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Technology Readiness Level: Guidance Principles for Renewable Energy technologies

Final Report

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Contact: Philippe Schild

E-mail: *Philippe.Schild@ec.europa.eu*
RTD-PUBLICATIONS@ec.europa.eu

European Commission
B-1049 Brussels

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DG RTD – TRL Project Technology Readiness Level: Guidance Principles for Renewable Energy technologies

Final Report

Authors: Antonio De Rose, Marina Buna, Carlo Strazza, Nicolo Olivieri, Tine Stevens, Leen Peeters, Daniel Tawil-Jamault

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List of abbreviations

Abbreviations	
ARENA	Australian Energy Agency
CSP	Concentrated Solar Power
EARTO	European Association of Research and Technology Associations
EC	European Commission
EU	European Union
GoG	Guide of Guides
GTP	Geothermal Technologies Programme
HLG-KET	High Level Expert Group on Key Enabling Technologies
KET	Key Enable Technologies
MRL	Manufacturing Readiness Level
NASA	National Aeronautics and Space Administration
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaics
R&D	Research and Development
RE H&C	Renewable Heating and Cooling
SRL	System Readiness Level
TRL	Technology Readiness Level
US DOD	United States Department of Defence
US DOE EERE	United States Department of Energy, Office of Energy Efficiency and Renewable Energy

1. ABSTRACT

The European Union's research framework programme Horizon2020 uses the concept of Technology Readiness Level (TRL) to describe the scope of its calls for proposals; the definitions provided, however, are meant as an overall guidance and do not refer specifically to renewable energy technologies.

This study was meant to firstly assess the use of TRL in the energy field at European level: a desk research, complemented by surveys and interviews with stakeholders coming from the institutional, industrial and research field, led to the conclusion that there is still a lack of common understanding around the concept of TRL and further guiding principles would be needed. The study aimed also to develop guidance documents defining TRL in 10 renewable energy fields; a Guide of Guides was conceived to be the backbone for any technology-specific definition and, based on its instructions, 10 guidance documents were produced and validated by stakeholders in a two step-approach: first through an online survey and then during a one-day workshop. A subcontractor, acting as reviewer ensured the documents produced were consistent to update the Guide of Guides; its analysis identified technology-specific issues as well as a set of common trends for each TRL that may serve as a reference to develop guidance documents in any other energy technology field.

Les appels à projets du programme-cadre de l'Union Européenne pour la recherche, Horizon2020, font référence concept de Niveau de Maturité Technologique (TRL) pour établir quels projets sont éligibles. Les définitions de chaque niveau telles que proposées actuellement restent générales et ne sont pas précisées spécifiquement pour les technologies d'énergie renouvelable. Cette étude a dans un premier temps établi un état des lieux des usages de l'échelle TRL dans le secteur de l'énergie au niveau européen sur la base d'une recherche documentaire et d'entretiens avec les parties-prenantes institutionnelles, de l'industrie et du secteur de la recherche. Cet exercice permit d'identifier une absence d'interprétation commune du concept TRL et la nécessité de mettre en place des principes généraux d'application. Un « Guide des Guides » a été conçu comme document de référence pour la rédaction de guides d'application pour dix secteur de technologies d'énergie renouvelable. Chacun de ces guides d'application a ensuite été validé par les parties-prenantes dans un processus en deux étapes : tout d'abord à l'occasion de la diffusion d'un sondage en ligne, puis lors de groupes de travail. Afin d'assurer la cohérence des documents une révision externe a été réalisée par un sous-contractant, pour ensuite permettre la mise à jour du « Guides des Guides ». Les spécificités de chaque technologie tout comme un ensemble d'éléments communs pour chaque TRL ont ainsi pu être relevés. Ceux-ci pourront servir de référence pour le développement de guides d'application de l'échelle TRL à d'autres technologies du secteur de l'énergie.

2. EXECUTIVE SUMMARY

The present document constitutes the draft final report of the Study 'Guidance on TRL for renewable energy technologies', issued by the European Commission (EC) through a framework contract intended to support its research and innovation policy in the areas of renewable energy (RE), carbon capture and storage and clean coal.
The report is aimed to introduce the scope and purpose of the project, describe the methodological approach proposed by the Consultant and present the overall findings and conclusions from the work. It is therefore articulated around 4 main sections:

- Introduction to the project;
- Results from Task A – Assessment the state of play of the use of TRL in the energy field through a desk research
- Results from Task B – Drafting of guiding principles
- Conclusive remarks.

Introduction to the project.

The context.
The report starts setting the background of the study, which is represented by the efforts from the EC to develop a strategy to make Europe more attractive for investments in research, technology, innovation and manufacturing; at present, the biggest challenge in this sense seems to be transferring excellent research and development results into innovative solutions for the markets, bridging the so called 'Valley of Death' that causes many would-be innovations to wither and die.

The Technology Readiness Level (TRL) scale is the most widely used tool for a maturity assessment and allows for a consistent comparison of maturity between different types of technologies. The European Union's research framework programme Horizon2020 is using the concept of TRL in the requirements for its calls for proposals. However, the concept of TRL still lacks a clear definition, in particular in the field of renewable energy technologies.

The approach proposed to meet the study's objectives.
The study aimed therefore to assess how TRL is used in the field of renewable energy technologies in Europe and to develop a set of guidance documents helping project developers to understand what it means to be at a certain TRL in their field. These guidance were validated by relevant stakeholders in each field during ten workshops.

EY was the leading partner for the implementation of the project, acting in a consortium with RINA Consulting S.p.A and with the involvement of Technofi as a subcontractor.
The project team proposed a well-designed methodological approach that could leverage on the following key elements:

- a centralized knowledge management process through the setup and maintenance of a database, storing the findings of the desk research as well as the feedback received from stakeholders;
- the definition of a 'Guide of Guides' as a backbone to the overall process of developing the guidance documents;
- a well-designed stakeholder engagement approach, ensuring a right balance in the categories of actors and in the geographies represented; and
- the appointment of an external reviewer to ensure overall consistency in the methodology used to draft the guidance documents and to analyse project outcomes.

The project was implemented during a period of 14 months and in close cooperation with the Directorate General for Research and Innovation (R&I); a series of meetings and conference calls were organized regularly with the contractor to ensure constant alignment and validate the main methodological steps.

A project website was also created to give visibility to the study amongst the wide community of renewable energy stakeholders.

Task A.
The project started with a desk research to assess the state of the art in the use of TRL in the energy field: existing TRL scales were analyzed to identify pitfalls and advantages and the findings were complemented by telephone interviews with relevant stakeholders both in Europe and in the US.

The project also reviewed the use of TRL in the US Department of Energy (DOE) calls, assessing from one hand the quality and the consistency of how each specific TRL was addressed and from the other the overall budget allocated to calls, to determine whether there was a correspondence.
An online survey led to the evaluation on how TRL is currently used in the energy research and development programs as well as in industrial and commercial projects; Task A ended with the identification of best practices and recommendations from the analysis carried out.

