaps not seen as such a significant driver in the early stages of wind and solar PV development. The United Nations Framework Convention on Climate Change entered into force in 1994 [147]. Growing awareness of the climate emergency since then will likely give a different focus to policy makers in future. Similarly, decarbonisation of sectors such as heating and transport will change the demand for electricity in future.
- ▶ The case studies cover a defined period, and this does not specifically align with the cost modelling scenarios, which cover the period between first commercial arrays to meeting cost parity/deploying 100GW worldwide. The case studies start from a significantly higher deployment 0.1–6.1 GW, compared with 25 MW and 40 MW in the cost modelling scenarios. The MP subsidies from the case studies also do not reflect the total subsidy for devices deployed in this period, as it was not possible to disaggregate this information. Instead, they cover the total subsidy paid in this period (including to devices previously deployed but excluding future committed subsidy). Similarly, the highest levels of public R&D funding for solar and wind in some key countries were invested in the 1980s, well before the period covered by the case studies.
- ▶ Solar and wind power were largely competing with conventional thermal power generation and nuclear fission. Ocean energy will be commercialised in a world market with a significant proportion of existing intermittent renewable energy (primarily solar and wind), but there will likely also be future developments in battery storage technology to adapt the power grid.
- ▶ Finally, it must be noted that the case studies are unlikely to represent an optimal policy mix for future ocean energy development given these differences.

Despite these caveats, it is a useful exercise to compare the cost modelling scenarios with the case studies of other sectors. They both reflect support to early-stage renewable energy technologies to enable reductions in LCOE. They also both cover a period where a number of innovative step changes have been undertaken or are expected to be in the case of ocean energy. Finally, many of the same forms of funding mechanisms are still being used in terms of TP and MP.

Additionally, it should be noted that ocean energy can also build on the learning previously observed and gained through the development of other renewable energy technologies such as solar and wind. Building on this knowledge and sharing learning between the wave and tidal sectors could thus mean that subsidising the cost reduction may be cheaper and faster than has previously been observed.



7.3 LIMITATIONS AND FURTHER WORK

To avoid overcomplicating the analysis and introducing additional layers of uncertainty, several key assumptions are required, and some factors have had to be excluded from the analysis. It is important to keep these limitations and assumptions in mind when interpreting the results. Additionally, considerations and limitations when comparing the cost modelling scenarios with the case studies of other energy sectors are covered in section 7.2.2.

7.3.1 COST MODELLING AND SCENARIOS USED

Global scope for the wave/tidal sectors separately

The modelling of costs and benefits considers a global scope for each technology separately. It does not model the geographical scope of development or deployment in different countries, although some cooperation between nations is implicitly included.

Similarly, the potential for joint or cross-cutting technology development for wave, tidal, and other sectors (e.g. maintenance vessel development common to all) is not explicitly modelled. This is, however, a factor in the cost-reduction rates assumed.

Uncertainty in LCOE estimates for early-stage technologies

As noted in section 2.2, there is significant uncertainty in the estimates of LCOE for early-stage technologies, especially when considering a sector with a wide variety of early-stage concepts that have not yet been demonstrated at sea for significant periods. The experience curve analysis needs a base point, which has been taken as the LCOE of each sector at 100MW cumulative deployment. This, however, cannot be predicted with accuracy. Indeed, the range of estimates from the literature for early-stage commercial arrays presented in section 2.3 highlight this matter, both in terms of LCOE but also project size/sector maturity corresponding to that estimate. Regardless of this, the trends shown in this work still hold as evidenced by the sensitivity analyses undertaken.

What-if cost reduction scenarios

The cost modelling is based on a series of 'what-if?' scenarios, illustrating the costs to the public purse if various policies enable the cost reductions proposed. These cost-reductions are not guaranteed to happen if the funding is allocated, particularly for the more radical step-change cost reductions. Some form of quantification of the uncertainty in whether the cost reductions are likely to occur or not could be addressed in a future study.

The cost reductions are modelled in a continuous manner. Incremental reductions in LCOE are assumed to be directly proportional to global cumulative deployed capacity of wave/tidal technology. The feed-in tariff or other market pull subsidy mechanism then perfectly matches this reducing LCOE of the sector. In reality, deployments with a market pull mechanism would need to generate a profit to remain viable, so this needs to be accounted for within the definition of LCOE. However, there are also examples where subsidies have been much higher than the LCOE, and thus provided huge profits, such as the UK FiDer CfD contracts that concentrated benefits to large established utilities [148].



For the step-change cost reductions, the resulting technology variant is assumed to smoothly transition across the sector over a set period, with perfect transfer of learning from previous versions.

Uncertainty in learning rate

As a technology sector matures from nascent through evolving to mature the learning rate might reduce. The learning rate is likely to vary by subsystem depending on the maturity and scope for innovation, but that has not been considered in this analysis. Assessment of component-based learning rates is addressed in other work, such as [91].

There is no established LR for nascent technologies such as wave and tidal. Historical learning rates have been used based on experience of the wind and solar sectors. The rates used are consistent with other studies for the ocean energy sector.

Deployment trajectories

The cost modelling is based on a smooth and continuous exponential growth in cumulative deployment, similar to the average observed in other renewable energy technologies, as discussed in section 2.4. In reality, deployment will be piecewise in both temporal and geographical scope, but this level of fidelity was not possible in this work, as it would introduce significant additional uncertainty. The overall findings are also not impacted by this assumption, as the timing of deployment does not have a significant impact on the total investment required.

The actual amount of deployment will depend both on the LCOE of the technology, and on the LCOE of other competing technologies at that point in time plus policies to support these other technologies. This, however, is beyond the scope of this work and has been addressed in other studies such as [149].

