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► To cite this version:

Aurélien Babarit, Diana Bull, Katherine Dykes, Robert Malins, Kim Nielsen, et al.. Stakeholder requirements for commercially successful wave energy converter farms. *Renewable Energy*, 2017, 113, pp.742 - 755. 10.1016/j.renene.2017.06.040 . hal-01563318

HAL Id: hal-01563318

<https://hal.science/hal-01563318>

Submitted on 17 Jul 2017

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Stakeholder Requirements for Commercially Successful Wave Energy Converter Farms

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ABSTRACT

In this study, systems engineering techniques are applied to wave energy to identify and specify stakeholders' requirements for a commercially successful wave energy farm. The focus is on the continental scale utility market. Lifecycle stages and stakeholders are identified. Stakeholders' needs across the whole lifecycle of the wave energy farm are analyzed. A list of 33 stakeholder requirements are identified and specified. This list of requirements should serve as components of a technology performance level metric that could be used by investors and funding agencies to make informed decisions when allocating resources. It is hoped that the technology performance level metric will accelerate wave energy conversion technology convergence.

KEYWORDS: Wave energy converter, wave energy farm, systems engineering, requirements, technology performance level, technology convergence

1. INTRODUCTION

Wave energy converter (WEC) technology development as a whole has not yet delivered the desired commercial maturity or, more importantly, the techno-economic performance needed to penetrate the electric utility marketplace. Both commercial readiness and market viability are required for successful entry into and survival in the energy market.

The ways in which WEC technologies have been developed have been analyzed in [1] and [2]. Technology development progress, technology value, and technology funding have largely been measured, associated with, and driven by technology readiness, measured in technology readiness levels (TRLs). Originating primarily from the space and defense industries, TRLs focus on procedural implementation of technology developments of large and complex engineering projects, where cost is neither mission critical nor a key design driver. The key deficiency with the TRL approach in the context of wave energy conversion is that WEC technology development has been too focused on commercial readiness and not enough on the economic viability required for market entry.

To compensate for this deficiency, technology performance levels (TPLs) have been introduced in [1], and further detailed in [2], as a techno-economic performance assessment metric for WEC technologies. The techno-economic performance assessment metric in [2] provides a means to measure the market viability of different WEC technologies and thus may be used by funding agencies or investors to make informed decisions when allocating resources. The metric was recently used as one of the performance measures in the *Wave Energy Prize* competition organized by the U.S. Department of Energy [4]. The initial form of the TPL assessment and its corresponding metric were developed based on experience in the wave energy sector, and knowledge of the key performance attributes needed for wave energy converters to be commercially successful [3].

An alternative approach used to identify the components and content of a techno-economic performance metric consists of applying systems engineering techniques. Systems engineering is an

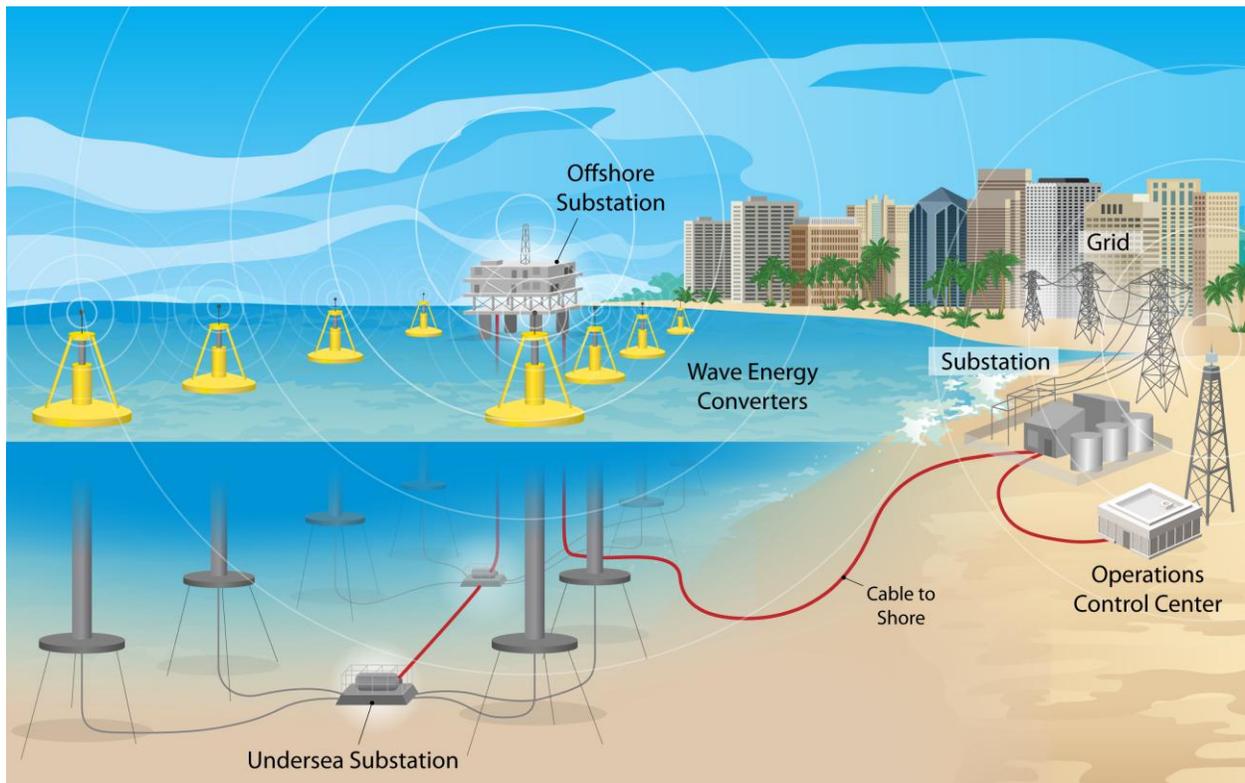
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50 interdisciplinary field of engineering that provides a framework to design and manage complex
51 engineering systems over the entire system lifecycle [5]. It is commonly used in various industries such as
52 aerospace, defense, and oil and gas; the success of the International Space Station is a famous example of
53 its application. The process begins by discovering the core problems that must be resolved to enable a
54 successful solution and, to do this, the framework of systems engineering stays agnostic by not selecting
55 specific design embodiments. It includes identifying stakeholders' needs and requirements with respect to
56 the system. By considering the whole set of stakeholders over the whole system lifecycle, systems
57 engineering provides a holistic list of these stakeholder requirements.

58 It seems reasonable to argue that market viability (i.e., prospects for commercial success) should be
59 judged based on how well a farm of WECs satisfies stakeholder requirements. To our knowledge, such a
60 list of stakeholder requirements is not available in the context of wave energy. In [6], requirements were
61 formulated in the wave energy conversion context, but only for the mooring system. Even in a more
62 mature industry such as wind energy, only one reference was found dealing just with technical
63 requirements for grid connection of wind energy farms [7]. Therefore, as a joint effort between Ecole
64 Centrale de Nantes, the National Renewable Energy Laboratory (NREL), Sandia National Laboratories,
65 Ramboll, Wave-Venture Ltd., and DNV GL, a list of stakeholder requirements for wave energy farms was
66 developed. This paper reports the outcomes of this work. Guidance from International Standards
67 Organization 15288 [5] as well as IEEE 1233 [8] has been followed.

68 2. MISSION STATEMENT FOR A WAVE ENERGY FARM

69 The first activity in systems engineering is to precisely identify what is the mission of the product [5].
70 The product must be considered for a fully mature industry over the entire lifecycle. Therefore, it must be
71 assumed that multiple wave energy farms have been deployed and that there are multiple proven
72 technologies to choose from.



73
74 **Figure 1. Artist's impression of a wave energy farm (Illustration by Alfred Hicks, NREL)**

75 In systems engineering, distinctions are made between systems, systems-of-systems, subsystems, sub-
76 subsystems, and so on [9]. A system is composed of subsystems. A subsystem is composed of sub-
77 subsystems. The lowest level in the list of sub-sub-subsystems is called components. A system-of-systems
78 is composed of systems. Systems are characterized by the fact that they are optimized for the specific

79 purpose of the system, and the elements of the system (subsystems) are optimized for that same overall
80 purpose. Taking these definitions into account, the wave energy farm is the system. A WEC, which itself
81 is composed of multiple sub-subsystems such as the primary absorber and the power conversion chain, is
82 just one subsystem in the farm. Indeed, for a fully mature wave energy industry, end users of wave energy
83 technologies will operate wave energy farms probably composed of many WEC units. Other necessary
84 subsystems to make a complete wave energy farm include: station-keeping subsystems (mooring
85 subsystems or foundations), grid-connection subsystems (e.g., electrical cables and substations), and
86 communication-and-control subsystems. Figure 1 shows an artist’s impression of a WEC farm. According
87 to systems engineering, it should be assumed that there are multiple suppliers available with proven
88 technologies for all the subsystems involved in the wave energy farm, including the WEC units. The work
89 presented here is clearly relevant for WEC technology developers because requirements for a successful
90 WEC technology will follow from the requirements for a successful WEC farm.

