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Identifying the Frontier of Knowledge for Marine Renewable Energy Research

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Abstract—Verification and validation techniques can provide a strategic framework for improving the predictive capability of numerical models used in the marine renewable energy sector. In addition, it is proposed that the adoption of open source community models make implementing such strategies more straightforward. A technique of particular interest is the Phenomena Identification and Ranking Table (PIRT). Such a table can be used to quantify the current state of knowledge and the subsequent requirements for improving the predictive capability of modelling software. After assessing and collating the current software usage trends within the wave and tidal numerical modelling community, an example PIRT is presented for tidal energy converter hydrodynamics.

Index Terms—Verification and validation, Numerical modelling, Marine renewable energy, Phenomena identification and ranking tables, Quality assurance, Open source software

I. Introduction

The 2010 UKERC/ETI Marine Energy Technology Roadmap [1] identified wave and tidal device modelling tools as a 'Priority A' requirement for the industry. A time frame of six years was given for such models to be completed. What was not clearly established was the scale of resources required to accomplish this ambitious goal in the given time frame. These requirements are, at this stage, difficult to determine as the level of technical capability within the research community as a whole is not well understood. This is particularly true of software models, where often the research community works at the cutting edge of applied science and a complete picture of the domain of applicability and level of validation for various approaches is currently unclear.

High level Verification and Validation (V&V) planning techniques, such as Phenomena Identification and Ranking Tables (PIRT), reveal the frontier of knowledge within the research community for meeting a particular modelling goal. These tables dissect this goal or software 'driver' into its constituent physics and then evaluate various metrics regarding the capability of software (or softwares) to simulate these physics and, most importantly, the validation experiments that have been (or must be) carried out to establish the accuracy of these codes. In addition, a PIRT provides a ranking for each phenomenon which, in turn, identifies and focuses research onto the most critical physics that must be simulated in order to deliver the overarching modelling goal.

It is postulated that such planning activities will lead to a more coordinated and collaborative research approach to meeting the modelling challenges for marine renewable energy. Open source community developed software provides such an opportunity by focusing the activities of researchers onto improving and testing a few codes (rather than many individual academic or commercial codes), allowing scalability at low cost, and meeting the tailored needs of the marine renewable energy community.

II. Methodology

A. Predictive Capability is Assured by the Verification and Validation Process

The ultimate goal of the verification and validation process is to ascertain the predictive capability of a numerical model. Even in the case where a simple trend or insight is sought, given limited validation data, credibility of the numerical results is pivotal. Over the past twenty years, work to formalise the question of predictive capability of numerical models has advanced. A recent, 'large' project was undertaken by the US Department of Energy's Accelerated Strategic Computing Initiative (ASCI) that was tasked with increasing the reliability of numerical software for defence and nuclear programs [2]. Their approach is based upon the gathering of evidence to estimate, quantitatively, the error and uncertainty inherent with a calculation used in a predictive mode. Verification and validation is an integral part of that evidence gathering process.

The recording of numerical and quantifiable experimental errors, known as 'acknowledged errors', is well understood. A less well understood concept is 'uncertainty'. Uncertainty can be subdivided into two groups:

Aleatory Uncertainty is the random uncertainty inherent in any physical system. The variability of this uncertainty is understood and quantifiable. It is also known as irreducible uncertainty.

Epistemic Uncertainty is uncertainty from a lack of knowledge. This can stem from insufficient knowledge of boundary conditions, for instance. It is also known as reducible uncertainty.

Both aleatory and epistemic uncertainty should be approached by representing the uncertain variable as a statistical distribution [3]. Obviously, designing a probability distribution for a variable suffering epistemic uncertainty is extremely challenging, if not intractable. For perfect predictability epistemic uncertainty must be minimised and this is achieved through the validation process. If epistemic uncertainty can be redefined as acknowledged error or aleatory uncertainty then predictive capability can be obtained in a more straightforward manner. Unfortunately, wave and tidal research is dominated by epistemic uncertainty.