The growth of deployment could also be linked to the amount of cumulative deployment. The rate of expansion of a technology tends to decrease as the market becomes mature or saturated. Similarly, demonstration and deployment in early stages may depend on the timing of funding sources such as grants affecting the rate of deployment. However, the value of these early subsidies is insignificant in overall terms as shown by the funding per year in Figure 5.3

7.3.2 CALCULATION OF GVA

The results derived within the GVA analysis are based on the CAPEX and OPEX spend used within the cost model and various other inputs/assumptions (refer to section 6.1.1). There is a certain level of uncertainty associated with these inputs and assumptions used because of immaturity of the sector itself and lack of availability of real-world data. Because the results are highly sensitive to these inputs, a range of scenarios have been used to understand the GVA benefit derived from the optimal balance of TP and MP funding options. However, the accuracy of the results can be further improved if we have operational data from wave and tidal devices around the world. Furthermore, the sectorial breakdowns from BVGA represent current arrays, these costs and cost centre proportions could change considerably with time, but the results would only change if the GVA effects were very different for the different cost centres.



The IO methodology can overestimate some GVA outputs compared with other available methods like the Computable General Equilibrium (CGE), but it is probably the best-documented methodology and most straightforward method to be used. Also, IO tables represent the global economy at a historic point in time (2014 in our case) rather than future economies.

Another limitation of the model is that because the GVA results are dependent on the overall spend invested within the project, a higher project investment will lead to a higher GVA benefit. Thus, the GVA benefits does not necessarily provide a holistic picture of the benefits derived from the global deployment of ocean energy projects but only an indication of the economic benefits that could be derived from the investment made within the sector.



8. ILLUSTRATING THE BENEFIT OF THE DTOCEANPLUS TOOLS

The DTOceanPlus tools developed within the H2020 funded DTOceanPlus project will contribute to the development of the ocean energy sector. The tools will facilitate both incremental and step-change cost reductions required to commercialise the sector. The former through deployment of optimised arrays using the Deployment and Assessment tools. The Structured Innovation and Stage Gate tools can be used in an innovation programme to deliver the step-change cost reductions postulated in the cost modelling in section 4.3. The following sections will include discussion on how the main features of the tools can contribute to this overarching aim and the expected impacts.

8.1 MAIN FEATURES OF THE DTOCEANPLUS TOOLS

This section collects and summarises the main features of each tool in the frame of the DTOceanPlus project to seize the benefits that they can provide to the sector. As noted in section 1.3, the suite of tools includes a Structured Innovation tool for technology concept selection, a Stage Gate tool for the technology development process and a set of Deployment Design and Assessment tools to design the system and its evaluation.

8.1.1 STRUCTURED INNOVATION TOOL

The Structured Innovation (SI) design tool comprises innovation methodologies that can enhance concept creation and selection in ocean energy systems, enabling a structured approach to address complex ocean energy engineering challenges where design options are numerous. Thus, it can facilitate efficient evolution from concept to commercialisation, and it can contribute to step-change cost reduction scenarios. The tool is one of a kind beyond the current state-of-the-art that will enable the transfer and adaptation of the combined Quality Function Deployment (QFD) and TRIZ (Theory of Inventive Problem Solving) plus Failure Modes and Effects Analysis (FMEA) methodologies to the ocean energy sector.

For a sector such as ocean energy, where the number of design options is still very high, the open-source Structured Innovation design tool is needed to help users to understand the complexity and interdependencies of the engineering challenge — resulting in a more efficient evolution from concept to commercialisation.

- ▶ The QFD methodology defines the innovation problem and identifies trade-offs in the system.
- ▶ TRIZ is a systematic inventive problem-solving methodology, which generates potential solutions to the often-contradictory requirements raised from the QFD.
- ▶ The output from the integrated QFD/TRIZ component comprises design requirements along with target engineering metrics.
- ▶ The FMEA assesses the technical risks associated with the proposed design concepts, specifications, and gap analyses.

The SI tool produces metrics and assessments, conflicts and impact reports, and a design report. The metrics and assessments include both ideality (a measure of what might be theoretically possible to



achieve) and development values (how difficult it would be to implement the selected solution), relevant to the benchmark assessments of ideal innovative concepts for wave and tidal renewable energy projects at different stages of development. The design report then includes requirements.

TABLE 8.1: MAIN FUNCTIONALITIES AND FEATURES OF THE STRUCTURED INNOVATION TOOL

Main Functionalities	Features
Quality Function Deployment (QFD)	▫ Determine attractive areas of innovation ▫ Define interactions & Correlation functional requirements ▫ Defining ideality ▫ Identify organisation Impact ▫ Specify and assess state of the art achievements
Theory of inventive problem solving (TRIZ)	▫ Identifying correlations between functions ▫ Implementing TRIZ alternative solution
Failure Mode Effects Analysis (FMEA)	▫ Identify potential failure modes ▫ Reduce the likelihood and impact of failure
Reporting	▫ Generate an exportable report that summarises: ▫ A set of functions for concept creation ▫ A conflict and impact report ▫ Assessment of Ideality and development impacts ▫ Mitigation measures to improve the design of the system

The Structured Innovation tool has six major functionalities:

1. **Defining objectives of the study:** This stage captures the project objectives and the list of the stakeholder needs (WHATs) broadly defined. In the context of developing a new product, this is a list of customer requirements. These requirements — often general, vague, and difficult to implement directly — are prioritised in order of importance.
 - Scanning the design space: The SI tool's QFD/TRIZ module is used for two purposes. Firstly, to scan the design space by mapping options for each of the key parameters which make up ocean energy concepts or projects, then ranking the attractiveness of these options through high-level physical and economic assessments. Secondly, to define the innovation problem space representing the voice of the customer and make an immediate objective assessment of the best solutions that fit the users' requirements.
 - Definition of functional requirements: This is when the customer needs are translated into measurable functional requirements (HOWs) that can satisfy the needs.
 - Definition of Impacts: In this stage, the relationships between the stakeholder needs (WHATs) and the functional requirements (HOWs) are determined using a predefined scale. Many of the HOWs identified affect more than one WHAT.
2. **Requirement interactions:** This establishes the interdependencies between functional requirements (HOWs). The purpose is to identify areas where trade-off decisions, conflicts, and innovation may be required.
3. **Identifying attractive areas of innovation:** The SI tool is developed to include fundamental relationships between key parameters in ocean energy concepts, evidence from the first ocean energy arrays, and a standard library of problem solution inter-relationships. QFD uses a set of requirements (WHATs) and answers them with a set of functional requirements

(HOWs). There will be various solutions to solve each requirement, with each solution aimed at producing the best requirement improvement. These solutions may contradict each other, and the QFD/TRIZ methodology allows these contradictions to be identified and their impact assessed. The possible concepts will be ranked in order of importance and achievability, highlighting options that would attract attractive investment opportunities. Evaluation of these options will be based on high-level metrics.

