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Strategic orientation for the ocean energy market roll-out: Coherent technology learning by system dynamics modelling of trans-organisational expert knowledge

为海洋能源市场的推出作战略定位：通过跨组织专家知识系统动力学建模进行相干技术学习

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Abstract – **The development of an alternative power generation method requires, apart from long-term political support, strong commitment on the technology and financing side. Tidal stream and wave energy presently move from full-scale prototype testing to the implementation of first multi-device arrays. With the intention to gain comprehensive insight into present ocean energy activities and plannings, a diversified interview series was conducted by which 44 experts from 13 stakeholder groups provided their knowledge in the form of 2,129 individual replies. To master the amount and complexity of the multi-level information received, all interview data were systematically consolidated and formed as such the input for the configuration of representative cause-effect relationship diagrams and detailed system dynamics computer models. Based on the calculated ranking of the top-level driving factors for the ocean energy commercialisation process and the subsequent allocation of representative interview statements, balanced propositions for the strategic orientation of technology-driving stakeholders can be made.**

Keywords – **Ocean energy commercialisation, semi-structured expert interviews, system dynamics modelling, competitive collaboration, technology convergence.**

I. Introduction

The UK is currently the global leader in ocean energy, with more wave and tidal devices installed than the rest of the world combined [1]. Marine renewables form an integral part of the UK energy system transformation and are expected to make a meaningful contribution to the nation's energy mix from around 2025 [2]. After significant technological advances in the last years, the industry now moves from full-scale prototype testing to the implementation of first tidal arrays ranging from 10 to 86 MW [3-5].

To efficiently pass the present pre-profit phase and to head towards regular commercial-scale project implementations, coordinated interaction within and between the stakeholders is required. A conclusive strategy to orientate the ocean energy development process must be capable to integrate the dynamic and complex interplay between all stakeholders. To ensure efficient interaction and long-term collaboration, continuous learning and adaptation efforts are required. Systematically conditioned wide-range expert knowledge provides the best basis herefore.

II. Objective of the Research

The academic objective of the research is on the systematic transposition and refinement of expert interview statements by means of system dynamics (SD) modelling in order to de-risk and accelerate the ocean energy commercialisation process.

The research is oriented around the hypothesis:

The right strategic orientation of the stakeholders engaged in ocean energy is crucial for efficiently reaching the goal of market-competitive electricity generation. The essential top-level drivers can be determined in a holistic and transparent manner by operating system dynamics computer models based on refined trans-organisational expert interview data.

The hypothesis acknowledges the importance of having access to different expert knowledge bases and emphasises the need of processing multi-level data. The term "strategic" shall underline the long-term focus of 5 to 10 years and the holistic research concept by integrating the technology, policy and financing sectors. By systematically analysing the wide

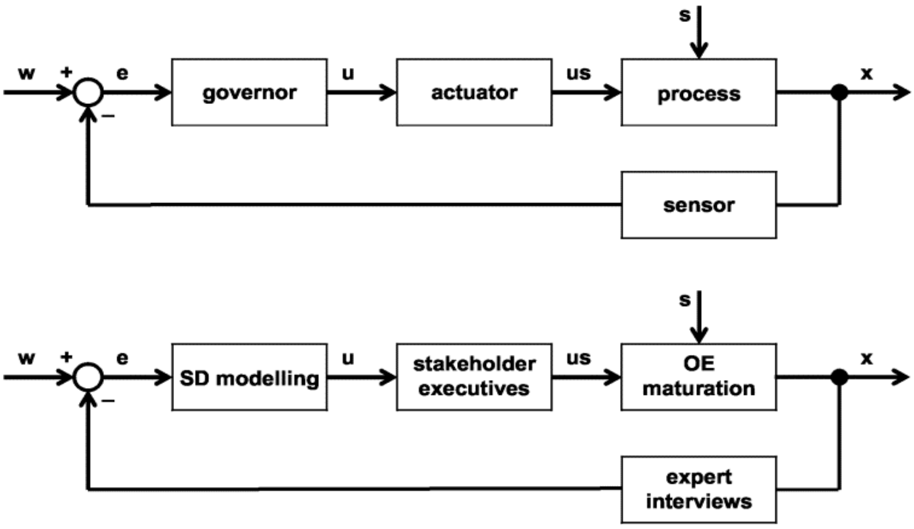

Fig. 1, Closed-loop block diagrams (top part: with ISO control theory terms / lower part: adapted to the present research context).

spectrum of stakeholder-individual strategies and concerns, potential misinterpretations and coordination deficits come to surface at time and viable superordinate strategies can be elaborated.