The validation process involves evidence gathering to reduce the quantity of the epistemic uncertainty in a numerical model. The following sections describe methods for structuring and reporting this evidence. It should be noted that, in the case where only sparse data is available, such as in ocean modelling, validation is even more challenging. In this case, calibration is often required, and although this process is not discussed within the current paper, assessment of predictive capability for calibrated models is another topic of great interest in the V&V research community [4].

B. Hierarchy of Difficulty

It is a well known fact that as the physics we choose to model becomes more complicated, the time and difficulty of a numerical computation increases in unison. A significant issue is that often an invalid or inappropriate approximation to the physics of interest is made. One particularly common error that affects wave device modelling is the application of linear wave theory. Linear wave theory is an exceptionally valuable tool which can make accurate predictions for the dominant conditions seen by an operating wave energy converter. Unfortunately, because of its popularity, it is also often applied to situations where linear theory is no longer valid, leading to unexpected consequences from ignoring the non-linear components. In contrast, some problems can become over-specified. For instance, work undertaken into quantification and modelling of turbulence with regards to tidal energy devices, although a noble scientific pursuit, requires large resources, both in terms of computing effort and skills required to develop and operate the models. Using a more specific model that perhaps does not capture the complete physics set, but does capture other important physics of interest may well prove to be a more tractable approach given the resources available.

Thus, it is proposed that a simple ranking system is applied that classifies where in the hierarchy of difficulty certain problems / models lie. Such a ranking may take the form:

**** Cutting edge problems requiring new models and techniques with no definite timetable for completion.

*** High resolution, high resource problems that are tractable using existing models and methods.

** Problems of greater resolution than the most simple that may require more complicated analytical or numerical models that are well understood.

* Low complication models for well understood problems e.g. linear wave theory or actuator disk models.

The ranking system above should allow a better understanding of the state of the art research challenges facing modelling for marine renewable energy and also give an appreciation of the difficulty certain modelling problems pose.

C. Quality Assurance and Open Source Community Models

A key technique for the production of accurate and usable numerical models is Quality Assurance (QA). If a code is unreliable, unstable or even difficult to use it will not be adopted by its target market - in this case, the marine renewable energy industrial sector. In addition, should the cost of applying the model, both financial and in time, be prohibitive, the provider of the model, i.e. the academic community, will have failed in its undertaking to advance the development of the marine renewable energy sector.

Incomplete QA is a particularly potent risk for the marine renewable energy community due to its dispersed nature. When a software package is only developed by one or two researchers in a single research group, and is not in use elsewhere for similar purposes, then the QA requirements of that code can only be met by those few users. It is suggested here that such small development groups are unsatisfactory given the overarching goals of the marine renewable energy community.

In the broader perspective, QA standards such as ISO 9000 have been shown to improve the financial position of companies [5] and it is easy to infer from that that a better product has been produced. In many commercial software projects QA teams make up a large proportion of the overall software team. Notably, they are separate from the development team and their sole responsibility is to ensure that the end product matches the design requirements.

The academic community probably does not require dedicated QA testers, per se, but it does need to understand the value of the process. Indeed, the verification and validation process provides a great deal of QA (see, for instance, the next section on the validation experiment). As mentioned earlier, the key consideration for good QA is the disassociation of the developer and the tester which is why cross-institutional codes are vital for the process to be effective.

If a smaller shared set of numerical models is advantageous, then how is it possible to encourage disparate institutions to employ the same software in their research?

Obviously, this is a high level strategic decision, but to make a unified approach possible the key is the availability of free community developed models. These models will provide a set of 'classes' of models (per modelling approach) that can be developed and tested across a range of institutions. Examples of such projects already exist such as the ROMS ocean model [6] or openFOAM-ext [7]. The software that the latter is based upon is an interesting example of an open source code with closed governance development. The business model of openCFD, the developer of openFOAM, is based around providing tailored solutions for commercial customers. Such an approach is a hindrance to potential developers of the code outside of openCFD as the code itself is not well documented and individual 'forks' may not be distributed to the wider user community. On the other hand, the openFOAM-ext project offers a true community port of the base openFOAM software where community participation is openly encouraged. Such a distinction should be important to academic institutions as work will be fully accredited and code development can be tailored to the needs of the community.