91 The mission statement for the wave energy farm defines what it takes to make the WEC farm
92 successful:

93 *“The wave energy farm converts ocean wave energy to electricity and delivers it to the continental utility*
94 *market in a competitive and acceptable manner across its lifecycle.”*

95 The continental scale utility system market means a very large electrically interconnected utility grid
96 market. Other markets may be available for WEC farm applications. Indeed, it has been proposed to
97 produce freshwater from seawater and wave energy through desalination (see [10] for example). A niche
98 market (in comparison to the continental utility market) is composed of users connected to micro-grids or
99 not grid-connected users (e.g., oil and gas offshore platforms, isolated science stations or equipment, or
100 island communities). According to [11], wave-powered navigation buoys were commercialized in Japan
101 as early as 1965. More recently, wave power has been used commercially for propulsion of an ocean
102 sensor platform [12]. In this work, the focus is on the continental scale utility market by choice. It must be
103 acknowledged that stakeholders’ requirements may be significantly different for the alternative markets
104 listed above. Identification and specifications of the requirements for these alternative markets are left for
105 future work.

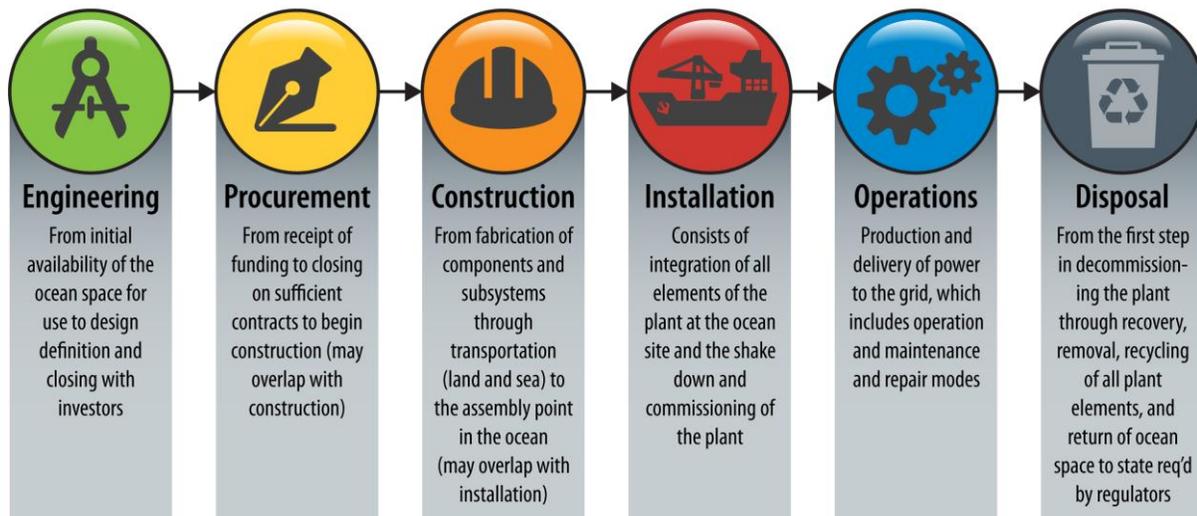
106 Competitiveness not only includes market-competitive levelized cost of energy (LCOE), but also
107 energy quality, availability of the farm, and investor attractiveness. Competitiveness of a particular wave
108 energy technology in providing electricity to the continental utility market should be judged not only with
109 respect to other wave energy technologies, but also with respect to other renewable energy technologies
110 (i.e., wind turbines or photovoltaics). Indeed, to become economically viable, a wave energy farm that has
111 the cheapest cost of energy of all wave energy farms still needs to be competitive with respect to other
112 renewable energy solutions (at least for certain deployment locations). Note that local public authorities
113 may put in place attractive financial incentives (e.g., feed-in tariffs or tax benefits) for wave energy farms.
114 This may be the case if the wave energy farm provides significant benefits to the society by being a low-
115 carbon-energy source, or by creating local jobs. This will be discussed further in Section 5.

116 Acceptability shall be considered across the lifecycle, including environmental acceptability, social
117 acceptability, socio-economic impact and/or benefit, legal and regulatory acceptability, and safety.

118 **3. LIFECYCLE STAGES OF A WAVE ENERGY FARM**

119 Systems engineering requires identification of stakeholders at each stage of the lifecycle. Six lifecycle
120 stages have been identified for a wave energy farm. These are depicted in Figure 2. The words
121 “Engineering,” “Procurement,” “Construction,” and “Installation,” for the first four lifecycle stages have
122 been used because they are the usual terms within the offshore construction industry. Engineering,
123 procurement, construction, and installation (EPCI) contracts are common forms of contracting
124 arrangements within offshore construction.

125



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127
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Figure 2. Lifecycle stages of a wave energy farm (Illustration by Alfred Hicks, NREL)

129 **3.1 Engineering**

130 Engineering is the first stage of the lifecycle. The objective is to design the wave energy farm,
131 including its technical, legal, and financial aspects. This stage starts with a wave energy farm project
132 developer identifying an opportunity to develop a wave energy farm. It includes identification of available
133 ocean space, estimating the wave energy potential, reviewing for possible environmental impacts,
134 identifying WEC technologies, and potential investors. Activities of the wave energy farm developer in
135 this stage shall aim to:

- 136 • Achieve complete wave energy farm technical design and specifications. This includes selecting a
137 suitable, qualified, WEC technology, designing the wave energy farm layout for mooring
138 subsystems, designing the grid connection, establishing procedures and specifications for
139 installation, operation and maintenance, and decommissioning; and developing schedules for the
140 next stages of procurement, construction, and installation. Some of the technical design
141 specifications may be subcontracted to consultants (e.g., ocean engineering firms). It is expected
142 that the final farm design and related procedures will be approved and/or certified by a certifying
143 body.
- 144 • Achieve a profitable business model. This may include negotiation of a power purchase
145 agreement (PPA) with a utility company for the electrical power generated by the wave energy
146 farm. Alternatively, the business model may aim to sell the electricity on the wholesale electricity
147 market.
- 148 • Obtain all necessary permits and authorizations. This includes both permits for grid connection
149 and use of the ocean space. Permit for use of the ocean space may include securing a lease from a
150 site-use management agency (e.g., the Crown Estate in the United Kingdom). Permits from other
151 regulatory agencies (e.g., environmental or health and safety regulatory agencies) are often also
152 required. Permits from agencies may include conducting environmental studies or monitoring
153 impacts.
- 154 • Secure financing from investors and financiers.
- 155 • Obtain buy-in from local communities and other users of the area. This may include public
156 meetings and consultations, and developing wave energy farm project-related activities that spur
157 economic development in the area.

158 **3.2 Procurement**

159 Once the wave farm technical design is specified and funding is available, the wave energy farm
160 project can enter the procurement stage. At this point, the wave energy farm developer who carried out
161 the work in the first stage may sell the wave energy farm project to another company that will take charge
162 of the project for the next stages of the lifecycle. The new owner of the wave energy farm may be a
163 construction company or investors for which the wave energy farm is an investment product. In the latter
164 case, construction activities will be subcontracted to a wave energy farm construction company. Such
165 transfers of ownership and responsibilities are common in the wind energy industry. If there is not such a
166 transfer, the initial wave energy farm developer may take the role of the construction company for the
167 next stages of the lifecycle. Alternatively, it may subcontract the construction of the wave energy farm to
168 a wave energy farm construction company, thus retaining ownership.

169 In all cases, the objective is to contract suppliers for all systems and services that must be provided
170 for the wave energy farm’s project until the operations lifecycle stage. Typical systems that may be
171 provided by suppliers are the WEC units, station-keeping systems, grid-connection systems, and
172 communication-and-control systems. Services related to installation of the wave energy farm’s systems
173 may be provided by marine contractors. Contracts should specify requirements for quality standards and
174 identify quality-control steps that will be taken during the next lifecycle stage. During this stage, it may
175 be necessary to update the wave energy farm project’s schedule and business model. It is also believed
176 that the maintenance service provider should be contracted in this stage of the lifecycle—at least for the
177 first years of operation of the farm. Some of the maintenance activities may be subcontracted to the
178 suppliers that provided the systems in the first place (e.g., subcontracting maintenance of the WEC units
179 to the WEC units’ suppliers).

180 **3.3 Construction**

181 Once contracts with suppliers of subsystems are in place, construction begins. Suppliers of
182 subsystems may rely on second-tier suppliers for sub-subsystems, components, or materials. Second-tier
183 suppliers may themselves rely on third-tier suppliers for sub-sub-subsystems, components, materials, and
184 so on. Indeed, the supply chain may be a highly complex tree of suppliers. For reliability and availability
185 in the supply chain, the size of the pool of suppliers should increase with decreasing rank of the suppliers.
186 Sub-subsystems or components provided by second-tier and subsequent-tier suppliers should be
187 commercial off-the-shelf products.

188 In this work, the analysis of the construction lifecycle is focused on the manufacturing and assembly
189 of first-tier subsystems suppliers and/or the wave energy farm construction company. In addition, the
190 construction stage may include activities such as land transportation and storage of subsystems and/or
191 sub-subsystems, land assembly of subsystems and/or sub-subsystems, ocean transportation and storage of
192 subsystems and/or sub-subsystems, ocean assembly of subsystems, quality control, and functionality
193 testing. Functionality testing and quality control are central to this lifecycle stage because these aspects
194 are key to reducing risk and attracting investors. These activities may happen in any order and with
195 possible repeats. Second-tier suppliers may be required to provide services related to land and storage
196 transportation, ocean transportation and assembly (ship providers and operators), and ocean storage.

