Technology Performance Level (TPL) Assessment

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1. INTRODUCTION

Technology development progress, technology value, and technology funding have largely been associated with and driven by technology readiness, measured in Technology Readiness Levels (TRLs) [1, 2]. Originating primarily from the Space and Defense industries, TRLs focus on procedural implementation of technology developments of large and complex engineering challenges where cost is neither mission critical nor a key design driver. However, wave energy converter (WEC) technology development as a whole has not yet delivered the desired commercial maturity or the desired techno-economic performance by following the TRLs.

For energy generation devices such as WECs techno-economic performance considerations should be considered early in the development process, when fundamental conceptual, operational and design choices are being made. Hence, the Technology Performance Levels (TPL) [3, 4] were designed to consider a wide range of WEC attributes that define the techno-economic performance potential as well as identify potential showstoppers at the earliest stages of WEC development. The original groups and attributes [3] of the TPL assessment used in the Wave Energy Prize [5] have been updated using a formal Systems Engineering approach [6].

Systems Engineering is a disciplined approach to holistically evaluating the goals that must be achieved by a technology and the systems that enable achievement of the goals. The first activity was to develop a concise mission statement for the system (i.e., the wave energy farm (WEF)). This statement sets the framework for the development of the stakeholder needs and the functions (detailed in the top box of Figure 1). Capabilities and functions are hierarchical structures (i.e. taxonomies). In the case of capabilities, the taxonomy embodies the list of characteristics that are desired, from the perspective of the stakeholders, for the system to be successful. In terms of the functions, the hierarchy represents the solution agnostic elements (i.e. independent of specific design embodiments) that are needed to meet the stakeholder requirements. A detailed explanation of the life cycle stages, stakeholders, and stakeholder needs can be found in [7] whereas an overview of the systems engineering approach and the functions can be found in [6].

The TPL is designed to be an assessment of the suitability of the technical solution for the customers' needs. Trade-offs in the overall design manifest themselves in the competing TPL criteria (the capabilities). The specific technical solutions chosen for a design are assessed and scored for each capability independently. When all of the capabilities are then combined for the final ranking, these trade-offs become clear. For instance, favoring small amounts of material may receive a high score in terms of capital expenditure (CapEx), but this may be balanced by a low score in power generation due to small device size.

This paper will detail the process of determining the assessment questions for each capability in the TPL taxonomy. These questions direct the assessor towards the most appropriate considerations for a given capability. The scoring criteria, not presented here, give guidance on how to rank the answer to the assessment questions. The assessment questions combined with the scoring criteria allow for the technology to be numerically ranked on the TPL scale.