Task B.
The 10 RE technologies under scope were:

- Photovoltaics;
- Concentrated Solar Power (CSP);
- Hydropower;
- Wind;
- RE Heating and Cooling (H&C);
- Geothermal;
- RE Alternative Fuels;
- Ocean Energy;
- Bioenergy - biological pathway; and
- Bioenergy - thermochemical pathway.

A lead expert for each technology was selected to draft the guidance document; to ensure the consistency of the work of the lead drafters, the project team developed a Guide of Guides (GoG), providing guiding principles and a stable procedure to be adapted to the specific context of the various RE fields. The GoG was meant to be a reference model, informing on how to identify a suitable scale to track progress of the technology's maturity, considering Critical Technology Elements (CTEs) and clear metrics to measure maturity attributes for both individual technology components and integrated systems/sub-systems.

Relevant stakeholders in each field (researchers, technology developers, manufacturers, consultants, representatives from the EC or other international organizations. etc.) were engaged in the overall process through a two-step approach: they firstly provided their feedback on the draft guidance document by means of an online survey and then they participated to a validating workshop, where the TRL definitions were thoroughly discussed and agreed upon.
The 10 workshops, lasting one-day each, were held in Brussels at EY premises and followed all the same agenda and validating procedure.

The draft guidance documents resulting from the interaction and discussions with stakeholders were assessed by the external reviewer with a view to identifying common trends and specificities across the different technologies to update the GoG accordingly.

Results from Task A

The main findings from the desk research and the interviews conducted led to the assessment that European stakeholders in the energy field typically use the EU Horizon2020 TRL scale, whereas in the US the most used scale is the one from the US DOE, and in less extent the US DOD TRL scale.
The main purposes to use TRL is to apply for funding or review project proposals in a call for funding; however, it is also used for internal and external communication, and to less extent as a planning or decision-making tool.

The general knowledge about System Readiness Level (SRL) and Manufacturing Readiness Level (MRL) is very limited and there is no alignment between the stakeholders on the advantages and disadvantages of these scales. Overall, stakeholders pointed out the need for a clarification of the way TRL is used to be able to assess each level more objectively and recommended the inclusion of examples for each level as an added value.

Findings led to the conclusion that the calls from the US DOE addressed the TR levels most consistently in the wind energy sector whereas RE Heating and Cooling was the sector where a clear and consistent form of addressing the TRL was lacking the most. Wind had also a dedicated high budget on high TRL. Overall, the use of TRL scale in the US DOE calls was consistent among the different technologies, and differences were related to the use of single words, without the addition of any element specifically linked to a technology.
However, for geothermal energy a further technology-specific detailing was found and the use of specific descriptions that are clear and verifiable was considered highly relevant. Although the description was perceived as too elaborate, the descriptive parts provided clear formulations that were taken into consideration by the project team while developing the guidance document,

especially in the refinement of the descriptions for each TRL and the identification of the checkpoints.

As an additional best practice resulting from the analysis, the scale developed by ESB International is worth mentioning, as it is very detailed with respect to functional readiness and lifecycle readiness, and contains an ESBI Verification Checklist as well as indicative information on costs. The idea of checkpoints at each TRL level was taken up by the project team in the development of the GoG.

Results from Task B

The approach proposed for the validation of the guidance documents seemed to be very appreciated by stakeholders: commenting the draft documents before the actual discussion proved to be beneficial in terms of acculturation with the objective, the scope and the content of the related workshop; moreover, the proposed interactive roundtable with the lead expert being supported by a moderator (involved horizontally along the ten sectors) was useful to manage the short time available.

The main challenge was to clarify that the guidance documents were not to replace the existing definitions of TRL used by the EC in the Horizon2020 calls, but rather to help project developers understand what it means to be at a certain TRL in their technological field.
Some other outstanding issues were raised by stakeholders during the workshops, such as the need to clearly define boundaries across sectors when these are potentially overlapping. Also, the terminology used in the guidance had to be made applicable to different dimensions, such as new materials, sub-components (e.g. wind turbine blade coating) or complete systems (e.g. new cycles in CSP). Non technological parameters were additionally addressed by stakeholders, such as the economic analysis (costs, business model and plan, marketing and commercial aspects), sustainability and risk mitigation and social acceptance. Prescriptiveness was another topic deeply discussed during the workshops, as participants argued that if TRL definitions are too prescriptive, there may be the risk to make financing conditional to the complete fulfilment of the TRL definition and exclude new ideas.

The analysis, complemented by the external review, helped identifying common milestones and trends at each TRL, and to update the GoG accordingly. At the same time, for each technology under scope, the discussions with stakeholders focused on technical specificities that were drivers of possible enrichments or deviations from the horizontal approach initially given by the GoG.
If one takes Photovoltaics as an example, it is a relatively mature technology with modular elements, hence the TRL guidance document was focused on the "upscale" concept, starting from the study of the photovoltaic cell up to the series of modules. TRL 8 was not conceived as "first of a kind" or "low rate production", but instead as limited and stable production of the modules' system and it was possible to consider a "mass production" at TRL 9. On the other hand, CSP does not entail mass/serial production at plant level, since specific conditions of the site influence the specific engineering practice; the focus in this case was on 'dimensions' and the guidance document had to be made applicable to either subcomponents or a complete system.
Another technology-related discrepancy observed concerns the manufacturing approach: while in most of the sectors considered it is relevant for TRL 6 or 7, in the case of ocean energy it is already applicable to TRL 2.

Conclusive remarks

An analytical comparison at a high level, i.e. without considering technology-specific features, showed that the common trends obtained from the 10 guidance documents are compatible with all the technologies considered. It seems therefore appropriate, in a first approach, to take into consideration the common trends and the associated checkpoints to get an overview of every technology readiness levels with accuracy, at least from TRL 1 to TRL 4-5.

From TRL 6 to TRL 8, some differences from one TRL to another are observable between technologies, especially regarding commercialization, manufacturing approach, standardization and in-field integration issues. At TRL 9, a global consistency is verifiable again between technologies.
Also, when considering the technology specific features, some differences are observable, especially regarding prototype and pilot production trajectories to validate the product and simulation approaches with numerical tools.

The GoG proved to be a solid and robust framework for the characterization of the different TRL of the several technologies, allowing the approach used for the implementation of this project to be actually replicable to other technologies.

3. INTRODUCTION TO THE PROJECT

This study, entitled '*Guidance on TRL for renewable energy technologies*' has been issued by the European Commission (EC) through a framework contract intended to support its research and innovation policy in the areas of renewable energy, carbon capture and storage and clean coal.

The project started in October 2016, with an expected duration of 14 months.

EY was the leading partner for the implementation of this project, acting in a consortium with RINA Consulting S.p.A and with the involvement of Technofi as a subcontractor.

A final meeting is scheduled on 7 November 2017 to present the findings of the study to the EC.

3.1.Project overview

3.1.1. Background information

In every field, from space and defence to energy, innovation is achieved in part through the application of new technologies. However, if on one hand a new technology ensures gains in performance advancements, on the other it brings a great deal of uncertainty and risk regarding the technology's capabilities, limitations and development trajectory. When technologies are not ready on time, the consequence could be budget overruns, schedule delays, performance shortcomings or even project cancellation. A better understanding of the state of the technology maturity is therefore critical in making good decisions about injections, development and integration of technologies.