III. Research Principle and Methodology

The basic principle applied in this research is to create new insight by compiling different sources of knowledge for the elaboration of an optimum strategy towards achieving market competitive generation. New knowledge is generally created through a process of applying multiple perspectives to the same information, as outlined in a study in the field of experimental behavioural science by Okhuysen & Eisenhardt [6]. In order to follow this principle of multiple perspectives, experts from all stakeholder groups were invited to contribute with their individual experience and know-how. Based on this multi-disciplinary attempt, an all-encompassing appraisal becomes possible by avoiding concentrating in a limiting manner on stakeholder-specific views or interests only.

The use of system dynamics modelling techniques assures the envisaged open-integrative instead of detailed-specialist character of the research. The methodology applied considers the long-term and dynamic development of the ocean energy sector by continuous information gathering and data processing oriented at feedback control principles. To master the amount and complexity of the cross-category information and to systematically identify the fundamental interview statements, all data were uniformly consolidated and formed as such the basis for the configuration of detailed cause-effect relationship diagrams[1]. The final system dynamics models emerged from “iterative cycles of data gathering, feedback analysis, implementation and evaluation” as described by Formentini & Romano [7] in a knowledge management context.

The research principle of data collection, information compression, system dynamics modelling and the creation of strategic propositions can be outlined by referencing to the closed-loop control model. In Fig. 1, one standard and one adapted block diagram are shown which comprise all elements defining a dynamic and complex process to be controlled – either of technical or organisational nature. The respective analogies between the terms and concepts in control theory and the present research context are shown in Table 1.

TABLE 1, Analogies Between Terms and Concepts in Control Theory and the Present Research Context

Control theory	Ocean energy commercialisation
Reference w	Full commercial power generation
Deviation e	Remaining development progress
Governor	System dynamics (SD) modelling
Actuating signal u	Calculated top-level driving factors
Actuator	Stakeholder executives
Actuating value us	Management decisions and actions
Process	Ocean energy (OE) maturation
Disturbance s	Setbacks, difficulties, risk impacts
Actual value x	Actual status of ocean energies
Sensor	Periodic cross-category interviews

The following chronological steps were necessary: (i) conduction of 44 expert interviews; (ii) analysis and sorting of replies; (iii) compression of information by introduction of ordering terms; (iv) configuration of system dynamics computer models; (v) calculated ranking of impact factors and definition of top-level driving factors; (vi) allocation of representative interview statements; and (vii) elaboration of recommendations for the strategic orientation of the technology, policy and financing sectors.

[1] System dynamics software used: Process Modeller, Consideo, Germany.

IV. Semi-Structured Expert Interviews

For the survey, a four-page questionnaire with a total of 90 questions was elaborated out of which 48 were yes/no questions and 42 of qualitative character asking for stakeholder-specific experience or assessment. By contacting 136 selected representatives from 15 stakeholder groups, we received 71 feedbacks out of which originated 11 personal and 15 telephone interviews as well as 20 filled-out questionnaires. 2 received questionnaires had to be discarded because they were greatly incomplete. As a result, the knowledge of 44 managers, experts and specialists from 13 stakeholder groups was ultimately retained for the analysis, corresponding to an effective return rate of 32.4 % which is more than usual for studies of this nature [8]. A total number of 2,129 individual replies had to be grouped in order to formulate higher-level correlations as basis for the computer-based SD-modelling.

Table 4 lists stakeholders that finally participated in the interviews or sent back filled-out questionnaires.

V. Survey Results and Statistical Findings

A) Virtual reference project

With the aim to harmonise and to uniformly direct the research, the interviewees were asked to give a prognosis on the development prospects of ocean energy. Utility-scale generation is expected in 2021 for tidal stream and 2024 for wave power. The average array rating is given for tidal stream at 36 MW and for wave power at 38 MW with investment cost of 102 m€ (2,900 €/kW) respectively 118 m€ (3,100 €/kW).

B) Interview-based ranking of selected risks

The interview participants provided estimations for risk levels focussing on the realisation of the virtual reference project (~40 MW, ~2025, ~100 m€) as follows:

(i) Top risks: achieving funding, keeping budget, reliability.
(ii) High risks: supply chain, time schedule, regional grid.
(iii) Medium risks: sea use license, marine flora/fauna, conflict of interest, capability of shipyards/ports, feed-in tariff, insurance cost, extreme weather, health and safety.

Apart from financial aspects, the key risk in ocean energy is related to uncertainty in device performance or reliability.

VI. System Dynamics Modelling

A) Referenced basic model: "Full commercial power generation by marine energy"

In total 3 system dynamics models were elaborated. For the basic model explained in [9], all positive (reinforcing) and negative (countervailing) influences on the final objective of full commercial power generation by ocean energy were grouped and inter-correlated.