4. **Assessing contradictions:** The SI tool's TRIZ component is used to produce solutions to the QFD requirements where an improvement is needed, or if there is no existing solution, or if the key performance indicators are not satisfactorily met. The TRIZ methodology can be used to ensure completeness in the key parameters, which define the design space with e.g. the use of the Effects Database and in the series of provocative prompts to provide the well-known forty inventive principles and other tools to solve contradictions contained within the QFD. The QFD and TRIZ components are integrated into a single component within the SI tool to visualise opportunity and risk areas.
5. **Assessing technical risk:** Technical risks are framed using the 'concept' or 'design' FMEA tool. The tool provides ratings for each defect or failure in terms of severity, occurrence, and detection. The FMEA uses a database of validated defect parameters to improve understanding of technical risk during the design assessment process. It offers both risk mitigation and cost reduction opportunities. The structured innovation process will conclude with a visualisation method to represent the process and results obtained and deviation from the SI tool's key performance metrics. The results will be expressed in terms of a ranking of attractive options and the QFD requirements presentation. The overall result will be an acceptability rating that allows an objective assessment of the design.
6. **Reporting outputs:** This generates a summary page of all the outputs, including a list of proposed innovative functions, metrics, conflicts and interrelationships, and impact. This can be in report format or as a set of data files for further analysis and future updates.

8.1.2 STAGE GATE (SG) TOOL

DTOceanPlus will support the development of ocean energy technologies at all stages of the project lifecycle — from concept creation through design development to commercial deployment — with increasing level of data available and detail required at each. It has been designed to support users with differing requirements in terms of detail: from investors wishing for a high-level overview of a technology or project, to developers performing more detailed technical assessments e.g. for project consenting.

The SG tool supports the objective assessment of technologies in the development process, ensuring a fair evaluation of sub-systems, devices, and arrays from early-stage concepts up to commercial deployment, guiding the technology development process. As a tool, it operates with close integration to the SI, Deployment Design and Assessment Design tools to support consistent assessment processes and ultimately guide decision making for the users of the tool. For more details on the SG tool.



TABLE 8.2: MAIN FUNCTIONALITIES AND FEATURES OF THE STAGE GATE TOOL

Main Functionalities	Features
Framework editor	Review the framework and specify any thresholds for the Stage Gate assessment
Activity checklist	Assess which stage gate the technology is eligible for
Applicant Mode	Complete the SG assessment with qualitative and quantitative questions
Assessor Mode	Simulate the assessment of a completed application
Improvement Area	Identify areas of improvement and link to the SI tool
Study Comparison	Compare the results of two or more stage gate studies
Report Generation	Produce a PDF standardised report summarising the SG assessment

8.1.3 DEPLOYMENT DESIGN TOOLS

The **Deployment Design tools** will provide optimised solutions and layouts for the deployment of ocean energy technologies and define all the technical design specifications required to subsequently run the Assessment Design tools for the evaluation of metrics.

This objective is pursued by delivering key calculations and objective information on optimal array development. The main functionalities of the tools are combined in seven sub-modules:

- ▶ **Site Characterisation (SC)**, which gathers metocean, geotechnical and environmental conditions. This module processes all the site information and elaborates the environmental constraints.
- ▶ **Machine Characterisation (MC)**, to post-process the technical data inherent to the prime mover in order to be directly usable by the different tools.
- ▶ **Energy Capture (EC)**: at an array level, this module assesses and defines optimal solutions for wave and tidal energy converters. The capture power estimated by the Energy Capture module is used as input for the Energy Transformation and Energy Delivery modules.
- ▶ **Energy Transformation (ET)**, which focuses on different PTO systems both for tidal and wave energy converters, considering not only their performance and costs but also their impact on reliability, logistics and environmental issues.
- ▶ **Energy Delivery (ED)**, which deals with the design of the electrical network used to transmit power from the devices to the shore. The module objective is to design and evaluate networks for different arrays, considering both network efficiency and network equipment cost, and to present the optimal designs.
- ▶ **Station Keeping (SK)**, to support the design of the mooring and foundation subsystems, defining a local optimal design solution based on the cost of all components.
- ▶ **Logistics and Marine Operation (LMO)**: to support the design of the installation, maintenance and decommissioning operations, with the aim of minimising the logistic costs in all lifecycle stages, considering different operation strategies, and combinations of ports, vessels and support equipment for a given project.