The EC has been paying a significant attention to developing a strategy to make Europe more attractive for investments in research, technology, innovation and manufacturing.
In 2009, the Communication SEC-1257 pointed out the importance of focus, deployment and re-industrialization to foster research and innovation; this led to the creation of the High Level Expert Group on Key Enabling Technologies (HLG-KET), where both industrial and research stakeholders were asked to assess the situation regarding KETs in the EU and to propose recommendations on further policy actions to an effective renewal of European industry and manufacturing.

One of Europe's major weaknesses in this sense is known as the 'Valley of Death', and relates to the difficulties in transferring excellent research and development results into innovative solutions for the markets. HLG-KET provided a specific action plan based on the 'three-pillar bridge' model:

- Technological research, to support transforming fundamental research into technologies;
- Product demonstration, to support transforming technologies into product prototypes;
- Competitive manufacturing, to support creating production systems to commercially produce the products.

The Technology Readiness Level (TRL) scale is the most widely used tool for a maturity assessment and allows also a consistent comparison of maturity between different types of technologies.[1]

The European Union's research framework programme Horizon2020 is using the concept of TRL in the requirements for its calls for proposals. However, the concept of TRL still lacks a clear definition, in particular in the field of renewable energy technologies.

[1] The TRL concept was originally developed by the National Aeronautics and Space Administration (NASA) to support the development of Space technologies and allow for more effective assessment of and better communication on the maturity of new technologies.

Technology Readiness Levels	
TRL 1	**Basic principles observed**
TRL 2	**Technology concept formulated**
TRL 3	**Experimental proof of concept**
TRL 4	**Technology validated in lab**
TRL 5	**Technology validated in relevant environment**
TRL 6	**Technology demonstrated in relevant environment**
TRL 7	**System prototype demonstration in operational environment**
TRL 8	**System complete and qualified**
TRL 9	**Actual system proven in operational environment**

Table 1 The TRL scale used by Horizon2020 for the eligibility assessment of projects

3.1.2. General objectives

The general objectives of this study were:

- to assess the state of play of the use of TRL in the field of renewable energy technologies in Europe;
- to develop a set of guiding principles explaining how to address the concept of TRL in 10 selected renewable energy sectors; and
- to validate the guiding principles elaborated by organizing 10 workshops with key stakeholders in each sector.

3.1.3. Services and activities required

The activities described in the Terms of Reference

The study was articulated around 2 Tasks, consisting in the following main activities.

Task A. Assessment of the state of play in the use of TRL in the energy field.

- A1. Assessment of the state of play in the use of TRL in the energy field.
- A2. Review of the use of TRL for renewable energy in the US Department of Energy calls.
- A3. Evaluation on how TRL is currently used both in the energy research and development programs and in energy industrial and commercial projects.
- A4. Identification of best practices.

Task B. Draft of guiding principles on the use of TRL in 10 renewable energy technologies.

The draft guiding principles are intended to define what is meant by 'being at a specific TRL' for each of the 10 areas analysed:

- Photovoltaics
- Concentrated Solar Power (CSP)
- Hydropower
- Wind (onshore and offshore [including floating])
- Renewable Heating and Cooling (RE H&C)
- Geothermal
- Renewable Alternative Fuels

- Ocean Energy System (wave and tidal)
- Bioenergy – Biological pathway
- Bioenergy – Thermochemical pathway

For each of the renewable energy areas a final workshop was held, with the main objective of presenting and validating the draft guidance documents.

The overall approach proposed and the added value brought by the consortium

The project team proposed a well-designed methodological approach that could leverage on the consortium previous experiences in similar projects. In particular, key to the successful implementation of the study were:

- a centralized knowledge management process through the setup and maintenance of a database, storing the findings of the desk research as well as the feedback received from stakeholders;
- the definition of a 'Guide of Guides' as a backbone to the overall process of developing the guidance documents;
- a well-designed stakeholder engagement approach, ensuring a right balance in the categories of actors and in the geographies represented;
- the appointment of an external reviewer to ensure overall consistency in the methodology used to draft the guidance documents and to analyse project outcomes;
- a learning by doing approach, combined with a constant monitoring of project risks and the application of mitigating measures as soon as they were needed.

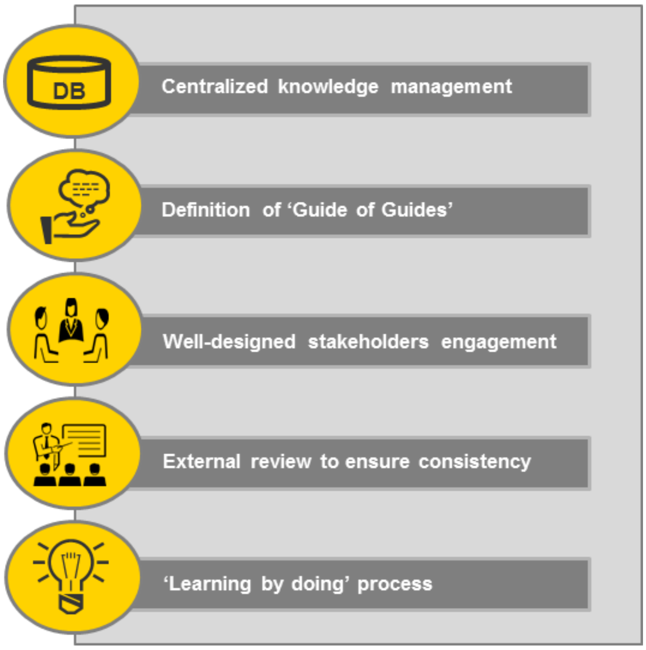

Figure 1 The added value brought by the consortium

The following picture shows how the services required by the Terms of Reference were translated into a process flowchart, so as to ensure the maximization of any interaction between the different tasks.