In fact, the advantages of community governed open-source codes are numerous. These include:

- Academic effort to advance the code is not lost once the specific project has completed.
- Scaling of commercial codes can be prohibitively expensive due to licence requirements which are not suffered by open codes.
- The academic community can make scientific gains by advancing modelling techniques.
- There will be greater integration and communication between researchers in the marine energy community.
- Code can be focused and optimised for the task at hand.

There are also disadvantages however, primarily stemming from the security that commercial codes offer due to their own QA processes. Nonetheless, the academic community must embrace the opportunity to be technology leaders and engage their own processes to develop high quality open source code for wider consumption.

D. The Validation Experiment

The 'validation experiment' is a fledgling research problem [3]. In the past, experiments have been used to improve fundamental understanding, improve theoretical models or improve reliability of existing systems. A validation experiment's goal is to determine the predictive accuracy of a numerical model. In other words a validation experiment seeks to quantify the ability of an approximation within a model to reproduce physical phenomena. With this goal in mind, the needs of the model must be placed before the needs of the experiment. It is appropriate, in this case, for the numerical model to lead the design of the experiment. It can be used to define expected results, but it can also reveal sensitivities that could lead to a re-evaluation

of the importance of a particular parameter or physical process that hadn't been expected before. In any case, the experiment designed for the needs of the model is likely to produce a more useful experiment than one without such intention. To achieve this goal [3] recommends a set of guidelines for validation experiments given as follows:

Guideline 1 : A validation experiment should be jointly designed by experimentalists, model developers, code developers, and model users working closely together throughout the program, from inception to documentation, with complete candor about the strengths and weaknesses of each approach.

Guideline 2: A validation experiment should be designed to capture the essential physics of interest, including all relevant physical modeling data and initial and boundary conditions required by the model.

Guideline 3: A validation experiment should strive to emphasize the inherent synergism between computational and experimental approaches.

Guideline 4: Although the experimental design should be developed cooperatively, independence must be maintained in obtaining both the computational and experimental results.

Guideline 5: A hierarchy of experimental measurements of increasing computational difficulty and specificity should be made, for example, from globally integrated quantities to local measurements.

Guideline 6: The experimental design should be constructed to analyze and estimate the components of random (precision) and bias (systematic) experimental errors.

The above guidelines emphasise validation as a collaborative effort, producing results that will be meaningful to the predictive capabilities of the numerical model. It is also important to attempt to use fundamental measurements to examine the correlation between experimental and numerical results rather than secondary information derived by a mathematical process. This reduces the uncertainty in the accuracy of the mathematics used to derive the secondary data.

E. Phenomena Identification and Ranking Tables

Regarding verification and validation as a evidence gathering process requires a strategic framework to organise and record such evidence. To formalise and facilitate this strategic approach, the ASCI program recommended the use of a Phenomena Identification and Ranking Table (PIRT) [3], [8], [9]. As the name implies, the table is used to disassemble a physical system into the baseline phenomena and then rank their importance. Once this ranking has taken place, the current state of numerical models and validation experiments, to illustrate these phenomena, are

identified. With the PIRT as a guideline, resources to improve upon the status quo can be prioritised effectively. In fact, the process of producing a PIRT is as important a record as the table itself.

The production of a PIRT is an opportunity (possibly a necessity) to consult all levels of an investigative team. Numerical modellers, experimentalists, theorists and managers will shape the choices and importance of phenomena identified for a particular physical system. The PIRT is a living document, being revised in the wake of new insight discovered through the verification and validation process. The PIRT formation process is represented as a flowchart in [8]. This provides an example of how the process for formal development of a PIRT should be undertaken.

The term 'driver' is used to describe the physical system chosen to be modelled. It is important that this driver not be too expansive. If, after investigation, it is found that the ranking of each phenomenon is indistinguishable, it becomes impossible to prioritise a development, verification and validation strategy. In this situation, it may be indicative of an over reaching project goal or driver. However, identification of this problem at an early stage of a project through the PIRT will be beneficial as the project goals can be redefined.