197 During this lifecycle stage, it may be necessary to update the wave energy farm project’s schedule and
198 business model to take into account delays and/or variations in costs. At the end of this stage, the
199 subsystems are ready (including quality control and certification by certifying bodies) and waiting to be
200 transported to the deployment location in the next lifecycle stage.

201 **3.4 Installation**

202 The next stage of the lifecycle is installation. The objective is to make the wave energy farm
203 operational. This stage may rely heavily on marine contractors. In turn, they may rely on ship providers
204 and operators. Consultants (e.g., ocean engineering firms) and certifying bodies may also be involved.
205 This stage may include transportation of subsystems from their last storage location to their deployment
206 locations, and their actual deployment. Numerous marine operations may be involved such as towing,

207 lifting, unrolling cables, and ocean assembling/connecting of subsystems. Installation is expected to occur
208 over a period of time during which part of the farm may be commissioned and operated.

209 During commissioning, the functionality of installed subsystems and sub-subsystems will be verified
210 (e.g., the communications, controls, and quality of power). This stage may require active participation of
211 the certifying bodies before the farm can begin to export power to the continental utility system.

212 During this lifecycle stage, it may again be necessary to update the wave energy farm project's
213 schedule and business model to take into account delays and/or variations in costs.

214 **3.5 Operations**

215 The next stage is operations. The objective is to maximize revenue by producing and selling
216 electricity while maintaining the capability of the farm to do so over the whole farm lifetime. The
217 operations stage starts with the first power delivered to the grid. At this point, the company that took
218 charge of the construction and installation of the WEC farm may sell it to another company that will take
219 care of it during operations. The new owner may be a WEC farm operator or investor for which the wave
220 energy farm is an investment product. In the latter case, the WEC farm's operation activities will be
221 subcontracted to a WEC farm operator. Such transfer of ownership and responsibilities is typical in the
222 wind energy industry. If there is not such a transfer, the company that took charge of the project in the
223 previous stages of the lifecycle may take the role of WEC farm operator. Alternatively, it may subcontract
224 the operation of the WEC farm to a WEC farm operator.

225 During the operations stage, it is likely that the farm will change its operational mode depending on
226 weather conditions and farm health. Operational modes may include an idle mode, a below-rated mode, a
227 rated mode, a survival mode, a partial shutdown mode, and a complete shutdown mode.

228 • In the idle mode, the WEC farm shall not produce power. However, all subsystems are ready to
229 start producing power as soon as required external conditions are met. Reasons for entering the
230 idle mode may be that sea conditions are below a minimum threshold (the power consumed by
231 the WEC farm would be larger than the produced power), permit-driven obligations relating to
232 the larger environmental conditions (marine life) or other users in the sea space, grid ancillary
233 requests superseding sea conditions, and fatigue concerns.

234 • In the below-rated mode, the WEC farm is producing power; however, all components, sub-
235 subsystems, and subsystems are on average functioning below rated conditions. The aim in this
236 mode is to maximize produced power. Reasons for entering this operational mode are moderate
237 sea conditions.

238 • In the rated mode, the WEC farm is producing power and at least one of the components, sub-
239 subsystems, and subsystems is being used at full capacity. The aim is to maximize power while
240 ensuring that operational limits are not exceeded for components, sub-subsystems, and
241 subsystems through some form of control mechanism. Reasons for entering this operational mode
242 are that sea conditions are optimal or above optimal with no complicating external factors
243 (environmental conditions, other users in the sea space, grid requests).

244 • In the survival mode, the WEC farm may or may not be producing power, but maximizing power
245 production is not the aim. The aim is to maintain structural and operational integrity until another
246 operational mode can be safely recommenced. The sea conditions are such that it is not possible
247 to make sure that operational limits will not be exceeded for at least one of the components, sub-
248 subsystems, and subsystems, which could lead to unacceptable failure. Reasons for entering this
249 operational mode are excessively large or energetic sea conditions or conflicting use of the sea
250 space.

251 • In the partial shutdown mode, at least one of the WEC farm subsystems is shut down because of
252 failure or maintenance. The rest of the farm is still operating. The aim of this mode is to enable
253 safe access to a failed system for repair or maintenance purposes. It requires that the failed
254 subsystem be de-energized for safe access. The rest of the farm is still operating as close as
255 possible to normal conditions.

- In the complete shutdown mode, the entire WEC farm is shut down. The WEC farm can be safely accessed since all subsystems are de-energized. The aim is to maintain structural and operational integrity. Reasons for entering this mode include: farm electrical interconnection system maintenance, grid failure, or loss of grid connection.

Note that because WEC devices are diverse and still under development, there is some uncertainty about these modes. For example, in some designs a survival mode might not be necessary (or the survival and rated modes might be one and the same). The exact nature of the partial and complete shutdown modes is particularly uncertain. It is assumed that most WECs shall be able to shutdown electrical output but some may not be able to prevent motion of the primary absorbers.

Activities of the WEC farm operator include controlling the operational mode of the WEC farm according to the status of the WEC farm systems and external factors, and maintaining the WEC farm in operational conditions. It shall include performing planned and unplanned maintenance activities. The farm is expected to enter the partial or complete shutdown mode during maintenance activities. The maintenance activities may be subcontracted to a maintenance service provider. Spare parts may be provided by WEC farm subsystems suppliers (including the supplier of the WEC units). Consultants (ocean engineering firms) and certifying bodies may be involved by providing services in this stage of the lifecycle.

Of course, activities of the WEC farm operator also include selling the electricity. Electricity may be sold to a utility company through a PPA or on the wholesale electricity market. In both cases, the WEC farm operator shall provide 20-minutes to day-ahead forecasts of the power production to its customers. Weather forecasts may be provided by consultants. Upon request from the grid operator, the WEC farm may also provide ancillary services to the grid.

The operations lifecycle stage ends at the end of the lifetime of the WEC farm.

3.6 Disposal

Eventually, the WEC farm operator shall dispose of the WEC farm. This stage includes uninstalling and decommissioning the WEC farm so that the deployment site is cleaned as required in permits and regulations. If permits and regulations allow, parts of the WEC farm or the WEC devices may be scuttled in order to create artificial reefs and additional marine habitat. Marine contractors and recycling firms may be subcontracted. Recycling of parts of the WEC farm may generate complementary revenues in this last stage of the lifecycle. Nonrecyclable parts shall be stored and destroyed, at a cost.

4. STAKEHOLDERS' LIST

With the mission statement and the lifecycle stages identified, systems engineering requires listing all stakeholders that interact with the wave energy farm. Stakeholders and their interaction with the WEC farm were discussed briefly in the stages of the lifecycle (see Section 3). Twenty-six stakeholders have been identified. They are shown in Figure 3 along with when they have an active role in the WEC farm lifecycle; they are grouped into four categories.

In the middle are the WEC farm core stakeholders. They are the WEC farm project developer, the WEC farm's owner, the WEC farm construction company, and the WEC farm operator. Note that the WEC farm's owner and the WEC farm construction company—or the WEC farm's owner and the WEC farm operator—may be one and the same stakeholder. The core stakeholders actually run the WEC farm project from its inception to its end. The WEC farm is their key concern because their business model, reputation, and future work depend on its success. The major difference with all the other stakeholders is their requirement to evaluate the farm at the system level—to understand the integration of all of the stakeholders' needs.

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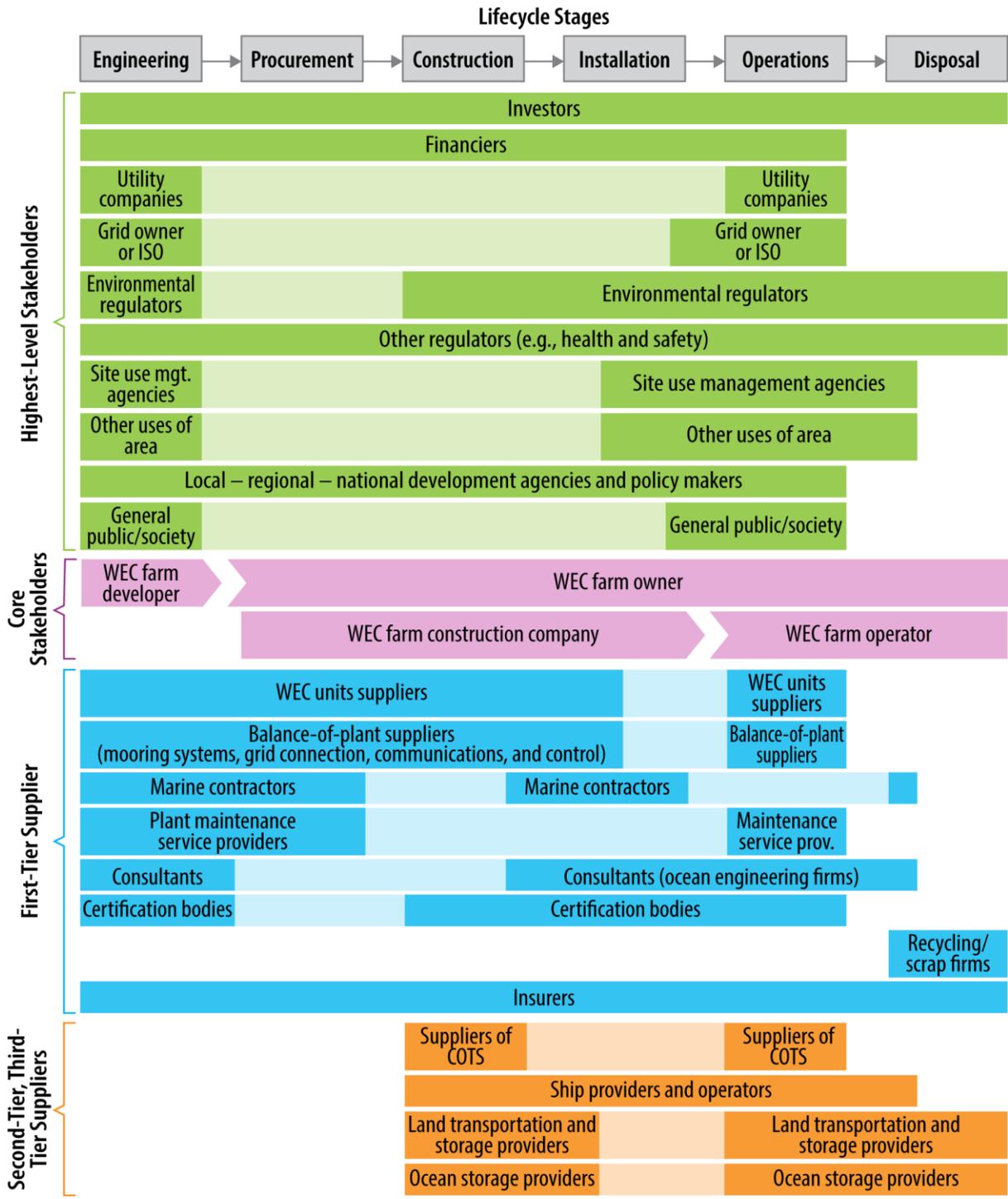