Out of 234 individual replies, 16 top-level driving factors essential for achieving commercial power generation were systematically identified and concentrated into 3 milestone terms:

(i) Government support: The long-term commitment from government represents the fundament for the further progress of the sector. Early stage developments depend on coordinated funding mechanisms and fiscal measures as well as an efficient consenting process.
(ii) Array-scale success: The 2nd ranked top-level driving factor (showcase commercial-scale projects / successful demonstrators) forms the essential element of this interim milestone that triggers the further development.
(iii) Cost reduction: After having successfully demonstrated the array-scale success, LCOE[2] will decline due to serial manufacturing and technology convergence processes.

As the singular characteristics of governmental support are outside the range of this contribution, the context around achieving the interim milestone "array-scale success" was examined in detail by identifying the respective reinforcing and countervailing impact factors.

B) Reinforcing model: "Showcase commercial-scale projects / successful demonstrators"

In this higher focussed model, the 2nd ranked top-level driving factor identified by the basic model of showcasing commercial-scale projects or successful demonstrators serves as new target factor. In the right hand middle area in Fig. 2 we find it being fed via 3 main nodes: (i) knowledge transfer and learning from neighbouring sectors; (ii) top-priority tasks in the work the government agencies; and (iii) having costs under control. These nodes correspond to the cornerstone elements for harnessing the potential of ocean energy presented by McSweeney as: technology, policy, financing [10].

The SD-model was configured one-on-one to the interview replies so that it directly reflects the first-hand experience and projections of all interviewed stakeholders. Based on the questionnaire, 11 representative group terms (i.e. "lessons learnt in the oil/gas industry") were pre-formulated. Out of 671 individual replies, 26 generic terms (i.e. "device operation experience") were defined. The number of replies received under a specific aspect defines the relative impact onto a node and finally on the target factor. The inter-correlation between the generic and group terms is determined by the distribution of the expert interview replies. Calculated weighting factors define the intensity of a correlation link and are displayed as normalised values. The simulation runs showed that the most important generic term (or impact factor) is "technology learning" being interconnected by strong causal links.

The elaborated cause-effect relationship diagram enables a factual representation and analysis of multi-level data.

[2] Levelised cost of electricity are defined as the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by that plant over its operating life.