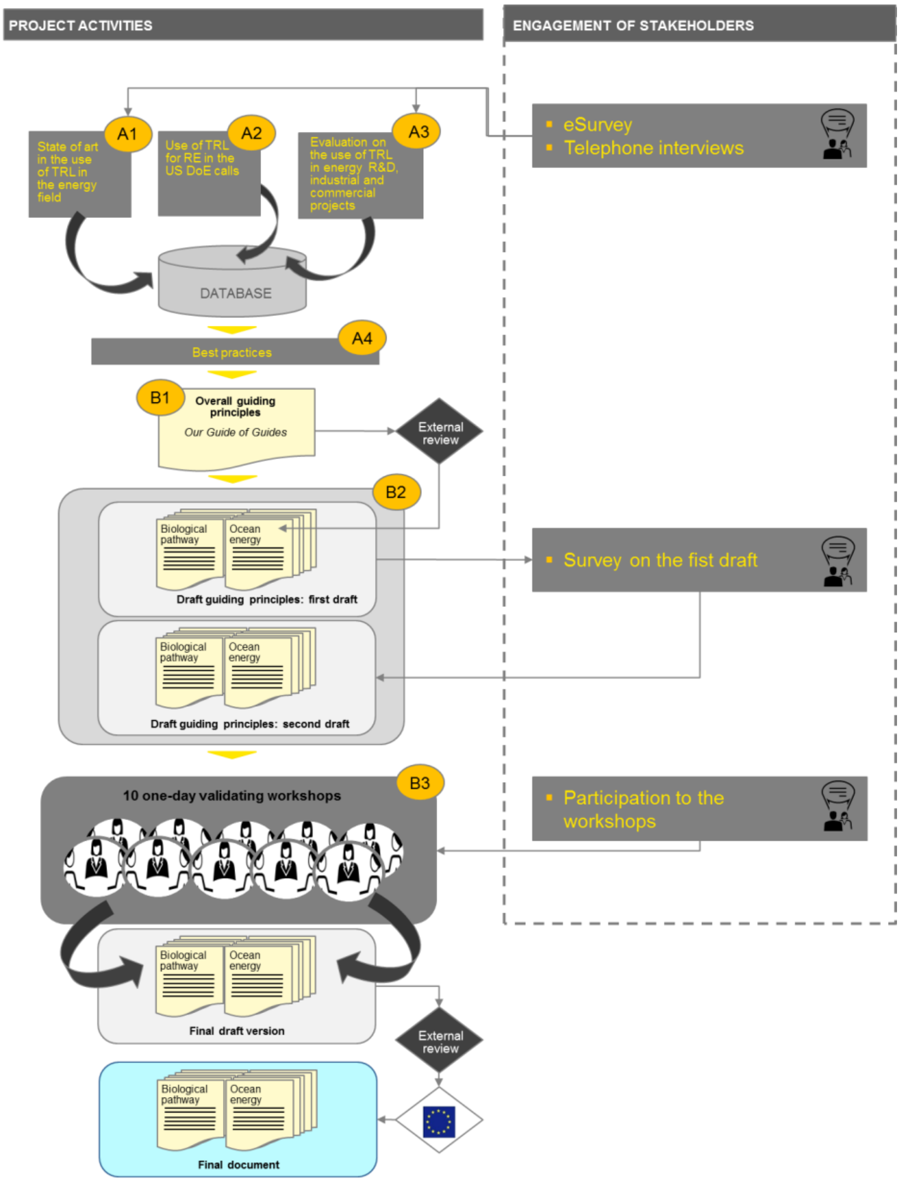

Figure 2 Our overall approach to the project

3.1.4. The project team

The team was led by a Project Manager and composed of:

- Renewable energies experts, focusing on data collection, analysis and elaboration;
- 10 lead drafters in charge of the guidance documents and 2 peer reviewers;
- A stakeholder engagement manager, coordinating the involvement of stakeholders both during the desk research phase and the development of guidance documents;
- An external reviewer to ensure overall consistency of the guidance documents elaborated as an outcome of the workshops; and
- Administrative support for the organization of the 10 workshops.

3.2. Process organisation

3.2.1. Regular checkpoints with the EC

To ensure constant alignment with the EC on the methodological approach as well on the structure of project deliverables, several conference calls and meetings were organized with the Project Officer and considered as checkpoints.

3.2.2. The project website

As soon as the project started the team set up a website specifically for this study, to increase its visibility and, at the same time, have a shared platform where to exchange information with relevant stakeholders and to inform them on the current and planned status of activities.

Our website is accessible under this link: http://www.ey.com/be/en/services/specialty-services/renewable-energy-technology.

The structure of the website, discussed with and validated by the EC, was organized as follows:

- Introduction on the project, specifying its background and the actors involved;
- The project, presenting:
    - the objectives and scope;
    - the approach proposed;
    - the project team, with short-bios of all the experts involved;
    - the project deliverables
- The sectors, providing a description of each renewable technology field;
- Stakeholders engagement, with relevant information to attend the validating workshops and pictures of those already held.

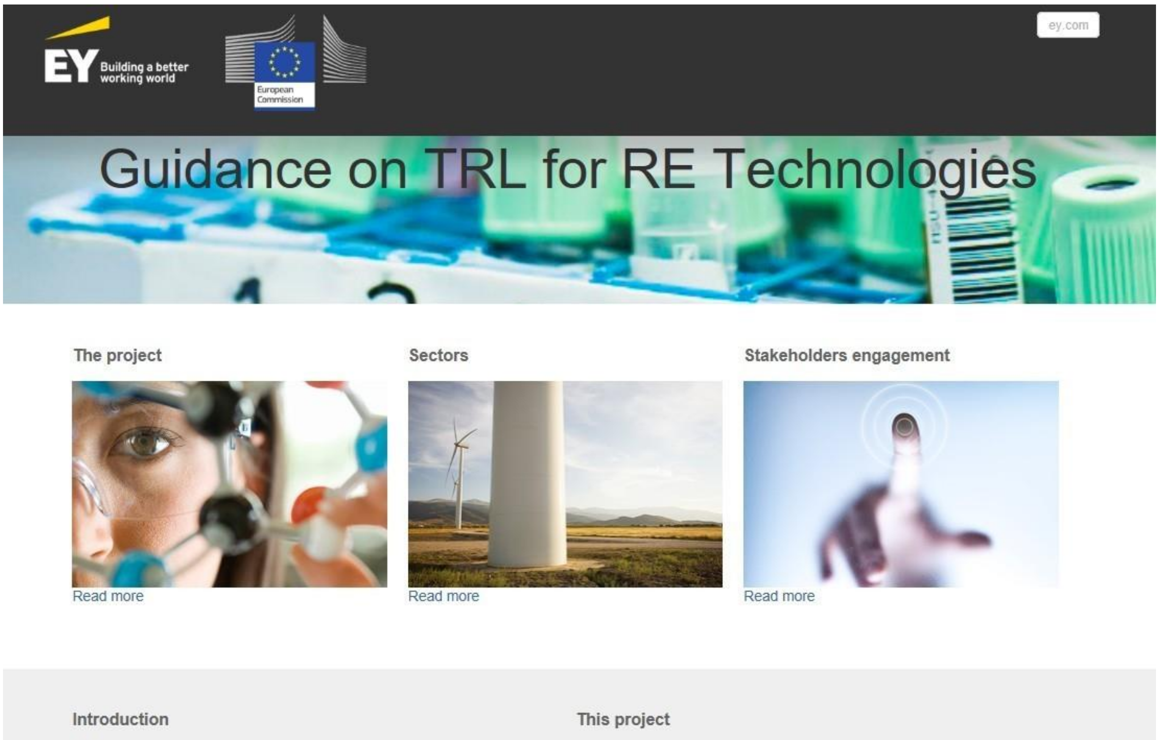

Figure 3 Screenshot of the home page of the project website

3.3. Task A

To respond to the objective of assessing the state of play of the use of TRL in the energy field through a desk research, Task A was divided into 4 main sub-tasks:

- Task A1: Assessment of the state of the art in the use of TRL in the energy field;
- Task A2: Review of the use of TRL for renewable energy in the US Department of Energy (DOE) calls;
- Task A3: Evaluation on how TRL is currently used in the energy research and development programmes and in industrial and commercial projects; and
- Task A4: Identification of best practices.