TABLE 8.3: MAIN FUNCTIONALITIES AND FEATURES OF THE DEPLOYMENT DESIGN TOOLS

Main Functionalities	Features
Site Characterisation (SC)	- Extract 1D direct values (no temporal dimension) from databases (DTOcean+ or user inputs), like bathymetry, bottom sediment types or endangered marine species - Extract 1D (punctual) or 2D (longitude/latitude) temporal data from physical databases (DTOcean+ or user inputs), like waves or currents databases - Compute statistics on these databases
Machine Characterisation (MC)	Prepare the machine data to be used in the rest of the design flow modules and to estimate the hydrodynamic coefficient for a single wave energy converter
Energy Capture (EC)	- Estimates the gross energy production of the array and individual machines. - Estimates the "best" placement and efficiency of the farm and the machines within the given lease area.
Energy Transformation (ET)	- Designs the mechanical parts and performs the calculation of the PTO mechanical efficiency and loads knowing: - Designs the electrical parts and computes the generator efficiency and loadings knowing the mechanical PTO power and operation range. - Designs the components for grid conditioning electrical power, mainly selects the power converter, computes its efficiency, and the electrical output power. - Control Strategy is dedicated to traducing device motions and loadings to specific velocity distributions to be accounted for in the conversion chain.
Energy Delivery (ED)	- Design of transmission system. - Design of array network, which includes: Clustering of devices around collection point(s), Connections within array network, and, Routing of array cables, including design of umbilical cables for floating devices. - Selection of suitable components. - Evaluation of network designs.
Station Keeping (SK)	- Mooring systems, foundation bases and anchors are designed based on the bathymetry description - Novel mooring layout configurations are made possible by the flexibility offered by the improved and customisable mooring system modelling capabilities - Ultimate Limit State (ULS) analysis and automated design of mooring system are now based on frequency domain analysis - Fatigue Limit State (FLS) analysis of mooring lines is implemented
Logistics and Marine Operations (LMO)	- Design of logistic solutions for the installation, maintenance, and decommissioning phases of ocean energy projects. - Definition of operation plans for each operation, based on specified components, project characteristics, and user preferences. - Estimation of weather delays based on operation duration, operational weather restrictions, and historical met-ocean data. - Estimation of operation costs based on operation durations, weather contingencies, as well as vessel daily chartering costs, fuel costs, port costs and equipment costs. - Selection of optimal and compatible combinations of vessels, ports and equipment that minimize operation costs.

8.1.4 ASSESSMENT DESIGN (AD) TOOLS

Structured in four modules, the **Assessment Design tools** will provide objective information to the developer or investor on the suitability of a technology and project and will support the other DTOceanPlus tools as well.

The main functionalities of the tools are combined in four sub-modules:

- ▶ **System Performance and Energy Yield (SPEY):** used in the evaluation of main Key Performance Indicators. This module allows the comparison between different technologies or comparison between the same technologies located at different sites. The main features of this module are computing the performances matrix, estimating the energy production (at an array and device level), and assessment of the power quality (both of active and reactive power delivered to the grid).
- ▶ **System Reliability, Availability, Maintainability, and Survivability (RAMS):** used to compute the RAMS of components and systems of the farms. Outputs of this module include: Mean Time to Failure (MTTF) and annual probabilities of failures, computing the availability of each device, estimate of the probability that failed components may be repaired within a given time window, estimate of the probabilities that the critical structural/mechanical components can survive the ultimate and fatigue loads during the design lifetime.
- ▶ **System Lifetime Costs (SLC):** which estimates costs for the ocean energy project, together with its economic and financial viability. The main features of this module are as follows: Bill of Materials (BOM) compilation, computation of economic and financial metrics to evaluate economics, bankability and financial attractiveness of a given ocean energy project, benchmarking of economic and financial attractiveness against reference values.
- ▶ **Environmental and Social Acceptance (ESA):** which, for each lifecycle operation of a given marine renewable energy project, estimates the potential environmental and social impacts of the project, also providing recommendations to reduce the potential environmental impact and to increase social acceptance. This module can identify potential endangered species and estimate the carbon footprint of the project.



TABLE 8.4: MAIN FUNCTIONALITIES AND FEATURES OF THE ASSESSMENT DESIGN TOOLS

Main Functionalities	Features
System Performance and Energy Yield (SPEY)	- Calculating the efficiency and energy production. - Calculating Alternative metrics and power quality metrics.
System Lifetime Costs (SLC)	- Compile Bill of Materials. - Economic assessment. - Financial assessment. - Benchmark analysis, comparing project results against reference values.
Reliability, Availability, Maintainability and Survivability (RAMS)	Reliability assessment - Estimating the time to failure (TTF) of basic components - Estimating the time to failure of subsystems and the array. - Calculating the maximum annual probabilities of failure of subsystems and the array. Availability assessment - Calculating the availability of all the devices and the average availability of the array. Maintainability assessment - Calculating the probability that the damaged components can be successfully repaired or replaced in a period of time, given the equipment and the resources. Survivability assessment - Calculating the probability that the critical structural/ mechanical components can survive the ultimate loads/ stresses during the design lifetime. - Calculating the probability that the critical structural/ mechanical components can survive the fatigue loads/ stresses during the design lifetime.
Environmental and Social Acceptance (ESA)	- Endangered Species mapping - Environmental impacts and interaction with potential receptors - Carbon Footprint during the different phases of the lifecycle of the project - Social Acceptance

8.2 EXPECTED IMPACTS OF DTOCEANPLUS TOOLSET

The following table summarises the expected impacts of DTOceanPlus and how the design tools can contribute to these impacts.

TABLE 8.5: EXPECTED IMPACTS OF THE DTOCEANPLUS SUITE

Expected impacts	Structured Innovation	Stage Gate	Deployment Design Tools	Assessment tools
Reduce the technological risks for the next development stages	✓	✓	All	All
Significantly contribute to an increase in technology performance	✓		EC, ET, ED	SPEY
Increase reliability and lifetime, while decreasing operation and maintenance costs			MC, ET, ED, SK, LMO	RAMS
Reduce the life-cycle environmental and socio-economic impacts			All	ESA
Reduce ocean energy technology installation time and cost and/or operational costs, hence easing the deployment of ocean energy sources within the energy mix			LMO	SLC
The new design tools will eventually result in more cost-effective arrays and hence will reduce the cost of energy			All	SLC

8.2.1 REDUCE THE TECHNOLOGICAL RISKS FOR THE NEXT DEVELOPMENT STAGES

DTOceanPlus aligns ocean energy innovation and development processes with those used in mature engineering sectors. These sectors have successfully reduced both technological and financial risk to a level where investment is attractive to private investors. DTOceanPlus facilitates technological risk reduction at all stages and all scales.