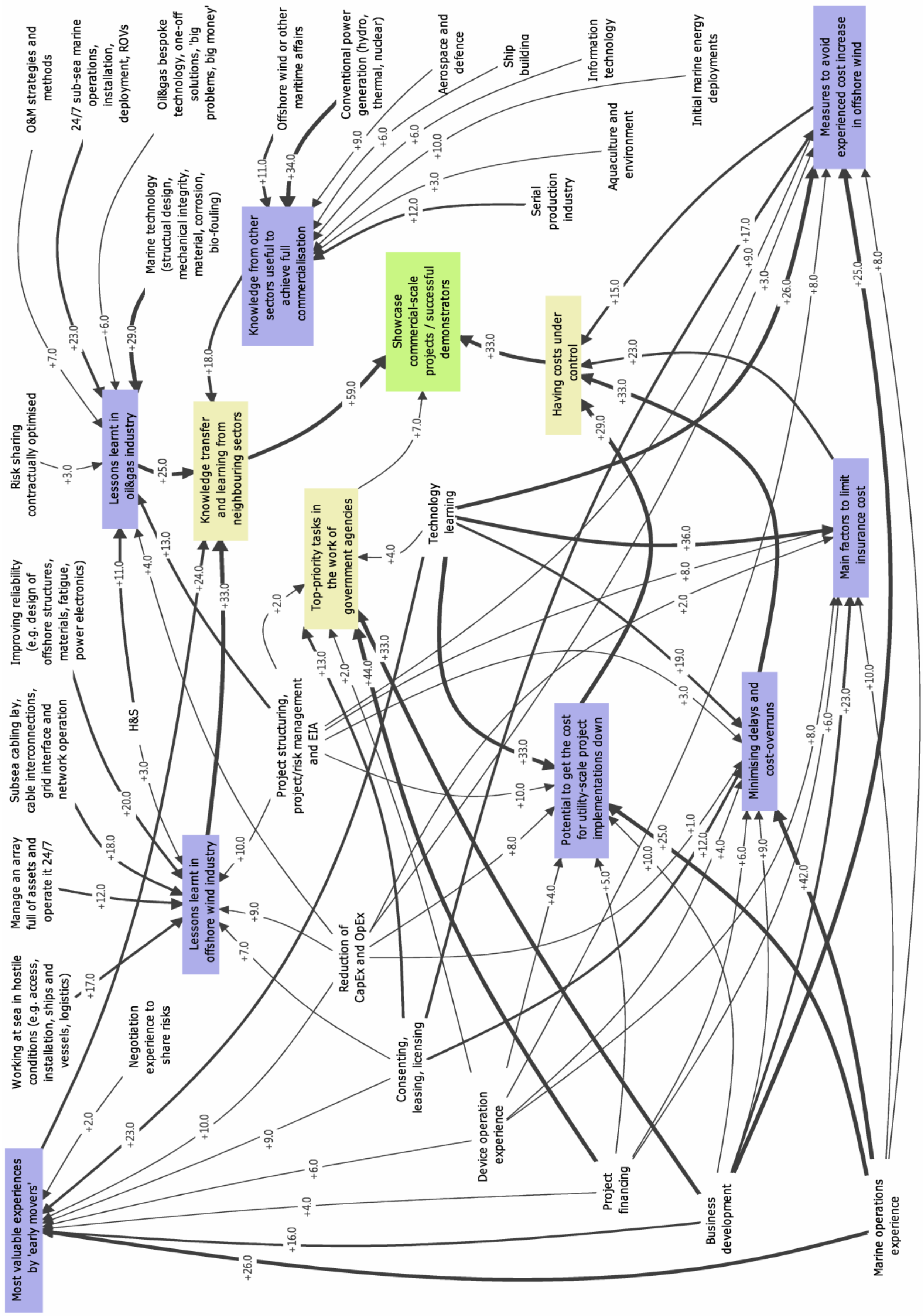

Fig. 2, Reinforcing system dynamics model: “Showcase commercial-scale projects / successful demonstrators”.

C) Countervailing model: "Negative impact on the development of ocean energy"

To make full use of the insight gained in the interviews, in a further system dynamics model exclusively negative, delaying or countervailing impacts (generated from 1,712 individual replies) on the development of ocean energy were considered.

D) Simulation results and grouping of impact factors

In Fig. 3 the simulation results of the two in-depth system dynamics models described under B) and C) are shown in combined manner in the so-called "insight matrix". On the left hand side, the impact factors with negative effect on reaching the target of full commercial power generation by ocean energy are located and on the right hand side the ones with positive effect. The y-axis indicates the impact intensity behaviour on the target over time. The greater the distance from the axes of coordinates, the more significant a factor is. As the axis scales in both examined system dynamics models are identical, the impact values can be directly compared.

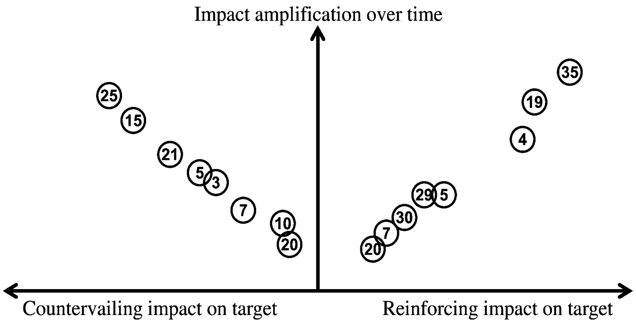

Fig. 3, Combined insight matrix showing countervailing and reinforcing impact factors on commercialising ocean energy.

Following the results of the system dynamics calculation runs on "showcase commercial-scale projects / successful demonstrators" and "negative impact on the development of ocean energy", in Table 2 the identified countervailing (–) and reinforcing (+) impact factors are grouped and ranked according to their summarised impact levels. The item numbering (#) refers to Fig. 3.

TABLE 2, GROUPED IMPACT FACTORS (WITH IMPACT LEVELS)

–	**Technology** *(summarised impact: 551)*	+
#25	Technology learning (83+100)	#35
#15	Marine operations experience (74+86)	#19
#21	Project/risk management, EIA (61+44)	#29
#7	Device operation experience (36+27)	#7
#20	Marine technology (21)	
	Project management (19)	#20
–	**Policy** *(summarised impact: 100)*	+
#5	Consenting, leasing, licensing (51+49)	#5
–	**Financing** *(summarised impact: 59)*	+
	Reduction of CapEx and OpEx (35)	#30
#10	Funding requirement (24)	

The by far strongest impact on the objective to showcase commercial-scale projects or successful demonstrators identified by the reinforcing system dynamics model is correlated to "technology learning" (for calibration purposes defined with an impact level of 100) followed by "marine operations experience" (impact: 86). The most significant "negative impacts on the development of marine energy" are similarly related to "technology learning" (impact: 83), "marine operations experience" (impact: 74) and in third place "project/risk management and EIA (environmental impact assessment)" by an impact level of 61. The high relevance of business development (#3 & #4) as the intermediary element between technology, policy and financing is underlined by a significant impact level of 123 (46+77).