Figure 3. Stakeholders interacting with the WEC farm over the WEC farm lifecycle (Illustration by Alfred Hicks, NREL)

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Immediately below the WEC farm core stakeholders are the WEC farm first-tier suppliers. These stakeholders have direct interaction with the WEC farm core stakeholders by providing major services or subsystems required to build the WEC farm (e.g., WEC units or marine operations). The supplied services or subsystems shall satisfy the specifications issued by the WEC farm core stakeholders in terms of technical characteristics, and also with respect to costs. Recalling that a fully mature wave energy industry is to be assumed when applying systems engineering, the WEC farm project is important to the

312 WEC farm first-tier suppliers, but it may not be as critical as it is for the WEC farm core stakeholders.
313 Indeed, the WEC farm core stakeholders may be one customer among many, like for wind turbine
314 manufacturers in the wind energy industry. Depending on the number of customers and number of
315 suppliers, the bargaining power may be higher either for the WEC farm core stakeholders or for the first-
316 tier suppliers. Bargaining power may also vary depending on the supplied subsystems or services, and on
317 other external factors such as the demand in other industries. In the early days of an eventually
318 commercial wave energy industry, it may be expected that the bargaining power will be on the side of the
319 WEC farm core stakeholders with respect to WEC unit suppliers, whereas it may be the other way around
320 for other suppliers. This may be expected to shift as the industry develops.

321 Below the first-tier suppliers are lower-tier suppliers. They don't interact directly with the WEC farm
322 core stakeholders. They are suppliers to the WEC farm first-tier suppliers. There are expected to be large
323 numbers of them, competing in a large market, likely to be broader than the wave energy market. The
324 bargaining power may be either with them or with their customers, depending on the size of the farm with
325 respect to their overall market.

326 On top of the core stakeholders are the highest-level stakeholders. The highest-level stakeholders are
327 defined as those stakeholders who are customers of the WEC farm (e.g., utility companies, but also
328 investors and financiers) or stakeholders that don't have direct economic interest in the WEC farm. The
329 common point among all of these higher-level stakeholders is that they put requirements on the WEC
330 farm project (and thus on the WEC farm core stakeholders) that must be satisfied for the WEC farm to
331 become a reality.

332 **5. STAKEHOLDERS' REQUIREMENTS**

333 The roles of the stakeholders in each of the WEC farm lifecycle stages were further analyzed, along
334 with their needs and desires, with respect to the WEC farm. These are reported in Table 1 to Table 4.

335

Table 1. Roles and Needs of the Highest-Level Stakeholders and Core Stakeholders

	Stakeholder List	Stakeholder's Role	Stakeholder's Needs and Desires
Highest-Level Stakeholders	Investors	<ul style="list-style-type: none"> • Provides funds to the WEC farm project developer and WEC farm project operator • Owns shares of the WEC farm project developer/construction company/operator • Sets return on investment and profitability 	<ul style="list-style-type: none"> • Market-competitive profitability and return on investment with minimal project risk • Well understood and manageable risks for revenues and lifetime • Maintain reputation to ensure future market share as an investor—projects should get good press
	Financiers	<ul style="list-style-type: none"> • Provides funds to the WEC farm project developer • Sets loan rate and collects on the loan • Makes profit during operations 	<ul style="list-style-type: none"> • Market-competitive interest rate for duration of loan and positive net present value • Well understood and manageable risks for revenues and lifetime
	Utility companies	<ul style="list-style-type: none"> • Buys the generated electricity on the wholesale electricity market or through power purchase agreements • Sells the generated electricity to customers 	<ul style="list-style-type: none"> • Wholesale market competitive electricity • Reliable electricity for electricity market operations including good timing between the load peak and generation output particularly on a seasonal basis
	Grid owner and operator or independent system operator	<ul style="list-style-type: none"> • Sets requirements for interfacing to the grid • Transports the generated electricity from the WEC farm point of connection to consumers 	<ul style="list-style-type: none"> • Reliable electricity for grid operations including predictable generation for efficient dispatch and demand matching
	Environmental regulators	<ul style="list-style-type: none"> • Reviews project environmental impact • Grants authorization and approves farm configuration for avoiding environmental impacts • Prosecutes violations of environmental laws 	<ul style="list-style-type: none"> • Regulatory requirements are met for environmental impact
	Other regulators	<ul style="list-style-type: none"> • Reviews project and farm for compliance with other regulations (e.g., health, safety, working conditions) 	<ul style="list-style-type: none"> • Other regulatory requirements are met (e.g., health and safety)
	Site use management agency	<ul style="list-style-type: none"> • Reviews project use of ocean space • Provides the lease or authorization for the ocean space 	<ul style="list-style-type: none"> • Regulatory requirements are met for site use • High socio-economic benefit of ocean space use
	Other users of the area	<ul style="list-style-type: none"> • Lobbies for or against the WEC farm based on how it impacts their lifestyle and/or livelihood 	<ul style="list-style-type: none"> • Acceptable modification of livelihood, acceptable impact on recreational use of ocean area, acceptable impact to social perspectives on the ocean area
	Economic development agencies and policymakers	<ul style="list-style-type: none"> • Facilitates the WEC farm project development (incentives, subsidies, revenue bonds, guarantee loans) 	<ul style="list-style-type: none"> • Positive societal impact in their area, such as tax revenue, jobs generation, tourism, and reduction of emissions • Acceptable environmental impacts
	General public and society	<ul style="list-style-type: none"> • Lobbies for or against the WEC farm based on its impacts to society • Buys the electricity generated by the WEC farm from the utility companies and consumes it 	<ul style="list-style-type: none"> • Positive impact for society, as listed above • Carbon free market-competitive electricity • Acceptable environmental impacts

Table 2. Roles and Needs of the Highest-Level Stakeholders and Core Stakeholders

	Stakeholder List	Stakeholder's Role	Stakeholder's Needs and Desires
Core Stakeholders	WEC farm project developer	<ul style="list-style-type: none"> • Develops WEC farm design and business model • Finds funding from investors and financiers • Obtains all necessary permits to construct, install, and operate the farm • Ensures the WECs will be certifiable and eligible for insurance • Sells WEC farm to next owner 	<ul style="list-style-type: none"> • WEC farm less costly than available sales price • Maintain good reputation to ensure future market share • Steady sales to maintain business • Easy permitting with no operating restrictions • A steady business and project development volume, without stops and starts
	WEC farm's owner	<ul style="list-style-type: none"> • Buys the WEC farm project from WEC farm project developer or previous owner • Subcontracts WEC farm construction to a WEC farm construction company • Subcontracts WEC farm operations to a WEC farm operator 	<ul style="list-style-type: none"> • Generated electricity less costly than available sales price • Cost takes into account all cost sources (capital expenditures (CapEx), operational expenditures (OpEx), financial costs, and decommissioning costs) and lifetime • No operating restrictions or monitoring requirements
	WEC farm construction company	<ul style="list-style-type: none"> • Contracts suppliers • Manages farm construction and installation • Coordinates the installation sequence and commissioning sequence 	<ul style="list-style-type: none"> • WEC farm construction less costly than available sales price • Maintain good reputation to ensure future market share • Well understood and manageable risks during construction and installation • Safe WEC farm to build and install • Steady sales to maintain business
	WEC farm operator	<ul style="list-style-type: none"> • Operates the farm • Sells electricity on the wholesale electricity market to utility companies • Maintains the farm in operational conditions • Performs decommissioning operations 	<ul style="list-style-type: none"> • WEC farm operations less costly than available sales price • Well-understood and manageable risks for revenues and lifetime • Safe WEC farm to operate and maintain