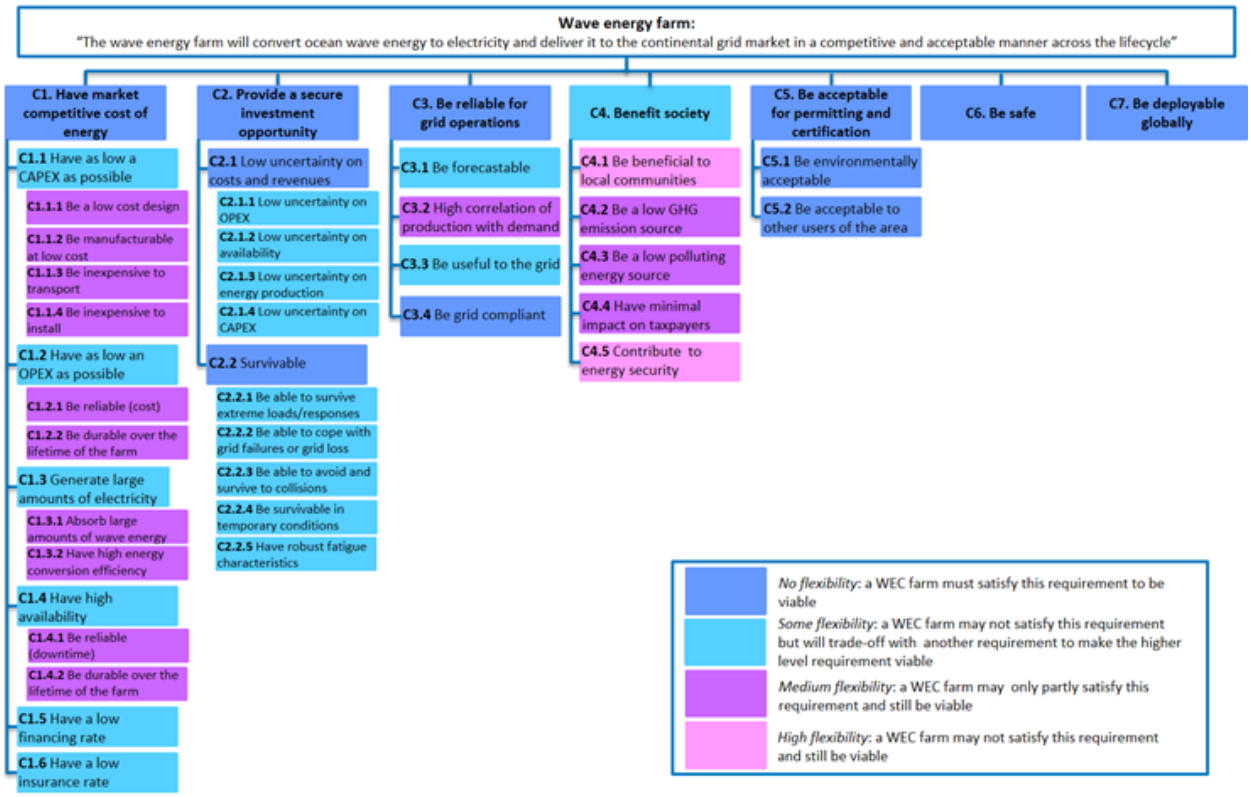

Figure 1: TPL Taxonomy

2. TPL TAXONOMY

Since the TPL is designed to be an assessment of the suitability of the technical solution for the customers' needs, the TPLs are now based on a systematic assessment and categorization of all of the stakeholder needs. The capability taxonomy, which identifies what the system must *be* from the stakeholders' perspective, constitutes the TPL groups and attributes that were originally developed through experience [3].

Analysis of stakeholders' needs leads to the specification of seven high-level stakeholder requirements. Five of these have been split into sublevel requirements. Some of the sublevel requirements have been split into sub-sublevel requirements. The full taxonomy is shown in Figure 1. Satisfaction of a requirement at a higher level depends on the satisfaction of the requirement at the sublevel. For example, the sub-capability *C1.1 Have as low a CapEx as possible* is achieved by: being a low cost design (C1.1.1), being manufacturable at a low cost (C1.1.2), being inexpensive to transport (C1.1.3), and being inexpensive to install (C1.1.4).

3. FUNCTION TAXONOMY

The functions define the fundamental elements of the solution that must be provided in order to achieve the mission and deliver the capabilities. They identify the behaviors the farm must possess, i.e. the farm must be able to generate and deliver electricity from wave power. High-level functions are independent of the technology or design used to implement the function.

The WEF is the *system* that is being optimized. The system is further broken down into subsystems and sub-subsystems and so on. It is not necessarily the goal to optimize these subsystems and sub-subsystems individually, but rather to optimize the farm.

The top level functions (5 of them) conceptually identify what the WEF must do to meet its mission. The subfunctions below the top levels further decompose the top level functions (e.g. WEC or electrical substation). These subfunctions identify the unique aspects that must be achievable to satisfy the higher level function. Further breakdown is given to subfunctions in the form of sub-subfunctions, further focusing in on the details that are needed (e.g. PTO within a WEC). In all cases, sub-levels fully identify the aspects that must be achieved to fully satisfy the higher level. Figure 2 details the full taxonomy.

4. TPL ASSESSMENT

The capabilities and the functions are united; the functions identify what the system must *do* in order to achieve what be system must *be*, i.e. the capabilities. As such, there are measures that can be identified at the intersection of functions that actually impact or implement a given capability. These measures are concrete and form the basis of the TPL assessment questions. By compressing all of the measures that have been identified across all of the functions, i.e. by collapsing all columns into one, a series of assessment questions to assess the capability were generated. Figure 3 illustrates