E) Compilation of corresponding interview statements

In Table 3 the most relevant recommendations and strategy options for the sector-specific orientation are given. They are based on the calculated prioritisation by the system dynamics simulation software and correlated expert statements.

VII. STRATEGIC ORIENTATION (TECHNOLOGY)

A) Systems engineering approach

When asking for significant potential to get the cost for utility-scale project implementations down, the CEO of an Irish wave energy converter manufacturer emphasised the clear recognition to orientate the development and research strategies at the US space-/aircraft industry and here especially on the systems engineering principles. The vice president of a multi-national engineering conglomerate underlined in similar manner the importance to prove that systems work reliably and to focus on end user requirements. This statement correlates with the central objective in systems engineering as to consider the finally envisaged functionality already in early project stages. An important element in the design and implementation process of complex technological systems is to perform regular system functionality checks. Finally, the ocean energy converters have to operate on the long term in open sea grid-connected multi-device arrays.

B) Multi-applicable technologies and joint concepts

According to the opinion of a utility's ocean energy project manager, one of the top-priority tasks in the work of academia & research should be to concentrate on multi-applicable technologies and standardised devices and components (e.g. moving parts, cable connector systems, control interfaces). The benefit by working along a robust engineering plan targeting on serial production and large-scale manufacturing was underlined. To finally ensure identical component design and delivery, effective supply chain management and leveraging logistics is required. Referencing to offshore wind, in [11] it is pointed out that joint installation and maintenance concepts for adjacent wind farm locations significantly increased installation and operating efficiency.

C) Standardisation (look at volume manufacturing)

The reply of a project developer's head of offshore when asking for the most valuable experience gained by the early

TABLE 3, STRATEGIC ORIENTATION FOR THE TECHNOLOGY, POLICY AND FINANCING SECTORS

Technology *with reference to interview replies under "technology learning, marine operations experience, project/risk management and EIA, device operation experience, marine technology, project management"*
▪ Adopt systems engineering principles inspired by the space-/aircraft industry ▪ Consider that extreme engineering is required with a focus on survivability and reliability ▪ Reduce the number of technological concepts (technology convergence) ▪ Develop multi-applicable technologies (standardisation of components) and joint concepts ▪ Design for installation and maintenance purposes ▪ Minimise the lack of collaboration and improve knowledge sharing ▪ Gain offshore deployment experience with full-scale devices ▪ Move from device testing towards array-scale activities under open sea conditions ▪ Integrate risk management into project management ▪ Consider the need to restructure and commit to the supply chain
Policy *with reference to interview replies under "consenting, leasing, licensing"*
▪ Facilitate consenting, leasing, licensing (i.e. with a single point of handling the process) ▪ Promote cross-interaction between renewables ▪ Stimulate appropriate risk sharing between the stakeholders ▪ Encourage initiatives to bring in expertise from offshore oil & gas marine operations ▪ Focus on availability of qualified personnel and heavy marine services ▪ Underline the importance of knowledge sharing (central bottleneck) ▪ Improve collaboration and alignment between industry, utilities, academia, device manufacturers and project developers ▪ Support grid-connected test facilities and pilot zones ▪ Support strategies for grid operation with significant wave and tidal power in-feed ▪ Simplify access to the international (out of Europe) market
Financing *with reference to interview replies under "reduction of CapEx and OpEx, funding requirement"*
▪ Recognise that pilot projects with availability records provide confidence in the performance of the core technologies ▪ Support technologies with declared synergies towards off-shore wind ▪ Consider the likelihood of early-stage failures and the failing in unexpected parts of project ▪ Keep in mind that realism is required when it comes to the (global) scale of the industry ▪ Focus on cost of energy and not on CapEx ▪ Consider that the cost of energy production is dependent on the capacity deployed ▪ Evaluate the insurability of projects ▪ Recognise differences to offshore oil & gas with regard to design, manufacturing and logistics ▪ Realise the advantage of working with the already existing companies in the market ▪ Encourage contract structuring and contract standardisation as in onshore wind

movers, was the "experienced negative impact by missing standardisation". Considering the urgent need for consensus over standardisation, one interviewee referred to the detected over-engineering in oil & gas standards (with regard to marine energy purposes). A marine renewables engineer employed with an energy consulting firm identified "consensus over standardisation" as a target that appeared more difficult to reach in the last years than originally planned. One interviewee summed up the situation as "no standards, no results". The overall importance of standardisation in ocean energy was emphasised by several interviewees when highly appreciating the published results by the standardisation group within one of the top three certification companies. The date of publishing new technical standards and the level of detail need to be carefully discussed with manufacturing companies to avoid early-stage limitations on non-published but promising R&D projects and unnecessary cost increase. A senior contracts expert of an international UK law firm mentioned the need for contract standardisation and collaborative contracts (contracts that allow purchasing goods, services and works collectively to achieve favourable contract terms). Contract splitting (e.g. in turbines, fundament, transformer station, inner-park cabling) as in offshore wind was recommended.