Table 3. Roles and Needs of the First-Tier Suppliers of the WEC Farm

	Stakeholder List	Rationale and/or Role Notes	Stakeholder's Needs and Desires
First-Tier Suppliers	WEC unit suppliers	<ul style="list-style-type: none"> • Provides certified WEC units and design specifications for WEC installation and balance of farm, grid connection, operation, maintenance, and decommissioning • Provides spare parts • Provides a warranty on the WEC units sold and power production capability in specified sea state 	<ul style="list-style-type: none"> • WEC unit less costly than available sales price • Steady sales to maintain business • No warranty claims (device compatible with site environment)
	Balance of farm suppliers (e.g., mooring subsystems suppliers, grid connection suppliers, communication and control suppliers)	<ul style="list-style-type: none"> • Provides general purpose subsystems and sub-subsystems needed to create the rest of the farm (e.g., cables, mooring lines, instrumentation, and equipment for communication and controls) • Provides spare parts • Provides a warranty on products sold 	<ul style="list-style-type: none"> • Supplied subsystems and sub-subsystems less costly than available sales price • Steady sales to maintain business • No warranty claims
	Marine contractors	<ul style="list-style-type: none"> • Provides necessary services for ocean assembly and installation of the WEC farm • Guarantees installation meets specifications 	<ul style="list-style-type: none"> • Integration and installation operations less costly than available sales price • Safe access to necessary facilities and equipment • Steady sales to maintain business
	WEC farm maintenance service providers	<ul style="list-style-type: none"> • Performs maintenance operations on the farm • Deals with stock of spare parts • May return major elements to vendors for maintenance • Guarantees minimum WEC availability 	<ul style="list-style-type: none"> • Maintenance operations less costly than available sales price • Safe maintenance operations • Steady sales to maintain business
	Consultants (ocean engineering firms)	<ul style="list-style-type: none"> • Provides information on meteorological ocean conditions for WEC farm design, installation, and operation 	<ul style="list-style-type: none"> • Available prediction methodologies and measurement data for determining meteorological and ocean forecasts
	Certifying bodies	<ul style="list-style-type: none"> • Reviews and certifies design and procedures according to existing standards and guidelines 	<ul style="list-style-type: none"> • Applicable standards and guidelines for WEC farm design and operating procedures
	Recycling and scrap firms	<ul style="list-style-type: none"> • Destroys, recycles, and disposes of the remains of the WEC farm 	<ul style="list-style-type: none"> • Operations less costly than available sales price
	Insurers	<ul style="list-style-type: none"> • Provides insurance, including WEC damage to third-party equipment, accidental damage to WEC, insurance against storm damage, and “construction all risk” insurance 	<ul style="list-style-type: none"> • Well understood and manageable risks for project assets.

Table 4. Roles and Needs of the Sublevel Suppliers of the WEC Farm

	Stakeholder List	Rationale and/or Role Notes	Stakeholder's Needs and Desires
Second-, Third-Tier Suppliers	Subsuppliers (second- and third-tier suppliers of specialized and off-the-shelf items)	<ul style="list-style-type: none"> • Provides critical materials, components, sub-sub-subsystems, processes that the first-tier suppliers need • Provides spare parts 	<ul style="list-style-type: none"> • Supplied materials, components, processes, sub-sub-subsystems less costly than available sales price • Steady, dependable business volume
	Ship providers, operators, and ocean storage suppliers	<ul style="list-style-type: none"> • Provides ocean transportation (e.g., towing) and lifting services at sea • Provides storage at sea for WEC farm components, sub-subsystems, and subsystems 	<ul style="list-style-type: none"> • Provided services less costly than available sales price • Steady, dependable use of equipment with low idle time
	Land transportation and storage suppliers	<ul style="list-style-type: none"> • Provides land transportation services • Provides land storage for WEC farm components, subsystems, and systems 	<ul style="list-style-type: none"> • Provided services less costly than available sales price • Steady, dependable business volume
	Ocean storage suppliers	<ul style="list-style-type: none"> • Provides ocean storage services for WEC farm subsystems 	<ul style="list-style-type: none"> • Provided services less costly than available sales price • Steady, dependable business volume

334 The needs of individual stakeholders have been further condensed into a distilled list of stakeholders’
335 requirements that ensure the WEC farm will satisfy all the needs of each stakeholder. This list is presented
336 and discussed in the following subsections.

337 **5.1. Cost of energy**

338 All of the stakeholders in the WEC farm supply chain (owners; first-, second-, and third-tier
339 suppliers) need to make money. At a minimum, this means the supplied materials, components, sub-
340 subsystems, subsystems, or provided services are less costly than available sales prices. Low costs are
341 driven by:

- 342 • Simple design
- 343 • Ease of manufacturing
- 344 • Ease of transportation
- 345 • Installation
- 346 • Maintenance
- 347 • Reliability
- 348 • Durability
- 349 • Steady, dependable product sales.

350

351 High available sales prices are driven by high quality (lifecycle performance) of supplied materials,
352 components, sub-subsystems, subsystems, or provided services in terms of energy conversion efficiency
353 and availability (reliability and durability).

354 The needs of the last link in the supply chain—the WEC farm operator—are believed to be
355 particularly critical. The product sold by this stakeholder is the electricity produced by the WEC farm.
356 Available sales prices are set by utility companies that want market-competitive cost of energy. Note that
357 market prices may vary among energy sources in some countries. There may be feed-in tariffs for wave
358 energy or renewable energy sources, or there may be renewable energy certificates or renewable
359 obligations. Some countries may also require that a certain percentage of the energy portfolio of utility
360 companies is provided by renewable energy. Cost of energy shall take into account:

- 361 • Capital expenditures (CapEx)
- 362 • Operational expenditures (OpEx)
- 363 • Financial and insurance costs
- 364 • Disposal costs
- 365 • Energy production (including high availability, and predictable output)
- 366 • Lifetime.

367

368 Regarding cost of energy, a first set of requirements is specified:

369 **SR1. Have market-competitive cost of energy**

370 Electricity from the wave energy farm may be sold on the day-ahead wholesale electricity market
371 or through a PPA. In both cases, the sales price of the produced electricity shall be competitive
372 with other energy sources. However, note that market price may vary among energy sources in
373 some countries. There may be feed-in tariffs, renewable energy certificates, or renewable
374 obligations for wave energy or renewable energy sources. Some countries may also require that a
375 certain percentage of the energy portfolio of utility companies is from renewable energy sources.

334 The subtler stakeholder requirements below identify the variables in the LCOE equation. The
335 LCOE of the wave energy farm is needed to determine if the project will have a market-
336 competitive cost of energy.

337 SR1.1 Have as low CapEx as possible.

338 CapEx includes all costs that occur in the development and construction of a WEC farm
339 until it starts producing electricity. It should also include decommissioning costs. The
340 WEC farm should have as low a CapEx as possible. Drivers of CapEx are design,
341 manufacturability, transportability, and installability. It includes costs related to grid
342 connection.

343 *SR1.1.1 Be a low cost design*

344 A WEC farm should have an elegant design and as few components/sub-
345 subsystems as possible with many suppliers for the components and sub-
346 subsystems. It should minimize the required material quantities and it should
347 make use of low-cost material types. It may maximize recycling
348 opportunities to provide additional revenues at the end of the WEC farm's
349 lifetime.

350 *SR1.1.2 Be manufacturable at low cost*

351 The WEC farm should be easy and quick to mass produce. It should
352 minimize the need for specialized tools and equipment, highly qualified
353 workers, and dedicated or specialized infrastructure for manufacturing,
354 assembly, and storage. The WEC farm may provide cost-offsetting by
355 performing more than one service.

356 *SR1.1.3 Be inexpensive to transport (excluding install)*

357 WEC farm components, sub-subsystems, and subsystems should be built
358 close to the manufacturing and/or deployment site to minimize shipping and
359 transportation costs. Alternatively, the sub-subsystems and subsystems
360 should be of a size and modularity for which standard transportation is
361 possible. They should be transportable in any weather conditions.

362 *SR1.1.4 Be inexpensive to install*

363 WEC farm subsystems should be installable in most weather conditions,
364 require minimal time to complete the installation, use readily available
365 vessels, and minimize the need for skilled workers.

366 SR1.2 Have as low OpEx as possible

367 OpEx includes all costs necessary to operate and maintain the WEC farm over its entire
368 service life. The WEC farm should have as low OpEx as possible. Drivers of OpEx are
369 reliability (unplanned maintenance) and durability (planned maintenance).

370 *SR1.2.1 Be reliable (to avoid costly unplanned maintenance)*

371 The WEC farm should be highly reliable to avoid costly unplanned
372 maintenance. High reliability is achieved with proven high-quality
373 components, by minimizing the number of parts or components subject to
374 well-known failure modes (fatigue, wear, abrasion, corrosion, chemical
375 attack, thermal overload, clogging, and photolysis), and by avoiding
376 impulsive loads (end-stops, shock loading, and snap loads). Cost of repair for
377 subsystems that are likely to require frequent unplanned maintenance should
378 be low. Costs could include replacement parts, transportation to and from the
379 site of repair, fees incurred as a result of wait times for weather windows, and

334 fees for trained workers. Costs do not include lost revenue as a result of
335 downtime.