3.3.1. Task A1 – Assessment of the state of the art in the use of TRL in the energy field through a desk research

The study started with a desk research phase, which included the review of literature, communications, testing procedures and national uses of TRL scales. Existing TRL scales[2] were thoroughly explored with a view to identifying key issues in their utilization and related challenges. In particular, the following issues were considered:

- pitfalls and advantages of existing TRL scales;
- where existing TRL scales originate from and how they are developed;
- what optimizations have been made amongst different TRL scales; and
- related available TRL calculators.

Considering that TRL scale measures the maturity of an individual technology, with a view towards its operational use in a system context and, as a consequence, lack information regarding the readiness of integration of the component in the system, the assessment of the project team was not limited to TRL scales, but looked also at other Readiness scales:

- System Readiness Level[3] (SRL) scales;
- Manufacturing Readiness Level (MRL)[4] scales;
- Commercial or commercialisation Readiness Level[5] (CRL);
- Other non-technological readiness scales (i.e. Global Maturity Levels scale – GML- developed in the FP7 funded GreenXpo project)and
- The technology risk perspective.

These other Readiness aspects are considered important as it is already concluded that NASA-based TRL scales are incomplete due to their disregard for negative or obsolescence factors. Indeed, a lack of comprehensive system thinking at the onset and failure at the integration points are two of the primary causes for unsuccessful system development. For instance, a lack of manufacturing knowledge at key decision points is a major cause for programme cost growth and schedule slippages. The MRL helps identify and resolve manufacturing risks early in development to avoid carrying risks into production where they often emerge as significant problems.

The project team also performed telephone interviews with key relevant stakeholders from the different renewable energy fields, aiming to:

- Gather insightful information on the use of existing TRL scales as well as recommendations on the perceived room for improvement;
- Fill the gaps left by the desk research/evidence review and investigate more in detail some specific issues; and
- Gather information on the knowledge of the SRL and MRL scales, the two scales most closely linked to the technical development process.

The focus topics addressed during the interviews are presented in Table 2.

Focus topic		**Questions**	
General introduction		*Q1*	Short introduction of your organization and your role in your organization
1 TRL scales	*1.1 Knowledge*	*Q2*	Which TRL scales do you know?
	1.2 Use in the	*Q3*	Which TRL scales do you use in your organization?

[2] Please refer to section 4.1.1 for the list of TRL scales considered.

[3] The SRL is a quantifiable metrics for measuring the readiness of a system.

[4] The MRL is a measure to assess the maturity of manufacturing readiness

[5] The CRL is a framework for *defining* the spectrum of *commercial* maturity, from basic market research to full deployment

	energy field	*Q4*	For which purpose(s) do you use the TRL scale in your organization?
	1.3 Use vs SRL MRL	*Q5*	Do you know SRL (System Readiness Level) and/or MRL (Manufacturing Readiness level) scales?
		Q6	If yes, how well would you score them as improvement compared to TRL? (scale from 1 to 10 with 1 not at all, 5 neutral and 10 a major improvement).
2 Recommendations		*Q7*	Do you think the TRL scale as you know it could be used for better purposes
		Q8	Do you have recommendations or suggestions on the use of TRL scales? Do you think there is room for improvement in the current use of TRL scales?
3 Best practices		*Q9*	Can you recommend best practices?

Table 2 Focus topics of the interviews

Stakeholders for the interviews were selected taking into account their technology field of expertise, their geographical spread and the type of organization they belonged to:

- For each technology field, 3 interviews were taken, 2 with EU stakeholders and 1 with a US stakeholder;
- Within the EU, a maximum spread amongst the different countries was ensured. The stakeholders came from 12 different countries: Austria, Belgium, Croatia, Switzerland, Finland, France, Germany, the Netherlands, Norway, Spain, Sweden and UK;
- Within the US, 3 different research institutes (national laboratories), 1 university and 1 policy maker (from US DOE Office Energy Efficiency & Renewable Energy) were selected to have a sufficiently representative sample;
- 60% of all interviewed stakeholders were from research institutes, 7% from universities, 20% from industry and 13% were policy makers.

The list of interviewed stakeholders as well as the interview guidelines were discussed and validated with the EC prior to the interviews.

The information gathered in this sub-task – collected and organized in an Excel database – provided the project team with a complete picture on the state of the art of the use of existing TRL scales in the field of renewable energy technologies. Data gathered and systemized helped assessing best practices and lessons learned (Task A4) and served as valuable input for the development of the Guide of Guides (Task B1), and therefore for the draft guidance documents per technology field (Task B2).

3.3.2. Task A2 – Review of the use of TRL for renewable energy in the US DOE calls

The main objective of this Task was to assess how the different technology families were associated to one or several TR levels in the past and present calls of the US Department Of Energy (DOE) and in the associated projects, documents and presentations.

As a starting point, the project team checked (November 2016) the website of the US DOE EERE Funding Opportunity Exchange[6], searching for "TRL" and "Technology Readiness Level" in the text of the published calls. The useful information was extracted from the documents associated to the call, namely:

- the pdf document with the description of the call;
- the "Requests for information";
- the "Frequently Asked Questions"; and

[6] https://eere-exchange.energy.gov

- integrations and presentations.

Only calls dating back to 2013 were investigated as, prior to that year, the team assessed that TRL was seldom specified.

For each of the calls under analysis, the assessment concerned the quality and the consistency of how each specific TRL. In particular, the team tried to answer the following questions:

- Was the TRL clearly stated in the call?
- If not, was it easily measurable from the call?
- Was the definition of TRL always consistent within the sector?

The analysis also took account of the budget allocated to the calls to determine:

- the sectors and TRLs where most of the budget resources were allocated; and
- whether there was a correspondence between the resources allocated and the quality of the call.

3.3.3. Task A3 – Evaluation on how technology readiness level is currently used in the energy research and development programmes and in industrial and commercial projects

In order to assess how TRL is currently used in the energy research and development programmes as well as in industrial and commercial projects, stakeholders were contacted through an online survey.[7]

For each of the 10 renewable technology fields, the survey meant to assess the stakeholders' personal experience with TRL scales. In particular, they were asked:

- to rate their experience on TRL;
- to describe the context they use TRL in;
- towards whom they used the assessment of TRLs while presenting or reporting on their technology field;
- whether they used other assessment scales or tools; and
- whether they were familiar with System Readiness Levels (SRL) or Manufacturing Readiness Level (MRL) scales.

Additionally, the project team asked stakeholders to rate the TRL of 5 technology descriptions in their area of expertise using the EU scale: this sexercise was meant to assess the consistency in the use of the Horizon 2020 scale by stakeholders.

3.3.4. Task A4 – Identification of best practices

The information collected through the desk research and the recommendations gathered from stakeholders led to the development of a list of best practices to further feed into the Guide of Guides and were thus instrumental to the drafting process of the guidance documents.

3.4.Task B

With a view to achieving the best possible quality and sustainability of results for the guidance documents, the Consultant's methodological approach was built on:

- a clear understanding of stakeholders'/users' challenges and needs;
- a deep knowledge of general usability requirements to be considered across the various RE fields' technologies;
- a well-designed stakeholder engagement process and a consistent development of draft guidance documents, opportunely pre-tested with the relevant stakeholders;
- an accurate organization of the validating workshops, to maximize results and promote open and collaborative exchange.