Once a PIRT is drafted it will provide a snapshot of the requirements to ensure predictive capability of the numerical model(s) simulating the physical system. This includes a ranking of the phenomena characterising the system and the state of verification and validation of related model(s). An example of a PIRT (called a I/U map in that case) is given in [10] and a draft PIRT for tidal energy converter hydrodynamics is presented within this paper as table IV.

III. RESULTS

A. Software in Use for Research

Tracing the use of modelling software within the marine renewable energy research community is somewhat challenging. As the industry and the research community is in its infancy (particularly for tidal energy) a clear picture is yet to emerge. Currently, there is a risk of an 'in-house' culture developing, where the software available to a particular institution, be that academic or commercial software, is applied to different problems regardless of the appropriateness to the task at hand. Also, pre-existing models designed for alternative applications are more prevalent than bespoke solutions to marine energy issues.

Tables I, II and III show the range of software packages applied to device modelling for wave and tidal energy converters and also to tidal resource modelling. The tables show some interesting trends and diversity of approach that should be explored.

Considering the device modelling tables first, a particularly notable result is the prevalence of generic CFD solvers. Also note the conspicuous absence of open-source

community models. One reason for this trend may be that commercial codes are often available at academic institutions for teaching purposes where licences may be reallocated to research when not in use for teaching. The difficulty is that should the commercial code available be deficient for the modelling purposes you require (and many are) then the cost of purchasing licences for another (non-teaching) CFD code can be exorbitant, much as it is for the developers of marine renewable devices. An additional drawback of commercial CFD also relates to scaling. If the models are to be of sufficient accuracy then large simulations are required. These simulations may require the regular use of licences beyond the portfolio of an academic department which will raise the cost of large scale computing.

Tables I and II show the utilisation of some in-house academic codes. Although these have advantages over commercial CFD, their limitations with respect to open source community models are discussed in section II-C. Traditionally, in-house academic codes are tested against each other [33]. This provides some rigour to the results of these numerical codes, but the speed and value of this traditional approach must be questioned given the stringent targets facing the marine energy sector. A verification or validation benchmark is invariant to the code attempting to produce it and the relative performance of code one to code two is not the goal of the development team. The speed at which the development of code one can be improved to meet the V&V benchmark would be greatly increased if the developers of code two were to also participate in its enhancement. There could be an argument for simply locating marine energy research at centralised locations and this trend may be apparent in the UK with EMEC and Wave Hub expanding their research activities. For traditional university research groups to remain competitive in the face of centralisation, a method of concentrating research efforts while being physically distributed is obviously desirable.

The use of numerical models for tidal resource modelling given in table III is in sharp contrast to the other sections, probably as a direct involvement of institutions from the U.S.A. There is a clear prevalence of open-source community models (admittedly using varying licences). These models were, and still are, developed by cross-institutional groups of researchers that have common aims in developing strong and reliable ocean models such as ROMS. The use of open source community models for tidal energy resource assessment is very positive although the number of models used that are based upon similar principles is very high. It would appear that there is currently little consensus on a particular model that can be advanced to serve the purposes of the sector.

Figure 1 illustrates the above issues clearly. The collected groupings or 'classes' identify multiple numerical models with similar underlying principles. From these groupings it is then easy to infer the demand for models

Table I

SOFTWARE IN USE BY THE MARINE RENEWABLE RESEARCH COMMUNITY INVESTIGATING THE HYDRODYNAMICS OF WAVE ENERGY CONVERTERS.

Software	Type	Licence	Example Application	Difficulty	Ref.
WAMIT	3D BEM (Frequency)	Commercial	Sloped wave energy converter modelling.	**	[11], [12]
Achil3D	3D BEM (Time Domain / Semi Nonlinear)	Unknown	Oscillating water column hydrodynamics.	***	[13]
Starccm+	RANS (VOF)	Commercial	Force on fixed horizontal cylinder.	***	[14]
CFX	RANS	Commercial	Force on fixed horizontal cylinder.	***	[14]
AMAZON-3D	Euler (Cartesian Cut Cell)	Academic	Force on fixed horizontal cylinder.	***	[14]
SPHysics	SPH	Open Source (Closed Governance)	Force on fixed horizontal cylinder.	***	[14]
FLOW3D	RANS (VOF)	Commercial	Surging point absorbing wave energy converter.	***	[15]

Table Key:	**BEM:** Boundary Element Method	**RANS:** Reynolds Averaged Navier-Stokes
	VOF: Volume of Fluid	**SPH:** Smoothed-Particle Hydrodynamics

Table II

SOFTWARE IN USE BY THE MARINE RENEWABLE RESEARCH COMMUNITY INVESTIGATING THE HYDRODYNAMICS OF TIDAL ENERGY CONVERTERS.