336 *SR1.2.2 Be durable over the lifetime of the plant (to avoid costly planned*
337 *maintenance)*

338 The WEC farm should be highly durable to avoid costly planned
339 maintenance. The WEC farm is ideally made of high-durability (long
340 lifetime) components. The number of parts and components subject to wear,
341 abrasion, and erosion is small. Ideally, the durability of a farm's components,
342 sub-subsystems, and subsystems is the same as the lifetime of the farm. Cost
343 of servicing for subsystems that require planned maintenance should be low.
344 Costs could include: replacement parts, transportation to and from the site,
345 fees incurred as a result of wait times for weather windows, and fees for
346 trained workers. Costs do not include lost revenue as a result of downtime.

347 **SR1.3 Be able to generate large amounts of electricity from wave energy**

348 The amount of electricity generation is an essential driver to the value of the WEC farm
349 (i.e., the sales price of the WEC farm as a product). Large amounts of electricity
350 generation enable a high energy yield and hence high revenues.

351 *SR1.3.1 Absorb large amounts of wave energy*

352 The WEC farm should absorb a high percentage of the wave energy that
353 passes through the farm. This implies that the farm can absorb energy across
354 a wide range of frequencies, heights, and wave directions. It should be
355 minimally affected by tide, current, and wind. Negative array interference
356 interactions should be minimal. Availability will not be covered here because
357 it is taken into account in requirement S0.

358 *SR1.3.2 Have high-conversion efficiency of extracted energy to electrical energy*

359 The WEC farm device power conversion chain and electrical collection
360 system should have a small number of conversion steps and each conversion
361 step should be highly efficient. Availability will not be covered here because
362 it is taken into account in requirement S0.

363 **SR1.4 Have high availability**

364 In this paper, we define availability as the ratio of the average annual power of the farm
365 to the theoretical maximum power capacity. We define the WEC farm rated power as the
366 maximum power that the farm can deliver to the utility system at the point of connection
367 to the utility grid. Thus, rated power is determined by the power carrying capability of the
368 interconnection cable from the WEC farm and the substation's power handling capacity.
369 A high availability will enable a high energy output and a dependable output thereby
370 increasing the value of the WEC farms electricity.

371 *SR1.4.1 Be reliable (to avoid lost revenue as a result of downtime)*

372 The WEC farm should be highly reliable to avoid downtime as a result of
373 unplanned maintenance. High reliability is achieved with proven high-quality
374 components, by minimizing the number of parts and components subject to
375 well-known failure modes (fatigue, wear, abrasion, corrosion, chemical
376 attack, thermal overload, clogging, and photolysis), and by avoiding
377 impulsive loads (end-stops, shock loading, and snap loads). Duration of
378 repairs for subsystems that may require unplanned maintenance (including
379 wait time between weather windows) should be short. Reliability with
380 respect to availability accounts for the lost revenue as a result of downtime.

334 *SR1.4.2 Be durable over the lifetime of the plant (to avoid lost revenue as a result of*
335 *downtime)*

336 The WEC farm should be highly durable to avoid downtime as a result of
337 planned maintenance. The WEC farm is ideally made of high-durability
338 (long lifetime) components, and the number of parts and components subject
339 to wear, abrasion, and erosion is small. Ideally, the durability of a farm's
340 components, sub-subsystems, and subsystems is the same as the lifetime of
341 the farm. Time of servicing for subsystems that require planned maintenance
342 (including wait time between weather windows) should be short. Durability
343 with respect to availability accounts for the lost revenue as a result of
344 downtime.

345 SR1.5 Have a low financing rate

346 Financing rate is the cost of the money borrowed from investors and financiers to build
347 and operate the WEC farm. Financing rate is dictated by investors and financiers
348 according to current market climate and reputation of the WEC technology. The
349 reputation of the WEC technology depends on its track record. The WEC farm project
350 controls the financial risk of the technology—the higher the risk, the higher the financing
351 rate.

352 SR1.6 Have a low insurance rate

353 Financial risk may be mitigated with insurance. Insurance may cover the risks that the
354 investors and financiers are not willing to take. To be insurable, these risks shall be well
355 understood and manageable. The criticality of these risks (i.e., the likelihood of these
356 risks and their financial consequences) drive the insurance rate.

357 5.2. Risks

358 Investors and financiers will dictate a financing rate based on financial risks (i.e., risks that the WEC
359 farm will not deliver the expected financial return). Risk shall be low to attract investors and financiers
360 with large financial capabilities (e.g., pension funds). High-risk projects need specialized investors whose
361 financial capabilities may be limited, thus constraining the size of the WEC farm. Some of the sources of
362 risks may be mitigated through insurance but most are mitigated through the experience of past projects.
363 Of course, insurance costs will depend on the risk's criticality (i.e., the likelihood of the risk and its
364 financial consequences). Thus, overall, the WEC farm shall provide a secure investment opportunity.

365 Assuming a fully mature industry, WEC farm risks are risks that the farm does not deliver on
366 expectations. As stated before, the concern for investors and financiers is the risk that the farm does not
367 deliver the expected return. For the WEC farm construction company, the risk is that the construction
368 work will take more time and money than initially planned (i.e., CapEx risks). For the WEC farm
369 operator, the risks are that revenues (energy production and availability) are lower than expected, that the
370 OpEx is greater than expected, and that the farm does not survive until the end of its expected lifetime.

371 The concept of survivability needs to be clarified. Recalling that systems engineering requires
372 assuming a fully mature industry, it shall be assumed that the limit states for the WEC farm design are
373 well defined and understood. It means that the WEC farm design fulfills the relevant design criteria up to
374 the limit states. Limit states shall include (this is a nonexhaustive list):

- 375 • Extreme environmental conditions and extreme loads response conditions during operations
- 376 • Extreme environmental conditions and loads response during temporary conditions (installation
377 and maintenance)
- 378 • Grid failure, grid loss, or grid interruption
- 379 • Collisions with other marine users, ships, or marine mammals.

334 Failure of a WEC farm’s subsystem, sub-subsystem, or component—despite conditions that are below
335 limit states—actually corresponds to a reliability or durability problem. It will impact OpEx and
336 availability of the WEC farm for which requirements have already been formulated.

337 However, because of the stochastic nature of the WEC farm environment (including other users of the
338 area and the grid), conditions that are beyond limit states, even if unlikely, may happen (e.g., a perfect
339 storm). It may be a great deal of risk for investors, financiers, and the WEC farm’s owner because the
340 consequences may be catastrophic. Thus, financial consequences of conditions that are beyond limit states
341 and their probabilities shall be well understood and as low as possible. In this work, survivability is
342 defined as the combination of probabilities and consequences of conditions beyond limit states.

343 Other risks relating to environmental acceptability and health and safety, both of which are relevant to
344 owners and management of all companies involved because of risks of legal consequences of any
345 incidents are considered separately in Sections 5.4 and 5.6.

346 This risk discussion leads to the specification of these requirements:

347 **SR2. Provide a secure investment opportunity**

348 For investors and financiers, it is critical that WEC farm risks are well understood and
349 manageable so investors and financiers know the financial risk (i.e., the risk that the farm will not
350 deliver the expected financial return). The financial risk results from the analysis of the
351 probabilities of the risks and of their financial consequences. Uncertainties on costs (CapEx and
352 OpEx), revenues (energy production and availability), and survivability are the drivers.

353 **SR2.1 Low uncertainty on costs and revenues**

354 Uncertainties and external factors may make CapEx, OpEx, energy production, and
355 availability deviate from expectations even though the WEC farm is operating in
356 conditions that are below limit states.

357 *SR2.1.1 Low uncertainty on OpEx*

358 OpEx may be greater than expected because of uncertainties in the reliability
359 and/or durability of components and sub-subsystems of the WEC farm. The
360 WEC farm shall be made of proven technologies. Standard deviations and
361 uncertainties on the mean time between failures of the WEC farm’s
362 subsystems, sub-subsystems, and technologies may be used to assess the risk
363 on OpEx.

364 *SR2.1.2 Low uncertainty on availability*

365 Availability may be smaller than expected because of uncertainties in the
366 reliability and/or the durability of components and sub-subsystems. If
367 unplanned maintenance activities are more frequent than expected, the farm
368 availability is less than expected. Availability may also be diminished
369 because waiting time between weather windows for planned and unplanned
370 maintenance is longer than expected.

371 *SR2.1.3 Low uncertainty on energy production*

372 Energy production may be smaller than expected because the resource may
373 be smaller than expected. Energy production estimates are normally made
374 based on the statistically worst year. First power delivery may be delayed
375 because of acceptability issues or delays in construction. This type of
376 uncertainty may be mitigated through insurance or penalties in contracts with
377 suppliers.

378 *SR2.1.4 Low uncertainty on CapEx*

379 CapEx may be greater than expected. It may happen because of an increase
380 in materials and/or component prices; and/or increased manufacturing

334 costs/durations; and/or increased transportation and installation costs. The
335 supply chain should be low risk.

336 SR2.2 Survivable

337 Because of the stochastic nature of the farm environment (including other users of the
338 area and grid), and uncertainties in the understanding of the response of the farm,
339 conditions beyond limit states may happen. These events may cause damage. The
340 financial consequences (loss of revenues because of downtime, loss of assets, cost of
341 repairs) shall be well understood and as low as possible.

342 *SR2.2.1 Be able to survive extreme loads and responses*

343 Because of the stochastic nature of the marine environment, weather
344 conditions or operational conditions may lead to extreme loads and
345 responses that exceed ultimate limit states or fatigue limit states design
346 conditions. The probabilities of such events and their financial consequences
347 (repair costs, loss of assets, or loss of production) shall be understood. If
348 relevant, possible cascade failures shall be taken into account.