D) Technology convergence

According to a senior principal surveyor of a global offshore classification society, a top-priority task in their work is towards technology consolidation. A utility's representative underlined the potential to get the cost for commercial-scale project implementations down by the positive impact of technology convergence. Augustine et al. [12] concentrate in their research on technology convergence and concept evaluation processes in industrial product development. They emphasise that rather than selecting the better among available alternatives, the progression towards better solutions by combining the strengths of all available concepts is a more robust approach for concept improvement. It is expected that the presently high number of technological concepts in ocean energy will be reduced in the course of competitive project implementations. Considering the dynamic development in wind power, it is noteworthy that since the beginning in the 1980ies until today the rotor diameter has increased from 15 to 124 m and the nameplate rating from 50 to 5,000 kW [13]. The next development step in offshore wind is expected to be the introduction of 7 or even 10 MW turbines [14].

E) Knowledge sharing and knowledge transfer

The limited knowledge sharing in industry is seen by the strategy manager of a public-private partnership and the head of energy of UK's innovation agency as a main reason why the ocean energy sector has not developed more rapidly. A senior policy officer of the Scottish government emphasised the need to transfer lessons learnt in the offshore wind industry to ocean energy in order to avoid duplication of time and effort. According to the vice-chair of the largest private R&D group in Spain, the transfer of knowledge from other sectors (under consideration of the specific aspects of ocean energy) is identified as a top-priority task in the commercialisation process. The project manager for the implementation of the world's first commercial breakwater wave power plant outlined that the need to improve the sharing of bad (!) experience and testing data is key. According to his commissioning experience, sometimes unspectacular and cheap items created unexpected difficulties. To support progress, his position is to inform (as far as possible) about such complications at conferences, to explain why things went wrong and to display the finally implemented solution.

F) Maximising collaboration and minimising competition

In line with the findings on limited sharing of knowledge, a lack of collaboration of the industry was reported. Apart from improving cooperation, a strengthening of interaction between the device manufacturers and the engineering consultancies companies was called for. The head of policy of a major UK developer emphasised the expectable benefits by enhanced collaboration between individual project developers. With regard to academia, he mentioned the need to intensify international collaboration. The artificial competition with on-/offshore wind was criticised by an Irish ocean energy development manager as negatively influencing an uninterrupted progress. A chance to improve cross-interaction between the renewable energies is seen in identifying prospective synergy effects by inter-coupling different kinds of carbon-free generation methods. The interviewed head of development of a wave energy device manufacturer – which recently entered into a research and development collaboration with a major offshore wind developer – underlined the attractiveness of exploring the prospects by combining wave and wind power. Seeking synergies with other manufacturers considering the use of similar technology is seen as a natural process. The experienced increasing involvement and interaction with major industrials in the ocean energy sector is seen as positive and will help to restructure the supply chain.

G) Offshore deployment experience

With the aim to demonstrate the viability of electricity generation by ocean energy, it is required to provide transparency to investors and to focus on "bringing some 10 MWs in the water" as the programme director of a leading UK centre of sustainable energy expertise and pioneering project delivery outlined. Especially the importance to design for installation and maintenance purposes was emphasised by the representative of a wave energy converter manufacturer. As lessons learnt in the offshore oil & gas industry to be transferred to ocean energy, a senior manager at a Canadian utility mentioned their focus on reliability and survivability.

H) Competitive collaboration and inter-firm alliances

Ocean energy needs to assert its position in the competitive renewable energy market. Regular commercial projects will finally be realised under established international procurement principles for which a number of similarly competent industrial bidders is required. In case natural competitors accept the high significance of jointly achieving the identified intermediate milestone "array-scale success", the motivation for inter-firm alliances will rise. Exemplary strategic alliances on how to develop new products and to penetrate new markets can serve as references. The benefits by inter-firm co-operations need to be individually examined in the course of risk/reward assessments. In a recently published paper from the European Ocean Energy Association [15], clear reference was given towards Airbus which was classified as a prime example of a successful venture that would not have taken off without transnational collaboration between industry and governments. Amanatidou & Guy [16] emphasise the increasing importance of knowledge-based industries and focus on aligning existing perceptions by maximising collaboration and minimising competition. As described by [17] cooperative relationships between firms in high technology can bring to market new innovations that neither firm alone could have accomplished. Especially for firms which are not part of the group of ocean energy front-runners, new inter-firm collaborations offer potential to prepare for global competition. The term "competitive collaboration" was introduced by [18] for strategic alliances that strengthen companies against outsiders (i.e. other renewables) even as they weaken each partner vis-à-vis the other.