Software	Type	Licence	Example Application	Difficulty	Ref.
PHYSICA	RANS (Level Set)	Commercial	Tidal turbine using blade element momentum theory. 'Rigid lid' free surface.	***	[16]
CFX	RANS	Commercial	Tidal turbine using actuator disk in 3D.	***	[17]
FLUENT	RANS	Commercial	Tidal turbine using actuator disk in 3D. Free surface as symmetry plane.	***	[18]
DVM-UBC	Discrete Vortex	Academic	Vertical axis tidal turbine including blades in 2D. No Free Surface.	***	[19]
PROPAN	BEM (Fixed Vortex Wake)	Academic	Horizontal axis tidal turbine including blades in 3D. No free surface.	***	[20]
Code Saturne	RANS - LES (Hybrid)	GPL (Closed Governance)	Tidal turbine including free surface and turbulence.	****	[21]
vort-transp	Vorticity Transport Equations	GPL (Unknown Governance)	Tidal turbine with blades in 3D. No free surface.	***	[22]

Table Key:	**BEM:** Boundary Element Method	**RANS:** Reynolds Averaged Navier-Stokes
	LES: Large Eddy Simulation	

within these classes. The set of open source models for each class and the subset of community models within that set are also illustrated. The clear requirement is to provide an open source community model for each of these software classes where one does not already exist. Thus, these models can be developed specifically for the marine renewable energy research community to tackle the unique problems that it faces.

B. PIRT for Tidal Device Modelling Software

As described in section II-E, the collation of the underlying physical phenomena for the required software drivers in a PIRT provides a clearer understanding of the current frontier of software verification and validation for marine renewable energy applications. This is achieved by examining the state of modelling for each constituent physical phenomenon making up a software driver.

To distinguish the phenomenon for a particular software driver, hierarchy diagrams as seen in figure 2 are extremely useful. Hierarchy diagrams provide the relationships between constituent phenomena within a software driver but lack the relative importance of the unit or combined secondary phenomena. In addition, they do not address the present state of verification and validation for each identified phenomenon. However, these diagrams remain useful for identifying the relationships between the dissected phenomena in a way that a PIRT can not. It is important to recall these relationships as the combinations of phenomena that will eventually produce the software driver are likely not to be linear and verification and validation

Software	Type	Licence	Example Application	Difficulty	Ref.
MARS	2D DI N-S 3D Primitive	Unknown	Tidal currents in the Bay of Biscay.	***	[23]
TELEMAC	2D DI N-S Boussinesq N-S	GNU GPL3 (Closed Governance)	Tidal resource assessment of Portland Bill.	***	[24]
ROMS	2D/3D Primitive	Open Source (Community Model)	Tidal energy dissipation in Chesapeake Bay.	***	[25]
MIKE 21	2D DI N-S Boussinesq N-S	Commercial	Irish tidal resource map.	***	[26]
POM	3D Primitive	GNU GPL3 (Out of Development?)	Tidal resource map of New Zealand.	***	[27]
ADCIRC	2-D DI N-S	Unknown (Community Model)	West coast UK tidal resource.	***	[28]
FVCOM	3D Primitive	Specialised Licence (Community Model)	Tidal resource of the Minas Passage, with extraction modelled as extra bottom friction.	****	[29]
SUNTANS	Boussinesq N-S	GPL (Uncertain Governance)	Tidal currents in Puget Sound.	***	[30]
TFD-2D	2-D DI N-S	Academic	Impact of harvesting tidal energy, with extraction modelled as retarding force.	****	[31]
TIDE2D	2-D DI N-S	Academic	Tidal resource in Johnstone Straight, with extraction modelled as drag.	****	[32]