The **Structured Innovation tool** allows developers to select the most technically and financially attractive concepts to take forward into the development process. Technical risks are framed using the 'concept' or 'design' FMEA tool. The tool provides ratings for each defect or failure in terms of severity, occurrence, and detection. The FMEA uses a database of validated defect parameters to improve understanding of technical risk during the design assessment process and offers both risk mitigation and cost reduction opportunities. The SI tool includes a visualisation of results obtained and deviation from the key performance metrics. Results are expressed in terms of a ranking of attractive options and QFD requirements. The overall result is an acceptability rating that allows an objective assessment of the design.

The **Stage Gate tool** allows developers and funders to take objective technology development decisions as they progress through the development process, ensuring that a measured path through

TRLs is followed and providing an objective method of measuring continued success against key metrics, thus ensuring that only the best technologies receive continued support. Technological risks are reduced by specifying the thresholds in the Stage Gate assessment, checking the development activities finalised and providing quantitative and qualitative evidence about performance levels achieved. The SG tool allows comparison and benchmarking with other technologies at a similar development stage.

Finally, the **Deployment and Assessment Design tools** ensure that all technologies are ready for implementation in the marine environment and can be integrated into optimal array designs. These tools rely on standard Site Characterisation information and various design steps to produce an optimal array layout, design of main subsystems, bill of materials and overall suitability metrics for the project including energy production, reliability, costs and impacts.

Therefore, users of the DTOceanPlus suite of tools will be able to reduce the technical and financial risk of the innovation and development process for sub-systems, devices and arrays. The target impact is to contribute to achieving an increase of 70% in the number of ocean energy technologies successfully brought to market within 5 years of project completion.

8.2.2 SIGNIFICANTLY CONTRIBUTE TO AN INCREASE IN TECHNOLOGY PERFORMANCE

DTOceanPlus tools provide **Assessment Design tools** capable of assessing all key attributes and characteristics of ocean energy technologies. One set of assessment tools, **SPEY**, particularly focuses on System Performance and Energy Yield. Using analytical and numerical methods, end-users will be able to compute system performance KPIs and compare results against a wide range of reference technologies. SPEY can calculate the efficiency, energy production and power quality metrics both globally and through the different transformation steps. Benchmarking with other technologies is facilitated thanks to the use of relative metrics that link energy yield with key design parameters such as rated power, mass, etc. This will allow developers at any stage to identify technologies that are set to provide class-leading performance.

Users will also be able to optimise developing technologies in terms of system performance. **Deployment Design tools** can model the three main conversion phases, namely **Energy Capture**, **Energy Transformation** and **Energy Delivery**.

With applicability at all stages of the innovation and development process, these tools will ensure that only high-performance technologies receive additional resources to progress towards deployment. The target impact is to contribute to achieving a 40% improvement in performance uncertainty contributing to achieving a 6% and 8% reduction in LCOE for wave and tidal respectively [101] within 5 years of project completion.



8.2.3 INCREASE RELIABILITY AND LIFETIME, WHILE DECREASING OPERATION AND MAINTENANCE COSTS

In a similar manner to the way in which assessment of system performance is provided, DTOceanPlus tools provide a set of **Assessment Design tools** that allow technology developers to assess and improve system reliability, availability, maintainability, and survivability — all of which contribute to overall system lifetime. These tools can estimate the time to failure of basic components, subsystems, and arrays, calculate their probability of failure, repair and survivability, and calculate the total availability of devices. At any stage in the innovation and development process, developers will be able to select, develop and deploy technologies that they have optimised for reliability and extended lifespan. The **Deployment Design tools** can transform the design selections and decisions regarding the device (MC), PTO (ET), station-keeping (SK) and electrical network (ED) to produce the underlying reliability information for RAMS.

Additionally, the **Deployment Design tools** provide a tool for the design of logistics, operations, and maintenance procedures. Using this tool, developers will be able to generate procedures which are optimised for a given technology deployment in terms of reduced costs and increased RAMS.

Use of the integrated suite of DTOceanPlus tools, therefore, ensures that all deployed technologies are optimised in terms of reliability and lifetime and are serviced using cost-effective logistics, operations, and maintenance procedures. The target impact is to contribute to achieving a 50% and 35% reduction in O&M costs for wave and tidal respectively [101] within 5 years of project completion.

8.2.4 REDUCE THE LIFE-CYCLE ENVIRONMENTAL AND SOCIO-ECONOMIC IMPACTS

The Environmental and Social Acceptance assessment tool can be used to establish both the costs and benefits that deployed ocean energy technologies will have for society and the environment. The **Deployment Design tools** can transform the design attributes to produce the underlying impact information for ESA.

By objectively evaluating technologies life cycle impacts against KPIs (e.g. energy yield, gross value added, job creation, marine life impact, and lifecycle emissions), users will be able to improve project outcomes as well as to mitigate any potential project design or operational issues. Such outputs can be used to support applications for project licences and to inform and reassure local communities.

The target impact is to contribute to achieving a 60% improvement in project licensing periods and 30% improvement in public acceptance within 5 years of project completion.



8.2.5 REDUCE OCEAN ENERGY TECHNOLOGY INSTALLATION TIME AND COST AND/OR OPERATIONAL COSTS, HENCE EASING THE DEPLOYMENT OF OCEAN ENERGY SOURCES WITHIN THE ENERGY MIX.

The Logistics, Operations & Maintenance design tool can generate procedures for the cost-effective installation and operation of ocean energy technologies. In conjunction with the System Lifetime Costs assessment tool, the generated procedures will be optimised for cost efficiency at an array and whole-lifetime level. It is this all-encompassing approach to cost reduction (considering how all cost reductions impact on each other) that will provide truly cost-effective designs and allow ocean energy to move towards being cost competitive with other energy sources.

The target impact is to contribute to achieving a 45% and 55% reduction in installation costs for wave and tidal respectively [101] within 5 years of project completion.