349 *SR2.2.2 Be able to survive grid failures, grid loss, or grid interruption*

350 The grid is an external system to the WEC farm. Grid failure is a critical
351 ultimate limit state. As such, the WEC farm design shall be able to cope with
352 it. However, characteristics of grid failure (particularly downtime) may
353 exceed the specifications in the corresponding ultimate limit state. Often loss
354 of the grid is highly correlated with extreme weather events and for that
355 reason WEC ultimate limit states may need to be considered simultaneously
356 with loss of grid events. Technical consequences of such events shall be
357 harmless for the WEC farm and the financial consequences should be
358 minimal.

359 *SR2.2.3 Be able to avoid and survive collisions*

360 Other marine users, ships, and marine mammals are external systems to the
361 WEC farm. They may collide with one or several subsystems of the farm,
362 resulting in an accidental limit state. It may result in cascade failures.
363 Technical and financial consequences of such events should be low.

364 *SR2.2.4 Be survivable in temporary conditions, including installation (tow-out, if 365 applicable) and maintenance*

366 Because of the stochastic nature of the marine environment, weather or
367 operational conditions may lead to extreme loads and responses that exceed
368 serviceability limit states during temporary conditions. The probabilities of
369 such events and their financial consequences should be understood.

370 **5.3. Utility grid operations**

371 In this work, the market for the produced electricity is the continental utility market. For utilities to
372 buy the produced electricity in this market, the WEC farm operator must be able to provide reliable
373 forecasts of energy production with a 20-minute to 24-hour horizon. Energy production forecasts are often
374 still needed even if the electricity is sold to a utility through a PPA.

375 Moreover, the increase of the share of intermittent renewable energy sources in the energy mix is
376 challenging for grid operators with respect to grid stability and load balancing. This may limit the
377 development of the wave energy industry. Thus, energy production from the WEC farm should have a
378 high capacity factor, as well as energy output that is correlated with the daily and seasonal demand. It may
379 also provide useful ancillary services to the grid, including energy storage automatic generation control as
380 well as voltage and frequency control. Providing these services may be an additional source of revenue
381 for the WEC farm operator and may increase the acceptability of the WEC farm for the grid operator.

334 Thus, the following stakeholder requirements have been specified:

335 **SR3. Be reliable for grid operations**

336 Reliability for grid operations covers several aspects. Energy production from the WEC farm
337 shall be forecastable to enter the day-ahead wholesale electricity market. Moreover, the increase
338 of the share of intermittent renewable energy sources in the energy mix is challenging for grid
339 operators with respect to grid stability and load balancing. This could limit the development of the
340 wave energy industry. Thus, the WEC farm should have a high-capacity factor and produce
341 electricity during periods of higher electricity demand. Moreover, a WEC farm may provide
342 useful ancillary services to the grid. These include energy storage, automatic generation control,
343 and voltage and frequency control.

344 SR3.1 Be forecastable and have high power quality

345 The electricity market requires prediction of energy production in advance to maintain
346 equilibrium with the load; thus, the energy production from the WEC farm should be
347 forecastable. Typical prediction horizons are in the range of 20 minutes to day-ahead.

348 SR3.2 Have stable annual power production

349 Long-term variability is an issue for the grid operator in planning future energy capacities
350 and reserves. Grid operators prefer power sources that can contribute to base load or are
351 available on demand. High-capacity factor, defined as the ratio of the farm output over a
352 year to its potential output if it were operating continuously at full nameplate capacity,
353 characterizes low long-term variability. The WEC farm should have a high-capacity
354 factor and produce power during periods of higher demand.

355 SR3.3 Be useful to the grid by supplying ancillary services

356 The integration of intermittent renewable energy sources is challenging for grid operators
357 with respect to grid stability and load balancing. However, WEC farms may provide
358 useful ancillary services to the grid. These include energy storage, automatic generation
359 control, voltage and frequency control, and operational reserves.

360 **5.4. Acceptability**

361 A WEC farm shall obtain buy-in and support from the local communities and the general public.
362 Indeed, the deployment of a WEC farm inevitably causes a change in the use of the ocean space at the
363 deployment site that is likely to disrupt the activities of other users of the area. For the general public, the
364 WEC farm may cause increased electricity prices or increased taxes if it is subsidized. To obtain buy-in
365 and support, the WEC farm shall bring benefits to local communities and the general public that largely
366 overcome the negative impacts. Benefits may include electricity from a local, low-carbon-emission
367 energy source, local job creation, and coastal protection. Otherwise, public concerns and actions against
368 the project may seriously delay the project or cause it to fail (even if permits are granted). Benefits for the
369 local communities and the general public may lead local, regional, and national economic development
370 agencies and policymakers to facilitate the WEC farm project development (e.g., incentives, subsidies,
371 revenue bonds, guarantee loans, or tax credits).

372 Thus, the following stakeholder requirements have been specified:

373 **SR4. Benefit society**

374 A WEC farm needs to obtain buy-in and support from the local communities and the general
375 public. Like any industrial project, a WEC farm is likely to cause some negative impacts (higher
376 cost of energy, disruption to other activities) that shall be largely overcome by benefits for society
377 (low-carbon-emission energy source, local job creation, or coastal protection). Otherwise, public
378 concerns and actions against the project can seriously delay the project or cause it to fail (even if
379 permits are granted).

380 SR4.1 Be beneficial to local communities

334 The WEC farm shall be beneficial to local communities to obtain buy-in and support
335 from them. Local benefits may include local job creation, increase of local gross
336 domestic product, protection from coastal erosion, increases in the local tax base, or
337 improvement of infrastructure. Local benefits shall largely overcome possible negative
338 impacts (e.g., visual obstruction in the seascape).

339 SR4.2 Be a low-greenhouse-gas-emission energy source

340 The WEC farm needs to be a low-greenhouse-gas-emission energy source over the entire
341 lifecycle. A measure of lifecycle greenhouse-gas emissions is the global warming
342 potential per unit of electrical energy generated. The global warming potential is the
343 ability of a greenhouse gas to trap heat in the atmosphere relative to an equal amount of
344 carbon dioxide, and is dependent upon a full lifecycle assessment.

345 SR4.3 Be a low-polluting energy source

346 The WEC farm should not pollute the environment during construction, operation, or
347 disposal. The use of readily available and environmentally inert materials is desired. The
348 entire lifecycle shall be considered.

349 SR4.4 Have minimal impact on taxpayers and electricity consumers

350 Electricity consumers are the final users of the generated electricity. They want market-
351 competitive electricity in the long term.

352 SR4.5 Contribute significantly to energy security

353 Like other renewable energy sources, a WEC farm contributes to energy security. It does
354 not rely on foreign countries for supplying necessary fuel. The contribution to energy
355 security should be significant (i.e., the WEC farm should be a significant share of the
356 energy mix).

357 **5.5. Permitting**

358 The WEC farm developer, the WEC farm construction company, and the WEC farm operator all need
359 permits for occupying in the sea space and connecting to the grid. These permits shall be obtained from
360 the appropriate regulators before starting the WEC farm construction. The requirements should consist of
361 assessing and addressing environmental impacts, impacts to other users of the area, and impacts to the
362 electrical grid.

363 **SR5. Be acceptable for permitting and certification**

364 Permits for occupying the sea space and connecting to the grid shall be obtained by the WEC
365 farm developer before starting construction of the WEC farm. Consequently, the WEC farm shall
366 fulfill all regulatory and permitting requirements. The requirements usually consist of assessing
367 and addressing environmental impacts, impacts to other users of the area, and impacts to the
368 electrical grid.

369 SR5.1 Be environmentally acceptable

370 The WEC farm technology and design shall enable the construction of a power farm that
371 meets all environmental regulations. Thus, it shall cause no unacceptable impacts on the
372 seafloor, no unacceptable impacts on local currents or sedimentation, no unacceptable
373 impacts on local or global wildlife, and no unacceptable impacts on local or global
374 marine life.

375 SR5.2 Be acceptable to other users of the area

376 The WEC farm technology and design must integrate smoothly with other users of the
377 area. Other users of the area are local and global fishing industries, other industries using
378 the local area, recreational users of the local area, tourists and entertainment users of the
379 local area, and local communities.

334 SR5.3 Be grid-compliant

335 The WEC farm shall deliver electrical power that meets grid operator requirements for
336 power quality, including voltage, frequency, and flicker.

337

338 **5.6. Safety**

339 Safety is a critical concern as soon as human activities are involved. For the WEC farm, the
340 stakeholders most directly concerned are the WEC subsystem designer, WEC subsystem manufacturers,
341 the WEC farm construction company, the WEC farm operator, marine contractors, and maintenance
342 service providers. Investors are indirectly concerned because they want to maintain good reputations to
343 ensure future market share. The stakeholder requirement is:

344 **SR6. Be safe**

345 Safety is a key requirement as soon as human activities are involved, particularly at sea. The WEC
346 power farm shall be safe at each stage of its lifecycle. The focus shall be on the construction, operations,
347 and disposal stages.