Table Key: **DI N-S:** Depth Integrated Navier-Stokes   **Primitive:** Primitive Equations

Boussinesq N-S: Navier-Stokes equation under the Boussinesq approximation
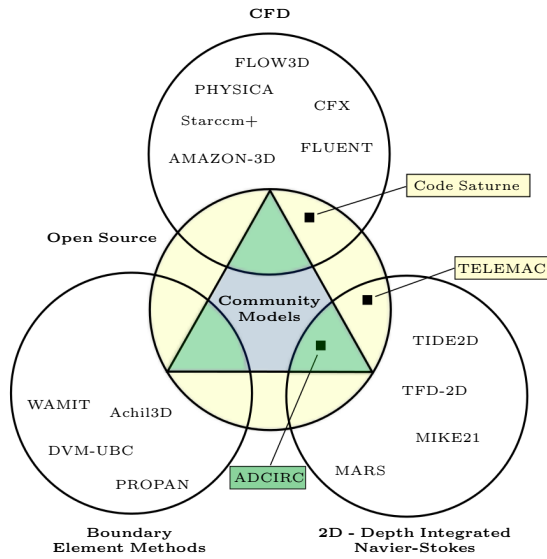

Figure 1. Venn diagram showing groupings of in use software packages. Highlighted are open source packages and, within that grouping, community developed models.

will be required for these combinations also. Obviously, such tests are more challenging and, thus, certainty in the ability to model the underlying unit phenomena is highly desirable.

A draft PIRT is provided for the hydrodynamics of tidal energy converters in table IV. The headings and
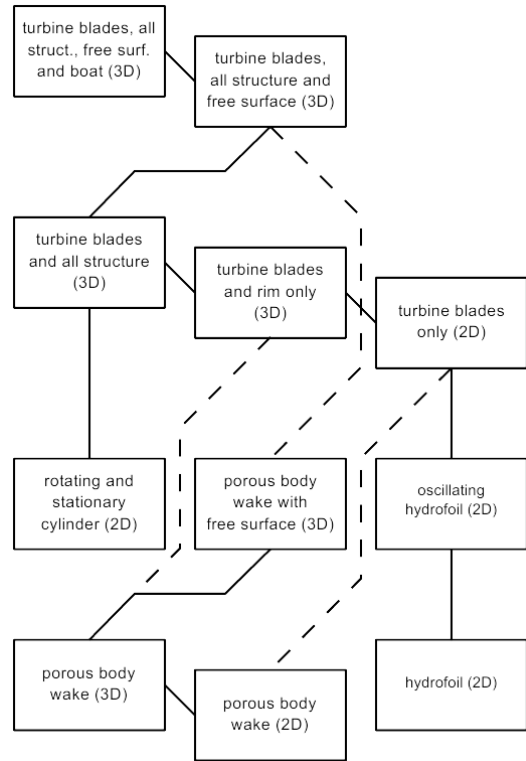

Figure 2. Hierarchy diagram for the modelling of a tidal turbine. Solid lines represent direct relationships between models, dashed lines indirect relationships. Reproduced from [34].

Table IV
PHENONEMA IDENTIFICATION AND RANKING TABLE (PIRT) FOR THE NUMERICAL MODELLING OF TIDAL ENERGY CONVERTOR HYDRODYNAMICS.
RATINGS FOLLOW THE SCHEME PRESENTED IN [9].

	Hydrodynamics	Importance	Conceptual Model Adequacy	Code Adequacy	Experimental Adequacy	Difficulty
Boundaries	Free Surface	High	Adequate	Incomplete	Medium	**
	Bottom	Medium	Adequate	Adequate	Medium	*
	Wave Action	High	Adequate	Incomplete	Medium	***
	Surface Piercing	Low	Adequate	Inadequate	Low	***
	Scouring	Medium	Adequate	Incomplete	Low	***
Structural	Interaction	Medium	Adequate	Incomplete	Low	****
	Vortex shedding	High	Incomplete	Adequate	Medium	***
	Cavitation	Medium	Incomplete	Incomplete	Low	**
	Stall	Medium	Incomplete	Incomplete	Low	***
	Buoyancy	Low	Adequate	Inadequate	Low	**
	Submersible Impacts	Low	Incomplete	Inadequate	Low	****
Fluid	Viscosity	Medium	Adequate	Adequate	Medium	**
	Turbulence	High	Inadequate	Incomplete	Low	****
	Density Variation	Low	Inadequate	Incomplete	Low	**