[7] The online survey was carried out through the EY eSurvey© tool.

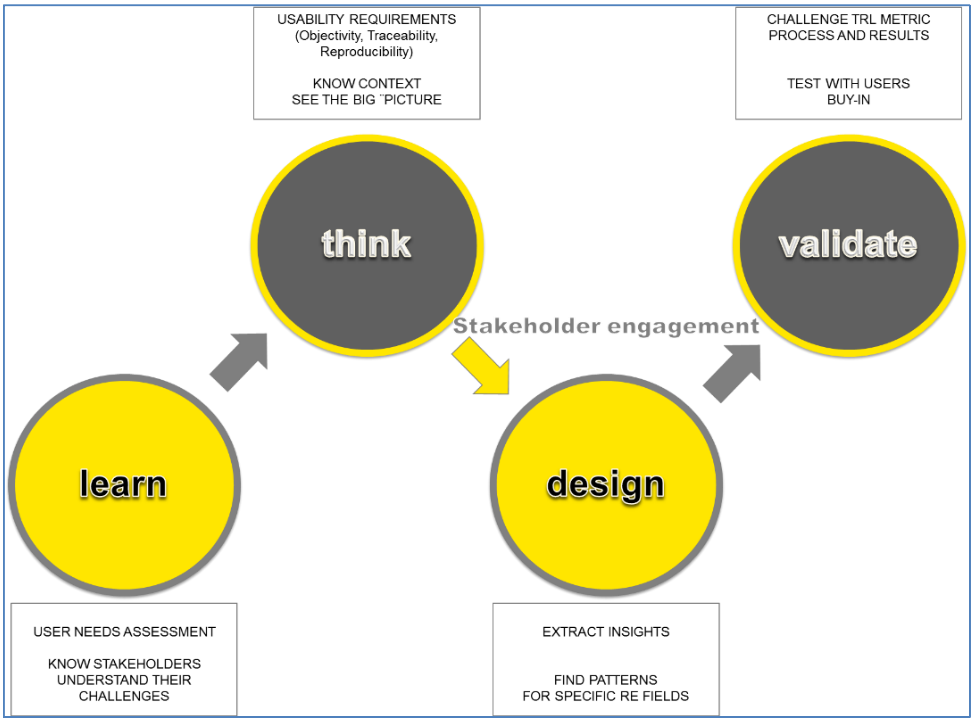

Figure 4 Our methodological approach

3.4.1. Task B1 – The development of a Guide of Guides

Even though the TRL scale has been widely adopted by Governments and various industries, this metric has been considered insufficient. As literature repeatedly denotes, the main weaknesses of the TRL metric can be summarized as follows:

- Lack of means to determine maturity of integration between technologies and their impact on a system (Sauser et al 2006)[8]. Since it is highly probable that systems fail at integration point, assessment of integration maturity is perceived as critical to the overall system success.
- There is no "how to" guideline when implementing the metric, meaning it may introduce risks in terms of interpretation/objectivity, due to lack of standard guidelines. Mahafza (2005)[9] argues that the TRL metric is insufficient because it does not "measure how well the technology is performing against a set of performance criteria." She claims that the TRL methodology rates the maturity of a technology on a subjective scale and that it is not adequate to label a technology as highly or lowly mature.

To ensure the consistency of the work of the lead drafters of the guidance documents, the project team developed a Guide of Guides. The document provided guiding principles and a stable procedure to be adapted to the specific context of the various RE fields.
The GoG was meant to be a reference model, informing on how to consistently identify and apply:

- a suitable scale to track progress for technology's maturity;
- Critical Technology Elements (CTEs) and respective assessment criteria;
- clear metrics to measure maturity attributes for both individual technology components and integrated systems / sub-systems; and
- independence criteria and checks.

A set of additional detailed scales fitting the specific technologies was set up, not only to fulfil the requirements of the study requiring a portfolio of dedicated technology readiness scales related to 10 RE technologies, but also to complement and support the general EU Horizon 2020 scale with specific concepts and wording when needed. This double approach has the twofold advantage of

[8] Sauser, Brian & Verma, Dinesh & Ramirez-Marquez, Jose & Gove, Ryan, "From TRL to SRL: The concept of systems readiness levels". Conference on Systems Engineering Research, 2006.

[9] S. R. Mahafza, "A Performance-Based Methodology to Assess Department of Defense Technologies" 2005.

meeting the requirements of the representative sample of future users in terms of use value and also to provide decision makers with a flexible tool to support them when specific technical precisions are required to best develop renewable energy technologies.

The GoG is therefore made of 9 global readiness levels, each one of these levels including:

- the level of readiness (ranging from 1 to 9);
- the statement of the readiness (i.e. title) covering technology, manufacturing, market and system integration aspects in a short yet comprehensive sentence;
- the detailed description of the readiness in terms of technology, manufacturing and integration maturity (i.e. integration of the technology within the system environment. This deals with system readiness level); and
- the checkpoints describing the milestone of the level n, completed with the corresponding achievements, that allows to jump to the next readiness level n+1. The set of checkpoints is to be seen as an ensemble of driving examples allowing the verification of the achievement of the related readiness level.

A particular attention was given to considering the use value of the GoG: this meant meeting the requirements of usefulness, usability and acceptability towards the future users of the readiness level framework developed within this project.

- The usefulness tries to answer what the intended utility of the GoG is, i.e. whether the solution is useful or not and if it brings added value or improvements beyond the state of the art. In the framework of the project, the usefulness of a GoG is related to the need to guarantee the consistency of the approach across the guidance documents for the different RE fields.
- The usability deals with the ease of use of the GoG, versus the degree to which the GoG can be used by the potential future end-users with effectiveness (fit for purpose), efficiency (work or time required to use), and with satisfactory results. The usability is assumed to be fulfilled by the two-level approach where the GoG provides the underlying structure of a general scale consistent with all technologies and a set of specific scales devoted to the RE technologies.
- The acceptability asks whether the GoG is acceptable towards potential future users and is therefore an effective instrument for energy experts.

Moreover, the GoG set out the development plan of the 10 draft guidance documents, allocating roles among the project team (e.g. lead drafter of the guidance document or peer reviewer) and defining a timeline for:

- the drafting of the guidance documents;
- the peer reviewing;
- stakeholders' consultation steps; and
- the final validation.

3.4.2. Task B2 – Preparation of draft guidance documents

The draft guidance documents were prepared by lead experts, appointed considering their familiarity with the relevant RE field as well as their capacity to get a bird's eye view of the value chain and the relevant TR level.

The overall guiding principles defined within the GoG served as a first conceptual basis to develop the draft guidance documents in the 10 RE fields. Then, while the study was progressing and in line with a learning-by-doing approach, the lead experts could also exploit the experiences gained with the guidance documents already discussed with stakeholders.
These documents indeed represented a best practice and a concrete example of application of the GoG to specific energy fields. Therefore, the documents produced could benefit from an incremental number of previous sources and experiences.