8.2.6 THE NEW DESIGN TOOLS WILL EVENTUALLY RESULT IN MORE COST-EFFECTIVE ARRAYS AND HENCE WILL REDUCE THE COST OF ENERGY.

By leveraging an extensive suite of **Deployment and Assessment Design tools**, DTOceanPlus users will be able to select, develop and deploy technologies that have been optimised for cost effectiveness in a fully integrated deployment scenario. This capability is expected to underpin a rapid reduction in the LCOE offered by ocean energy technologies and allow them to become more cost competitive with other power generation technologies. Such cost competitiveness is crucial since private financiers are to be convinced of the benefits of investment.

The target impact is to contribute to achieving tidal stream energy costs of 150 €/MWh or less and wave energy technology 200 €/MWh or less [102] within 5 years of project completion, and to continue supporting cost reduction in the sector thereafter.



9. CONCLUSIONS AND PERSPECTIVES: ANALYSIS OF COSTS AND BENEFITS

Transitioning the world towards net-zero carbon emissions will require significant renewable electricity generation amongst many other changes. Ocean energy (OE) can play a crucial role, especially with the predictable nature of the tides and complementary generation profiles of wave to wind and solar.

This study has presented case studies of the balance of funding policies in other renewable energy technology development, focusing on technology push (TP) to increase innovation and market pull (MP) to subsidise deployment. The costs of commercialising ocean energy have been calculated using a range of 'what-if?' scenarios. The benefits are illustrated as in monetary terms of GVA plus other socio-environmental benefits.

The previous sections 4 and 5 show the potential costs to the public purse of differing pathways of commercialising ocean energy — reducing the LCOE to meet cost-parity with an average wholesale market price (WMP) for Europe. The costs have a wide variation depending on the input conditions and policies chosen, as the sensitivity analysis shows. The two most attractive scenarios that include both a higher learning rate and a step-change cost reduction have total costs of approx. €13 bn for tidal and approx. €115 bn for wave, respectively deploying 11 GW and 118 GW of technology to meet cost-parity. While these are relatively large costs, they are global in scope and are spread over many years.

For context, Denmark and Germany together spent around €80 bn subsidising the wind sector between 2000 and 2018, with over €160 bn spent in Germany and Japan on solar in the same period. It is noted that these costs may not have been optimal interventions and the initial LCOE was much higher in the case of solar PV. Section 7.1 discussed the lessons learned from the experience of commercialising the other energy sectors reviewed in section 3. Understanding that it was not possible to compare like-for-like, trends between similar sectors were drawn which helped us explore suggestions for the more nascent OE sector. Some common lessons can come in the form of target setting, adopting a mix of support mechanisms, investing in local supply chain capabilities, ensuring a competitive environment, etc. For example, the case studies showed us that consistent investment support from governments for the OE sector will be pertinent in bringing about innovations and cost reductions within the sector.

More specifically, the German Solar sector showed that significant investment in the OE sector could also prompt economic stimulus in other associated sectors (particularly as it shares similarities with other mature renewable energy sectors like offshore wind, onshore wind etc.). At the same time, it was seen from both German solar and onshore wind sectors that investing in local manufacturing capabilities from an early stage will allow the OE sector to be less dependent on foreign sources and to retain the investment made within the region itself. From Japanese solar it was learned that ensuring competition between the manufacturers and developers while providing opportunities for international companies to participate in the local sector will be highly influential in driving down the costs and bringing technological improvements for OE. In addition, it should be ensured that the OE sector is competitive enough to sustain without any form of economic support before drastically



readjusting MP funding strategies. Finally, with many exports, the Danish wind showed that transferrable learning experience can prove to be quite valuable for the OE sector. Particularly in terms of supply chain strengthening, taking advantage of spillover learning from associated industrial sectors, export strategies, and the establishment of financial support mechanisms. While the case studies bring to light some examples from the wind and solar PV sector within a particular period (2000-2018), it is also seen that lessons through spillover effects from other sectors such as aerospace, oil & gas, automotive industry etc. can also prove to be quite valuable for the OE sector.

The assessment of benefits in sections 6.1 and 6.2 show for the scenarios considered, the benefits in monetary terms of Gross Value Added outweigh the costs of funding TP and MP policies to reach cost parity by a factor of 2.5–3, and this does not include the non-monetary benefits covered in section 6.3. It should be highlighted, however, that a higher GVA is not necessarily better—as higher GVA can require additional spend on funding policies to achieve.

The costs for the scenarios without enhanced learning rate or step-change cost reductions are significantly higher, showing the importance of these actions. Relative to the base scenario without these TP funding mechanisms, the savings in MP subsidy could be very significant — tens of billion euro for tidal energy and many hundreds of billion euro for wave energy, as the latter requires greater subsidised deployment to reach cost parity.

Both enhanced learning and step-change cost reduction requires a continuing process of research and development, bringing new innovations into the sector, and adopting technology transfer from other sectors. Policies and actions (such as the European Commission's Horizon 2020 and Horizon Europe programmes) to increase collaboration and knowledge sharing between those involved within the sector are also vital to maintain a high learning rate and efficient cost reductions.

Indeed, without a step-change cost reduction from the baseline 350 €/MWh at 100 MW cumulative deployment taken for the wave-energy scenarios, the costs are unpalatably high — nearly €400 bn with the higher learning rate (scenario 2). Compounding this with a lower learning rate (scenario 1) would require more than €1.1 trillion in subsidy and could require more subsidised deployment (>1TW) than some estimates of the global resource for wave energy.

The cost modelling shows that increased spending on TP which lead to faster/larger cost reductions in the early stages can significantly reduce the overall subsidised deployment required (a MP mechanism). The case studies ranged from spending 25–117 times more on MP subsidies than TP, whereas most of the scenarios modelled were lower at between 3 and 51. In terms of MP to deployment, the case studies were in the range of €1.2–2.1 million/MW with most of the cost modelling scenarios around €0.8–2.0 million/MW, i.e., similar or slightly lower than has been seen in other sectors.