descriptions for the table are taken from Appendix D of [9]. The descriptions chosen for table IV are qualitative rather than quantitative, as there remains a high level of uncertainty about the rankings given to each phenomenon listed. In addition to the headings used by Trucano et al., the difficulty rating as described in section II-B is included. This addition is to emphasise the difficult and cutting edge nature of many of the research challenges within the marine renewable energy community, which can often be overlooked by policy makers.

Note that the 'Validation Adequacy' heading described in [9] has been omitted from table IV. The relative novelty of the validation experiment (see section II-D), means that the requirements of this heading are beyond the scope of the research activities of the marine renewable energy research community at present.

Of particular interest is the relatively poor performance of the experimental adequacy for each of the phenomenon. This is not because the quality of experimental research within the marine community is poor, in fact the opposite is true. Experimental science has led marine renewable energy research for some time and only recently have numerical simulations become more commonplace. As such, the experimental community is often not focused on producing validation experiments for numerical models. In general, greater focus on the reporting of uncertainty and the synchronisation of both numerical and physical experiments are required to ensure that the software used and developed within the marine renewable energy community has the predictive capabilities it is being relied upon to produce.

Table IV is a 'first iteration', taken from the authors' experience and is presented more as a guide, rather than a true picture of the state of verification and validation activities within the community. Indeed the PIRT formation process is meant to be dynamic as more information and experience is compiled into the tables. Through ongoing research and consultation the subjectivity of these rankings will be reduced and a clear picture of the research landscape established.

IV. DISCUSSION

The title of this paper is 'Identifying the Frontier of Knowledge for Marine Renewable Energy Research'. It is hoped that the value of the techniques presented for achieving this goal are clear. Indeed, the value of a verification and validation led approach goes beyond the assessment of predictive capability of numerical models. The evidence gathering as part of that process elucidates the present state of numerical and experimental modelling for the many phenomena present in wave and tidal energy conversion. Thus, the results of this paper attempt to map out the current trends of software usage within the research community, noting some interesting disparities between the device and resource modelling communities. Currently, device modellers lack the portfolio of open-source community software that is available for resource modellers. This is an important point to address for device modellers as a lack of freely available and widely tested codes will lead to excessive expense, hinder academic progress and make quality assurance extremely challenging. Development of a limited set of open source community models providing the required 'classes' of numerical models or adoption of existing community software which can be applied to marine renewable energy problems must be a desirable approach for the future.

Where such community models are already prevalent in marine renewable energy research, such as for tidal resource modelling, there remains a lack of consensus regarding which of these softwares is the most appropriate. This has led to disparate adoption of numerous codes that

have very similar foundations. Until the community begins to focus on a particular development path, the adequate implementation of quality assurance to numerical models will be extremely challenging given the restricted resources available to the research community.

The phenomena identification and ranking table is probably the most useful tool in highlighting the current state of the art for model verification and validation, a clear indicator of the frontier of knowledge for modelling within marine renewable energy research. Table IV illustrates a draft PIRT for tidal energy converter hydrodynamics. This table, in itself, should simply be the pinnacle of a greater body of research and collaborative effort to produce this summary, as it were, of the current state of V&V activities for a particular software driver. This body of work would resemble a technology roadmap in its construction, although the consulted stakeholders now represent the research community rather than the industrial community. The resources required to produce a complete PIRT document for numerical modelling within marine renewable energy were not available at the time of producing this work, but further research and consultation will reduce the subjectivity of the rankings presented. When mature, the process will illuminate the most important phenomena that should be allocated resources and provide an interface between technology roadmaps and the research community. In particular the required level of resources to meet the stringent timetable set for the marine renewable energy sector should become apparent. Appropriate and efficient allocation of resources will increase the likelihood of the research community delivering high quality numerical tools to the wider community within the allotted development schedule.

V. Acknowledgements

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