Two team members acted as peer reviewers and provided advice to the lead experts during the drafting of the guidance documents. This feedback ensured that the final outcomes of the study are complete and accurate. The peer-reviewers were also appointed as moderators during the validating workshops, to stimulate a collaborative approach among their stakeholders and get their buy-in.

The following table provides the names of the lead experts in charge of the elaboration of the 10 guidance documents.

Sectors		Lead expert
1	Photovoltaics	Jonathan Harper
2	CSP	Alberto Traverso
3	Hydropower	Mario Caruggi
4	Wind	Luca Villa
5	RE H&C	Matteo Porta
6	Geothermal	Raffaello Nannini
7	RE Alternative Fuels	Giorgio Urbano
8	Ocean	Maurizio Collu
9	Bioenergy - biological pathway	Alessandro Venturin
10	Bioenergy - thermochemical pathway	Giorgio Bonvicini

Table 3 Lead sector experts

Once the draft guidance document per each of the RE technology was prepared, key relevant stakeholders were engaged and their feedback collected, as further described in section 3.4.3.

Technofi, as external reviewer, was involved at the beginning of the drafting process, to ensure the guidance documents were compliant with the Guide of Guides and at the end, to analyse main recurring issues, common trends and differences across technologies.

3.4.3. Tasks B3 and B4 – Stakeholder engagement and organisation of 10 validating workshops

Ten validating workshops were organized at EY premises in Brussels from March to September 2017, following the calendar shown in the picture below.

Workshops		Date
1	Photovoltaics	Thursday, 9th March 2017
2	CSP	Friday, 10th March 2017
3	Hydropower	Tuesday, 4th April 2017
4	Wind	Wednesday, 5th April 2017
5	RE H&C	Wednesday, 9th May 2017
6	Geothermal	Thursday, 10th May 2017
7	RE Alternative Fuels	Tuesday, 20th June 2017
8	Ocean Energy	Wednesday, 21st June 2017

9	Bioenergy - biological pathway	Tuesday, 12th September 2017
10	Bioenergy - thermochemical pathway	Wednesday, 13th September 2017

Table 4 Calendar of the validating workshops

Two back-to-back workshops were organized each time to allow for cross-participation of stakeholders when their expertise was relevant (this proved especially pertinent for the workshops on RE H&C and geothermal as well as for the last two covering the bioenergy sector). The project team also scrutinised if similar events were held in Brussels the day before or after the workshops to possibility cross-pollinate.

The invitation process

Invitation emails were sent to our network of stakeholders one month and a half before each workshop, aiming to get 15 to 20 people attending each time and to ensure a balance in terms of:

- geographical coverage of people attending; and
- role and expertise (researchers, technology developers, manufacturers, consultants, representatives from the EC or other international organizations. etc.).

The invitation emails included a presentation of the project and of the event, practical details (date, reimbursement, advice on hotel arrangements etc.) as well a link to the registration page. Registrations were monitored on a daily basis and the project team reverted back to interested stakeholders with a confirmation email and further information if inquired. The team kept in close contact with registered stakeholders to build trust and secure their participation.

The workshops were also advertised on the project website, providing information on agenda, logistics and the contact of the stakeholder engagement manager in case of interest/questions.

The preparatory work: the engagement of stakeholders

Three weeks ahead of each workshop, the draft guidance document developed by the lead expert and assessed by the peer reviewer was sent to stakeholders registered to the workshops as well as to those not being able to attend but having expressed their interest in the project. These stakeholders were also requested to compile an online survey.[10]

The survey consisted in a presentation of the new guidance document and a series of questions repeated for each of the nine levels, apt to evaluate the document proposed and collect preliminary feedback and comments on the document. The questions were focused on:

- Agreement on the definition of the TR level, with comments;
- Modification, addition, removal or movement of checkpoints provided;
- Addition of any examples of technologies at that level;
- Possible presence of subareas having a dedicated scale or level.

The results of the eSurvey were compiled and incorporated in a consolidated version of the draft guidance documents, serving as a basis for discussion during the workshop.

How workshops were conducted

The 10 workshops followed the same agenda, as described in the table below. The discussions were conducted by the lead drafter and moderated by the peer reviewer.

[10] The online survey was carried out through the EY eSurvey© tool.

Timing	Activity
9:00 – 9:30	Registration of participants Breakfast and coffee time
10:00 – 10:30	Welcome by the Project Manager, tour de table and short introduction on the study and its first findings
10:30 – 10:45	Introduction on the objectives of the workshop and on the approach to the validating discussion
10:45 – 12:30	Discussion on TRL: Session TRL 1-3
12:30 – 13:15	Lunch
13:15 – 15:00	Discussion on TRL: Session TRL 4-6
15:00 – 15:15	Coffee break
15:15 – 17:00	Discussion on TRL: Session TRL 7-9
17:00 – 17:15	Conclusions

Table 5 Agenda of each workshop

All TRL were assessed one by one, the basis of discussion being the comments made by stakeholders to the first version of the guidance document drafted by the lead expert. The workshops were therefore very interactive and all participants could share and motivate their arguments.

The outcome of each workshop lead to the production of a new version of the draft guidance documents, to be further analysed by the external reviewer and validated by the EC.

Follow-up with stakeholders

All stakeholders involved in the workshops and those providing comments to the first draft of the guidance documents were sent the document validated during the discussion, with the request to keep it confidential as not yet officially approved by the EC.

The 10 drat final guidance documents, validated by stakeholders during the workshops, are presented as Annex to the present Report.

3.4.4. Task B5 - The External review

The main purpose of the external review was to:

- Ensure the compliance of the draft guidance documents with the GoG;
- Update the GoG with lessons learnt and best practice coming from the workshops;
- Ensure overall consistency of the draft guidance documents.

The review consisted of a bottom-up approach aiming to gather the feedback on the 10 guidance documents derived from the workshops and identify the common trends as well as the specificities across the different technologies considered. To this end, a three-step approach was carried out:

- Extracting the key outputs from the workshops and listing the common trends for each TRL, regardless of the considered technology.
- Gathering the common concepts for all the technologies and designing a robust basis of cross features (i.e. description of the level, checkpoints that should be achieved and milestones specific to each TRL) to update the GoG initially developed.
- Identifying the features which were very specific to one or several technologies that were taken into account to provide a realistic and applicable tool towards future users.

As a result, a tree-like structure with two stages corresponding to the common trends and the specific features for every TRLs and technologies was obtained, as illustrated in Figure 5.