It is important to have a mix of policies, especially in the early stages of deployment of ocean energy. Forcing technology developers to focus purely on lowest cost deployment and generation, funded through subsidised deployment, may reduce the scope for broader innovation. Therefore, focus must also be on creating and demonstrating novel concepts (devices and/or subsystems) that could have



significantly reduced costs in the long term; however, these will likely need some form grant funding given the increased risk involved.

The costs and benefits in this study are primarily intended to illustrate the balance of different policy mechanisms. They are derived from LCOE estimates for first commercial arrays for wave and tidal sectors, taken from literature as discussed in section 2.3. It may be that ongoing work by technology developers can reduce costs further and faster than these predictions suggest. In turn, this would reduce the overall costs of reducing LCOE to around the European WMP as shown by the sensitivity considered in the modelling.

It is important to note that the cost modelling results demonstrate that wave and tidal energy technologies can reach a target LCOE of 50 €/MW under a range of potential future scenarios. These are consistent with the European SET Plan cost targets for ocean energy [102] and global deployment targets from OEE and the IEA.

In all the scenarios discussed in this report, the open-source design tools being developed in the DTOceanPlus project can contribute to the development of the ocean energy sector, facilitating both incremental and step-change cost reductions. The Structured Innovation and Stage Gate tools can assist with step-change cost reductions as part of structured, staged innovation programmes. The Deployment and Assessment tools can then be used to design optimised arrays, facilitating incremental cost reductions through wide scale deployment of ocean energy technologies to generate renewable electricity.



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11. ANNEX I: INNOVATION PROGRAMME METRIC ESTIMATES

This annex presents metrics from relevant ocean energy subsystem development and demonstration projects, summarising values quoted in the Community Research and Development Information Service (CORDIS) database¹² of EU-funded projects.

TABLE 11.1: DEVELOPMENT PROGRAMME METRICS

Project name/ Acronym	Type	Subsystem(s)	AEP	OPEX	CAPEX	LCOE	Funder(s)	Funding (€m) (1)	Time (months)
AQUAGEN	Wave	PTO	+20%	-25%			FP7	1.7	39
CableFish	Tidal	Installation			-75%		MRCF		12
CF2T	Tidal	Foundation			-30%		Ocean ERA-NET	1.5	35
CORES	Wave	PTO, control, moorings, risers, data acquisition and instrumentation					FP7	3.45	42
D2T2	Tidal	PTO				-30%	H2020	2.2	42
DemoTide	Tidal	Array + foundation				-375% (2)	H2020	20.3	36
ELEMENT	Tidal	Control				-17%	H2020	5	36
EnFAIT	Tidal	Array + O&M		-20%	-20%		H2020	14.9	60
FloTEC	Tidal	Device + mooring + blades	+50%			-20%	H2020 + Saltire Prize	9.7 + £3.4 m	50
GEOWAVE	Wave	Mooring					FP7	1.1	35
IMAGINE	Wave	PTO			-50%	-48.5%	H2020	3.8	42
InToTidal	Tidal	Device					H2020	2	24
LAMWEC	Wave	Device + Mooring & Foundation testing					Ocean ERA-NET	0.9	36
MacArtney wet-mate connector	Both	Installation					ETI	£1.1 m	
MAT4OEC	Both	Materials/ coatings				-reduce	Ocean ERA-NET	0.64	30
MegaRoller	Wave	PTO	+26%	-75%		-26.6%	H2020	4.9	36
NEMMO	Tidal	Blades/Materials				-70%	H2020	4.98	42

¹² <https://cordis.europa.eu/projects/>



Project name/ Acronym	Type	Subsystem(s)	AEP	OPEX	CAPEX	LCOE	Funder(s)	Funding (€m) (1)	Time (months)
OCEAN_2G	Tidal	Device					H2020	1.9	22
Pelamis ETI	Wave	Structure							
POLYWEC	Wave	Novel PTO material					FP7	2.06	51
PowerKite	Tidal	PTO	+17%				H2020	5.1	24
REMO	Tidal	Maintenance		-50% (maintenance)			FP7	1.1	24
SEABLADE	Tidal	Blades		-reduce			Ocean ERA-NET	0.39	24
Sea-Titan	Wave	PTO					H2020	3.9	36
TAOIDE	Both?	PTO (wet-gap generator for tidal)							48
TIDAL-EC	Tidal	PTO	+increase			-reduce	FP7	1.04	18
TIM	Both	Mooring					Ocean ERA-NET	0.29	24
TIPA	Tidal	PTO				-29%	H2020	4.4	36
TOPFLOTE	Tidal	PTO (pitch regulation)	+increase		-reduce		Ocean ERA-NET	1.2	29
UMACK	Both	Mooring + installation			-50% (mooring) -50% (installation)	-9.5%	Ocean ERA-NET	2	35
UPWAVE	Wave/ wider	Device					H2020	20.7	60
WaveBoost	Wave	PTO	+25%			-18% (low) -27.5% (high)	H2020	4	36
WavePiston	Wave	Device					H2020	2.5	32
WEP+	Wave	PTO + Storage							18
Notes: (1) Funding in €m unless otherwise noted. Values as quoted and have not been adjusted for inflation. (2) Quote in JRC (2018) "The project aims to reduce cost of electricity from 450 EUR/MWh to 120 EUR/MWh."									



12. ANNEX II: TABULATED RESULTS FOR COST MODELLING FIGURES

This annex provides tabulated results for key results of the cost modelling scenarios presented graphically in section 5.