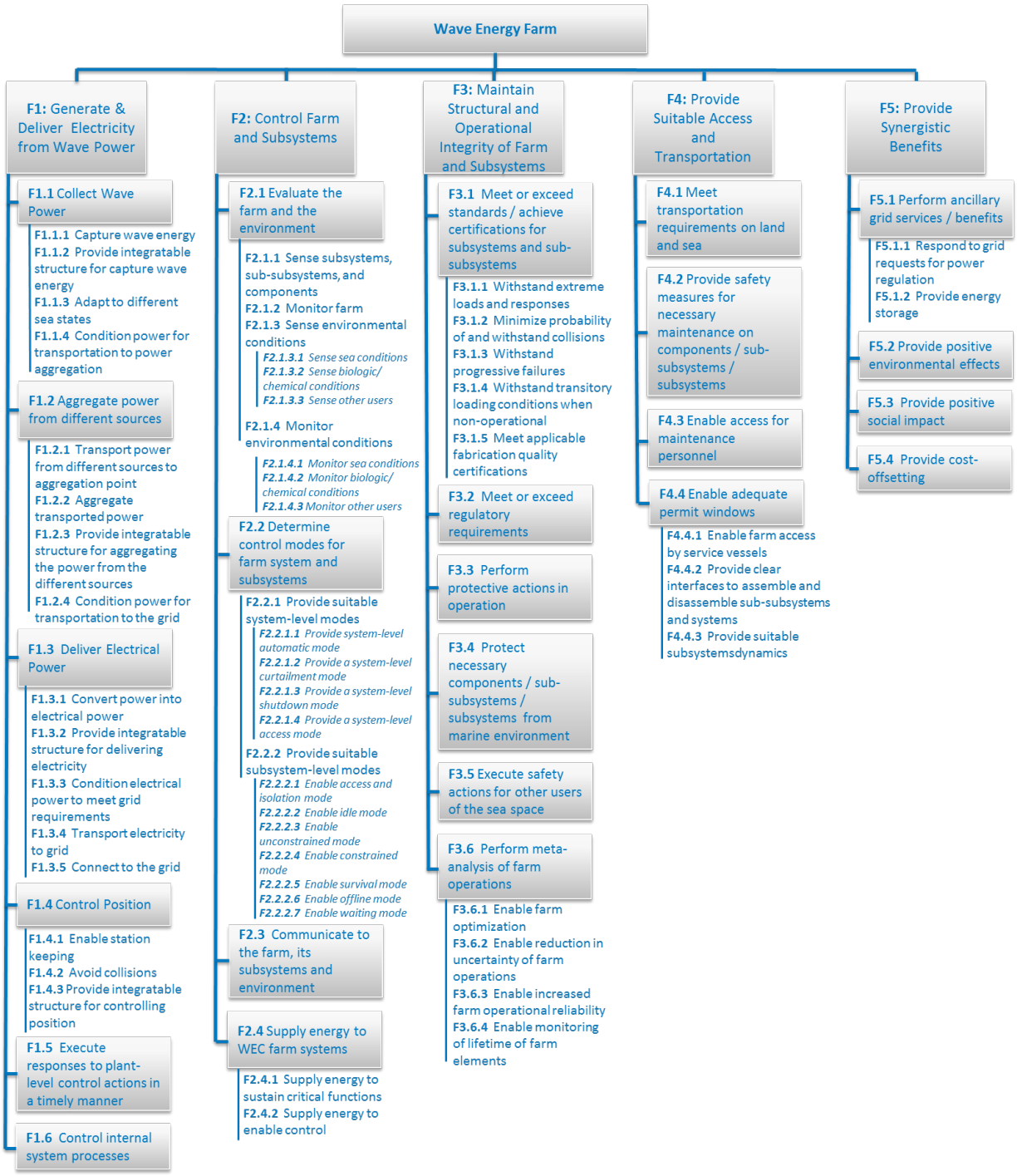

Figure 2: Function Taxonomy

Capabilities - functions mapping matrix		Functions			
		Function 1	*Sub-function 1.1*	Function 2	Function F
Capabilities	Capability 1	Measure 1			
	Capability 2			Measure 1	Measure 1
	Sub-capability 2.1		Measure 1 Measure 2		
	Capability C				Measure 1

Figure 3: Generalized capabilities — functions mapping matrix.

a generalized version of this concept.

This revised version of the TPL assessment addresses the question of appropriate levels of detail at different TRL levels. The assessment questions are grouped according to three levels of TRL (1, 3, and 5). The most basic questions are addressed to TRL1 technologies. An expanded more detailed set of questions is addressed to TRL3 technologies and these must also update their answers to the TRL1 questions when requested. Finally technologies at TRL5 and above must present quantified and verified evidence for the assessment process.

Further, *C1: Have a market competitive cost of energy* contains all of the elements needed to calculate the levelized cost of energy (LCOE) for the technology, and at TRL5 it will be expected that this calculation is completed. The CapEx (C1.1), operational expenditure (C1.2) and energy production (C1.3 and C1.4) are all directly represented in this capability and at the lower TRLs each of these facets are queried with development appropriate substitutes for cost. The financing and insurance are also represented in the TPL taxonomy as these alter the LCOE, however since they are not technology specific they are not included in the TPL assessment.

For instance, assessment questions in *C1.1.1 Be a low cost design* at TRL1 query the following concepts:

- The technical maturity of the subsystems (new solution never been tested before to proven technology tested in a relevant environment),
- WEC specific questions: size, dominate material type, loading, and physical profile changes,
- Position control specific questions: deployment depth and connections to sea floor.

In particular *F1.1.2: Provide integratable structure for capture wave energy* and *F1.4.3 Provide integratable structure for controlling position* in Figure 2 are highlighted because they are TRL1 intelligible cost drivers. The questions at TRL3 and TRL5 become much more specific and prescribed in terms of the accepted verification methodologies. For instance, the TRL3 general loading concerns are now queried through a design utilization factor (the ratio of the structural design load (before factor of safety) to the P50 structural load).

At each intersection a similar process was followed: first the measures that allow one to assess how well a function is meeting a capability are identified. Then these measures are prioritized and crafted into TRL specific questions. In this manner assessment questions, targeting the lowest levels of the taxonomy in Figure 1, have been generated to produce a comprehensive TPL assessment methodology.

5. CONCLUSIONS

The TPL assessment identifies the technology independent "performance requirements" by setting a holistic approach to assessing a technical solution. It is not enough to simply have a low LCOE, one must also mitigate risk and uncertainty as well as consider the ability to be globally deployable. By achieving a high score in the TPL assessment, the technical solution has met the "performance requirements" of the stakeholders. Hence, the TPL assessment identifies the technology independent "performance requirements."

An initial version of both the assessment questions and the scoring criteria have been finished; these will be publically released after they have been used on multiple technologies and revised through this experience.

6. ACKNOWLEDGMENTS

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