348 **5.7. Market size**

349 To ensure a sustainable business, the WEC farm developer's ability to provide steady sales is a key
350 requirement for the WEC farm construction company, and for industries in the supply chain. It may also
351 be an important requirement for the local, regional, and national development agencies, policymakers,
352 and general public to know that the WEC farm business is replicable, sustainable, and large enough to
353 warrant policy, agency, and public support. Thus, the WEC farm shall be deployable at many different
354 sites that represent a large national and global market share:

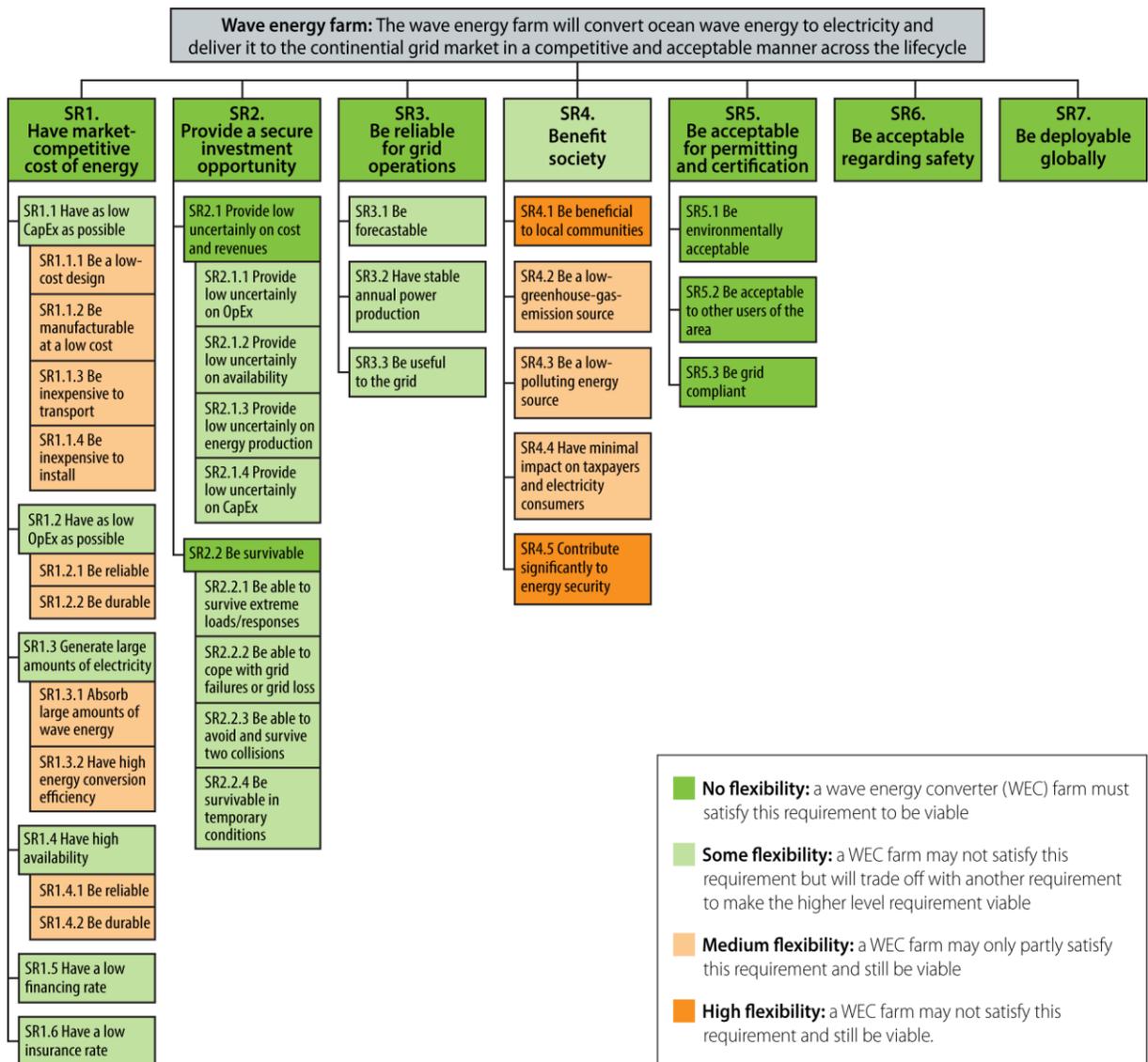
355 **SR7. Be deployable globally**

356 The ability to provide steady sales is another key requirement for sustainable business for the WEC
357 farm developer, the WEC farm construction company, and for the suppliers of the supply chain. It may
358 also be an important requirement for the local, regional, and national development agencies,
359 policymakers, and general society with respect to the overall benefits from the WEC farm. Thus, the
360 WEC farm shall be deployable at many different sites that represent a large national and global market
361 share. It shall be able to adapt to variable site characteristics, including wave resource, geophysical
362 conditions, distance to shore, and local infrastructure.

363 **6. DISCUSSION AND CONCLUSIONS**

364 Analysis of stakeholders' needs leads to the specification of seven high-level stakeholder
365 requirements. Five of these have been split into sublevel requirements. Some of the sublevel requirements
366 have been split into sub-sublevel requirements. Satisfaction of a requirement at a higher level depends on
367 the satisfaction of the requirement at the sublevel. For example, satisfaction of the low CapEx
368 requirement (S0) depends on the satisfaction of lower-level requirements such as S0, Design for low cost;
369 S0, Manufacture at low cost; S0, Be inexpensive to transport; and S0, Be inexpensive to install. Thus, one
370 should focus first on the lower-level requirements when assessing the performance of a particular WEC
371 farm with respect to stakeholders' needs.

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336 **Figure 4. Stakeholder requirements for a commercially successful WEC farm (Illustration by Alfred**
337 **Hicks, NREL)**

338
339 Figure 4 shows 33 requirements to consider at the lower levels. However, the most important
340 requirements are the seven at the highest level. Assessing the performance of the WEC farm at the
341 sublevels is only a necessary step to enable assessment of the performance of the WEC farm with respect
342 to stakeholders' requirements at the highest level.

343 It must be acknowledged that most requirements are flexible. For example, a technical solution may
344 not fully satisfy one particular requirement, but trade-off with another requirement may make the higher-
345 level requirement viable. Also, not all stakeholders are equally important; thus, a technical solution may
346 not satisfy a requirement of a lower-importance stakeholder and still be viable. Four degrees of flexibility
347 have been identified:

- 348
- No flexibility—any WEC farm must satisfy this requirement to be viable
 - Some flexibility—a WEC farm may not fully satisfy this requirement but will trade-off with another requirement to make the requirement at the higher level viable
 - Medium flexibility—a WEC farm may only partly satisfy this requirement and still be viable
- 349
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351

334 • High flexibility—a WEC farm may not satisfy this requirement and still be viable.

335 Flexibility in the requirements is shown with colors in Figure 4.

336 It is believed that the present list comprehensively captures the requirements for a WEC farm to
337 successfully accomplish its mission (i.e., convert wave energy to electricity and deliver it to the
338 continental grid market in a competitive and acceptable manner across the lifecycle). Indeed, all identified
339 needs and desires of all identified stakeholders of the WEC farm in all the identified stages of the
340 lifecycle are captured by at least one of the requirements in the list. Therefore, this work is expected to be
341 helpful for new WEC technology developers because it provides guidance and objectives for the design
342 process. Existing WEC technology developers may already have developed their own lists of
343 requirements that may have different structures and specifications. It must be acknowledged that these
344 lists should be equally satisfactory provided that all stakeholders' needs in Tables 1 to 4 are captured.

345 Historically, WEC technology value has largely been measured by technology readiness and TRLs.
346 Deficiencies with this approach were analyzed in [1] and [2]. The need for a measure identifying market
347 viability was highlighted, and the concept of TPLs was introduced. It is now widely acknowledged in the
348 wave energy industry that both technology readiness (TRL) and economic viability (TPL) needs to be
349 taken into account to assess the value of a WEC technology.

350 It is believed that the list of requirements that have been developed in this work should serve as the
351 components of the TPL metric. The TPL score could be used by investors and funding agencies to make
352 informed decisions when allocating resources to wave energy technology developers. The TPL metric
353 could also be used to perform benchmarking studies between different WEC technologies. Such studies
354 would be much more comprehensive than other recent studies such as [13], [14], [15], [16], and [17] that
355 essentially used proxies for cost of energy or energy performance. In the long term, it is believed that
356 using a TPL metric based on the present or improved list of stakeholder requirements may prove helpful
357 toward WEC technology convergence.

358 Nevertheless, assessing precisely to what extent a given technology satisfies the requirements may
359 prove to be difficult in the early TRL stages. It may require detailed technical information that may
360 become available only at a later TRL stage. However, the Pareto principle may apply for most of the
361 requirements, and it may be possible to develop simplified methodologies for the early TRLs that could
362 capture, for example, 80% of the technology performance with 20% of resources needed for the precise
363 assessment. Future work may be carried out in this direction. Also, the focus of this paper was on the
364 continental grid market. Stakeholders' requirements may need to be updated for other markets
365 (desalination or nongrid-connected users).

366 7. ACKNOWLEDGEMENTS

367 This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-
368 08GO28308 with the National Renewable Energy Laboratory. Funding for the work was provided by the
369 DOE Office of Energy Efficiency and Renewable Energy, Wind and Water Power Technologies Office.
370 Sandia National Laboratories is a multiprogram laboratory managed and operated by Sandia Corporation,
371 a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's
372 National Nuclear Security Administration under contract DE-AC04-94AL85000.

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