TABLE 12.1: TABULATED VALUES OF TECHNOLOGY PUSH, MARKET PULL FUNDING AND GENERATION FOR TIDAL SCENARIOS

Scenario	Technology	Push	Market Pull	Total subsidised deployment (GW)	Total LCOE reduction	Year target met	Step-change TP funding (€bn)	Enhanced LR TP funding (€bn)	Subsidy MP funding (€bn)	Total funding (€bn)	Total WMP (€bn)
	Step-change cost-reduction	Policies for enhanced LR	FIT subsidy timescale								
To meet cost-parity (CDC ₀ =40MW, LCOE _C =200€/MWh, R _{CI} =30%/year)											
(1)	None	No	Deployment only, from start	100.3	-75.0%	2051	0	0	76.7	76.7	307.7
(2)	None	Yes		37.5		2047		2.7	34.4	37.1	114.9
(3)	25%	No	Deployment in parallel from start	24.2		2045	0.5	0	19.2	19.7	74.2
(4)	25%	Yes		11.0		2042		2.2	11.0	13.7	33.7
(5)	25%	No	Delay deployment	24.2		2047		0	18.6	19.1	74.2
(6)	25%	Yes	after step-change	11.0		2047		2.2	10.4	13.1	33.7
To deploy 100GW (CDC ₀ =40MW, LCOE _C =200€/MWh, R _{CI} =30%/year)											
(1)	None	No	Deployment only, from start	100.0	-75.0%	2051	0	0	76.7	76.7	306.7
(2)	None	Yes		37.5	-80.2%			3.0	34.4	37.4	282.9
(3)	25%	No	Deployment in parallel from start	24.2	-81.3%		0.5	0	19.2	19.7	269.5
(4)	25%	Yes		11.0	-85.2%	3.0		11.0	14.5	228.2	
(5)	25%	No	Delay deployment	24.2	-81.3%	2056		0	18.6	19.1	269.5
(6)	25%	Yes	after step-change	11.0	-85.2%			3.0	10.4	13.9	228.2



TABLE 12.2: TABULATED VALUES OF TECHNOLOGY PUSH, MARKET PULL FUNDING AND GENERATION FOR WAVE SCENARIOS

Scenario	Technology	Push	Market Pull	Total	Total LCOE reduction	Year target met	Step-change TP funding (€bn)	Enhanced LR TP funding (€bn)	Subsidy MP funding (€bn)	Total funding (€bn)	Total WMP (€bn)	
	Step-change cost- reduction	Policies for enhanced LR	FIT subsidy timescale	subsidised deployment (GW)								
To meet cost-parity (CDC ₀ =25MW, LCOE _C =350€/MWh, R _{CI} =30%/year)												
(1)	None	No	Deployment only, from start	1000†	-75.0%	—	0	0	1164.2	1164.2	3068.0	
(2)	None	Yes		411.0	-87.5%	2058		3.7	380.9	384.6	1260.9	
(3)	25%	No	Deployment in parallel from start	384.9		2058	0.5	0	300.2	300.7	1180.9	
(4)	25%	Yes		118.2		2053		3.3	112.5	116.3	362.6	
(5)	25%	No	Delay deployment after step-change	384.9		2063		0	299.5	300.0	1180.9	
(6)	25%	Yes		118.2		2058		3.3	111.8	115.6	362.6	
(7)	50%	Yes		21.0		2047		2.6	21.5	24.6	64.4	
To deploy 100GW (CDC ₀ =25MW, LCOE _C =350€/MWh, R _{CI} =30%/year)												
(1)	None	No	Deployment only, from start	100.0	-84.3%	2053		0	0	364.5	364.5	306.7
(2)	None	Yes			-80.2%		3.2		248.9	252.1	306.7	
(3)	25%	No	Deployment in parallel from start		-81.3%		0.5	0	198.1	198.6	306.7	
(4)	25%	Yes			-85.2%			3.2	111.3	115.0	306.7	
(5)	25%	No	Delay deployment after step-change		-81.3%	0		197.4	197.9	306.7		
(6)	25%	Yes			-85.2%	3.2		110.6	114.3	306.7		
(7)	50%	Yes			21.0	-90.1%		2053	3.2	21.5	25.2	258.5
To meet cost-parity (CDC ₀ =25MW, LCOE _C =350€/MWh, R _{CI} =60%/year)												
(1)	None	No	Deployment only, from start	1000†	-75.0%	—	0	0	1171.5	1171.5	3068.0	
(2)	None	Yes		413.4	-87.5%	2042		2.1	384.2	386.3	1268.4	
(3)	25%	No	Deployment in parallel from start	397.6		2042	0.5	0	306.0	306.5	1219.7	
(4)	25%	Yes		118.1		2039		1.8	116.5	118.8	362.1	
(5)	25%	No	Delay deployment after step-change	397.6		2047		0	302.3	302.8	1219.7	
(6)	25%	Yes		118.1		2044		1.8	113.0	115.3	362.1	
(7)	50%	Yes		21.1		2035		1.5	27.7	29.7	64.6	



Scenario	Technology	Push	Market Pull	Total subsidised deployment (GW)	Total LCOE reduction	Year target met	Step-change TP funding (€bn)	Enhanced LR TP funding (€bn)	Subsidy MP funding (€bn)	Total funding (€bn)	Total WMP (€bn)
	Step-change cost-reduction	Policies for enhanced LR	FIT subsidy timescale								
To deploy 100GW (CDC ₀ =25MW, LCOE _c =350€/MWh, R _{CI} =60%/year)											
(1)	None	No	Deployment only, from start	100.0	-84.3%	2039	0	0	365.7	365.7	306.7
(2)	None	Yes			-80.2%			1.8	250.0	251.8	306.7
(3)	25%	No			-81.3%			0	202.1	202.6	306.7
(4)	25%	Yes	Deployment in parallel from start		-85.2%	2044	0.5	1.8	115.2	117.5	306.7
(5)	25%	No			-81.3%			0	198.5	199.0	306.7
(6)	25%	Yes	Delay deployment after step-change		-85.2%			1.8	111.7	114.0	306.7
(7)	50%	Yes		21.1	-90.1%			2039	1.8	27.7	30.0
† note that scenario (1) does not meet cost-parity but is limited at 1TW deployment.											





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