I) Strategic risk management

Conventional risk management procedures are mainly tailored for stakeholder-specific duties or project-related functions. When opening risk management towards accompanying an energy system transformation project – for which the development and grid-integration of ocean energy is a good example – the usually considered time frame and the grade of complexity increase. Frigo & Anderson [19] explain that strategic risk management encompasses the interdisciplinary intersection of strategic planning, risk management and strategy execution. The development manager of a wave energy converter firm explained that their company approach towards risk management is to collaborate with a multi-national oil & gas exploration corporation. He generally stressed the requirement to share risk by collaboration and to integrate risk management into project management. Modern strategy-based and life-cycle oriented management incorporates real-time management of risks. Risk sharing shall be contractually optimised to identify the most appropriate risk owners.

J) Adjusting the "installed capacity / capacity factor"-ratio

The principal scientist of UK wave power developer underlined that the cost of energy production is dependent on the capacity deployed. In Bucher [20] this relationship was examined for an envisaged 600 MW tidal array in Korea. Based on a full lunar cycle 3D tidal regime model, detailed statements on optimising the "installed capacity / capacity factor"-ratio and consequently limiting the financial risk could be made. The possibility to select a preferred ratio of capital investment to profit widens the circle of potential investors and helps to effectively de-risk early-stage project initiatives.

K) Detail complexity and dynamic complexity

When asking for measures to increase equipment reliability, a renewable energy consultant recommended to "design out complexity/failure points". For managing complexity, the differentiation between detail (or combinatorial) and dynamic complexity as in the complex systems theory [21] is helpful:

(i) Detail complexity is characterised by many elements and a large number of combinatorial possibilities. Groesser [22] explained that in detail-complex situations methods to reduce complexity might be useful. In the present context potential to reduce detail complexity is seen in applying systems engineering, standardising components and using multi-applicable technologies. When taking a look at the wider picture, a reduction of detail complexity can be achieved in commercial project implementations in the course of a "competitive technology qualification routine" (as described further below). The long-term best-performing device or system would be identified in a transparent process.

(ii) Dynamically complex systems contain non-linear feedback, time delays and accumulations. Cause and effect are subtle and obvious interventions can produce non-obvious consequences. It might arise even in simple systems and can usually not be reduced but managed. Dynamic complexity is characteristic for large-scale engineering and construction projects with multiple feedback-processes, non-linear relationships and the need to integrate hard and soft data [23,24]. The process of commercialising ocean energy comprises high dynamic complexity because of the continuously varying interaction between heterogeneous stakeholders over a decade's long period of time. In order to improve project success rates, Groesser [22] recommends qualitative feedback modelling as a method to analyse and manage dynamic complexity. In the ocean energy context, potential to handle the high dynamic complexity is seen in the "interview/modelling/action"-approach in Fig. 1.

Research revealed that in conventional project management mainly aspects of detail complexity are considered [25]. Senge [26] underlines that the real leverage in most management situations lies in understanding dynamic complexity. According to his research, most established planning tools and analysis methods are designed to handle detail complexity but are not equipped to deal with dynamic complexity.

L) Competitive technology qualification routine

The interview participants identified reliability concerns as the top-ranked non-commercial risk and on the opposite side poor liability was mentioned as key operational risk. The widespread perception of high cost and unproven reliability was mentioned by the strategy manager of a public-private partnership as negatively influencing the sector. A US academic named the need for longer baselines for systems reliability and an R&D vice-chair emphasised that (currently) reliability is more important than efficiency. The managing director of a UK financial firm and the vice president of a Canadian project developer emphasised that concerns for delays and cost-overruns mainly relate to reliability, durability and performance of ocean energy converters. According to a Scottish government employee, the failure of devices was the fundamental and greatest single reason for projects being delayed or cost increase. Reasons why the ocean energy sector has not developed more rapidly were repeatedly identified in the uncertainty of device performance and reliability. The requirement to demonstrate equipment reliability at utility-scale devices was formulated by the machinery manager of a global maritime classification society. The division head of an Irish state agency replied to the question on where research is most required to accelerate the development of marine energy that reliability and integrity of devices are essential.

When asking for measures by which the experienced cost increase in offshore wind can be avoided in ocean energy, a marine energies project manager of a large utility recommended to compromise cost and reliability. As main factors for reaching commercial generation, two senior members of classification societies stressed uncertainty about reliability and the need to focus on it. To achieve a satisfactory technology reliability record, experts recommended to put more focus on reliability in system design and to introduce reliability modelling.

In all above listed interview statements the key importance of technology reliability was uniformly emphasised. As years will pass until full technology maturity will be reached, Bucher [27] proposed for early commercial project implementations a competitive technology qualification routine to achieve the required safety for investment. The principal idea is to extend the execution of utility-scale projects by a qualification procedure in the course of which different manufacturers' power conversion devices are deployed and operated in real-sea conditions in the final project area for a defined period of time. The individual device performance is independently assessed and the manufacturer of the best-ranked system is awarded the principal supply contract. Non-successful competitors are compensated.

The competitive technology qualification routine represents a transparent and evidence-based selection procedure to identify most suitable technology for a site. In a carefully selected project environment, the approach might apply.

VIII. Conclusions and Recommendations

The principal objective of this research is to create strategic knowledge to orientate the ocean energy (technology) learning processes towards reaching commercial power generation. Considering the dimension and potential of ocean energy, elaborate measures to coordinate the development of the sector are necessary. The inherent high dynamic complexity of such an undertaking makes it necessary to apply tools and methods that are capable to reflect the entire process and to identify top-level driving factors in a holistic but systematic manner.

In order to rapidly overcome the present pre-profit phase, the clearing of the interim milestone “array-scale success” represents a key target, which will pave the way towards the envisaged market roll-out. To safely identify the decisive technical-organisational principles to be applied, the unbiased inclusion of trans-organisational expert knowledge is required. The use of cross-category interview data to configure system dynamics computer models is seen as the adequate basis to comprehensively assess the prevailing situation and to provide effective recommendations for the stakeholders’ medium- and long-term strategy planning and adjustment.

Referencing to the initial hypothesis, the paper makes the following contribution:

The top-ranked risks for utility-scale ocean energy projects (achieving funding, uncertainty in device performance) are directly intercorrelated as investor confidence mainly depends on track records of continuous device operation. Clearing the identified interim milestone “array-scale success” will create confidence and de-risk investments. Intensified technology learning is seen as determinant for the development of the sector. It comprises strategic principles such as applying systems engineering, strengthening standardisation and minimising competition by competitive collaboration. System dynamics computer modelling provides the tools to master the complexity of multi-level interview data and to impartially identify top-level drivers. Representative expert interview statements can be directly allocated based on the calculated ranking of priority and subsequently be analysed in detail.

With the presented principles, specific experience can be integrated for the benefit of a coordinated way towards commercially viable electricity generation by ocean energy.

The paper shall conclude with a convincing statement given by one interviewee:

“Generally, if device developers can successfully operate their demonstration devices at a high level of availability for an extended period of time (at least 3 years) then most of the other desirable outcomes, such as investment, takeovers by large companies, grid upgrades and so on, would follow automatically”.

Acknowledgement

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TABLE 4, List of Participating Stakeholders

Government (associations) & trade organisation: The Scottish Government (UK), Marine Scotland (UK), Energy Technologies Institute (UK), Carbon Trust (UK), Department of Energy and Climate Change (UK), The Crown Estate (UK), Scottish Natural Heritage (UK), Centre for Environment, Fisheries & Aquaculture Science (UK), RenewableUK (UK), Technology Strategy Board (Ireland).
Certifying authorities: Det Norske Veritas (UK), Lloyd’s Register (UK).
Investors & lenders: Green Giraffe (UK).
Law firm: Eversheds International (UK).
Academia & research: University of Washington (USA), University of Edinburgh (UK), National Taiwan Ocean University (Taiwan), Irish Marine Institute (Ireland).
Engineering consultancies: Natural Power (UK), Xodus Group (UK), Tecnalia Research & Innovation (Spain), South West Renewable Energy Agency (UK), Royal Haskoning (UK).
Project developers: Emera (Canada), EDF (France), Electricity Supply Board (Ireland), Iberdrola (Spain).
Owners & operators: ScottishPower Renewables (UK), Ente Vasco de la Energía (Spain).
Transmission system operator: Scottish and Southern Energy Renewables (UK).
Device manufacturers: Marine Current Turbines (UK), Pelamis Wave Power (UK), Wavebob (Ireland), Siemens (Germany), Wave Star (Denmark), Ocean Renewable Power Company (USA).
Offshore contractors: 6 contacted (no feedback).
Test site operators: European Marine Energy Centre (UK), Fundy Ocean Research Centre for Energy (Canada), National Renewable Energy Centre (UK), Minas Basin Pulp & Power (Canada), France Energies Marines (France).
NGO: Greenpeace (UK).
Offshore wind industry: Dong Energy Power (UK).
Oil & gas industry: 4 contacted (no feedback).

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