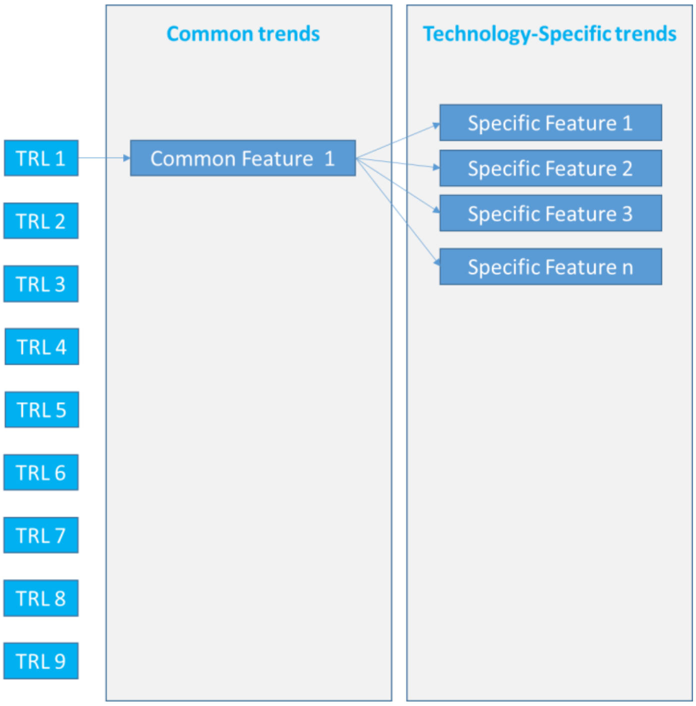

Figure 5 Result structure of our methodology

4. RESULTS FROM TASK A

4.1. Task A1 – Assessment of the state of the art in the use of TRL in the energy field through a desk research

4.1.1. Results from desk research

The desk research initially focused on the analysis of the following TRL scales and documents:

- the US Department of Energy (DOE) TRL;
- the Australian Energy Agency (ARENA) TRL;
- the Government of Canada TRL;
- the European Commission TRL;
- the European Association of Research and Technology Associations (EARTO) proposal for improvement of EU TRL scale;
- the OECD TRL;[11]
- the wave energy development protocol; and
- the ESBI TRL for wave power conversion systems.

From its assessment, the project team concluded that most existing TRL scales look very much the same. They have 9 levels (TRL 1-9) and the differences among them are merely limited to the detailed descriptions (if provided), not to the general characterisation of the levels.

Moreover, no difference is made between different energy technologies and only ocean and wave energy systems have their own developed scale, the ESBI TRL scale.

4.1.2. Findings from the interviews

A comprehensive summary of the findings from the interviews is presented in the following tables, grouped according to the following focus topics:

- Knowledge of TRL scale;
    - Use of the TRL scale in the energy field;
    - Knowledge of SRL and MRL scales;
- Recommendations; and
- Best practice.

1.1: Knowledge of TRL scale (Q2)
Key findings
• More than 90% of the interviewees knew what TRL scales are and used them on a regular basis. • More than 60% of the interviewees had a good to very good knowledge of the TRL scale. • Less than 7% of the interviewees indicated to have a very low knowledge on TRL scales. • The US stakeholders typically knew the NASA, US DOD and US DOE scales, and did not mention the EU scale. • The EU stakeholders typically knew the EU scale used in Horizon2020 calls, but also the US DOE scale, and to some extent also the US DOD scale. • Several other scales were mentioned by interviewees: Swedish TRL, a 3-level and 10-level TRL (in US), standard ISO 16290 about TRL, EARTO TRL and ARENA TRL (Australia). • A 3-level scale is often used in the US for internal and external communication: TRL 1-3 (basic research), TRL 4-6 (development and demonstration) and TRL 7-9 (commercialization), as sometimes there is no need to be so detailed on the 9-level scale.

[11] The OECD TRL scale has only 4 levels. It considers several TR levels together to be more practically useful in the financial world. They make only the difference between level 1 (TRL 1-3: basic research), level 2 (TRL 3-5: development), level 3 (TRL 6-7: demonstration) and level 4 (TRL 8-9: early deployment).

Main conclusions

- The general knowledge on TRL scales is good.
- In Europe, the EU Horizon2020 TRL scale is known the best.
- In the US, the US DOE TRL scale is known the best.

1.2: Use in the energy field (Q3, Q4)

Key findings

- The following main uses were identified for TRL scales in the energy field:

1. To indicate status or readiness of a technology development.

The assessment of the status or readiness of a technology is the main reason TRL scales are used, and the actual result of this assessment can be of interest for companies for different reasons. These are all directly linked to the other uses of TRL mentioned below.

2. For funding (both applying for projects within funding programs as well as reviewing project proposals).

Almost all calls for proposals mention TRL-scales for the use of project developers who are eligible to receive funding. These scales are related to different types of proposals and sources of funding. Fundamental research resources are given to the lower TR levels, while innovation actions and demonstration projects are typically funded in the higher TR levels. The very high TR levels (TRL 8-9) are so close to commercialization that they are normally not funded.

All interviewed stakeholders mentioned the use of TRL scales for applications to grants within funding programs as the (main) purpose of using TRL scales. Some of them also mentioned the use for reviewing project proposals in these funding programs as well.

3. As planning tool

The status of a technology gives interesting information on the next steps to take in further developments. In that way, it can be used as a planning tool. The status gives an indication where to focus on, not only with respect to technological development, but also to the financing and potential steps towards commercialization (for the higher TRL scales).

From the interviewed stakeholders, only research institutes indicated to use the TRL as a planning tool. 30% of the research institute stakeholders uses TRL as planning tool on a regular basis. The other research institutes and industrial companies with research departments use other tools for planning, as they do not consider the TRL scale as an efficient KPI (key performance indicator) for planning tools.

4. Internal communication

The TRL scale is also used as an internal communication tool to discuss about project development status. From the interviews, it can be concluded that almost 50% of the research institutes use TRL scales for this purpose. No industrial company that was interviewed used TRL scales for internal communication.

5. External communication

The TRL scale can also be used for external communication, typically between research institutes and industry (their clients). Therefore, industrial companies should also use it. However, companies that have activities corresponding to high TRL scales (and typically do not have a dedicated research department) declared to not make use of TRL scales at all.

6. As a decision-making tool

The TRL scale could be interesting to use as a decision-making tool, but in order to be suitable for this, major changes to the scales are needed. From the interviews, it can be concluded that industrial companies typically have their own systems (typically stage-gate processes) for management purposes of their business development, also taking into account cost-effectiveness, business models, and intermediate goals between the stages.

Statistical summary:

- More than 75% of the EU interviewees only used the EU Horizon2020 scale. Another 15% also used other scales. This could be an own developed scale, but also the US DOD seems to be used. The other 10% didn't use TRL scales.
- Almost all US interviewees used the US DOE scale. Some used the US DOD scale (e.g. solar energy and biofuels are also supported by US DOD). Other used in combination with TRL also Technology Performance Levels (TPL).
- Except from 2 interviewees that said they didn't use the TRL scale, all the others reported to use it for funding purposes. This means both applying with a project in a call for proposals for funding as well as reviewing project proposals.
- Almost 85% of the interviewees used the TRL to categorize a development in a certain

readiness level.

- TRL is also used for communication. Almost 45% used it for internal communication and almost 55% used it for external communication (e.g. between research institute and industry).
- Only 23% used TRL as a planning tool and only 10% as a decision-making tool.

Main conclusions

- The EU stakeholders in the energy field typically use the EU Horizon2020 TRL scale.
- The US stakeholders in the energy field use the US DOE TRL scale, and in less extent the US DOD TRL.
- The main purposes to use TRL is to apply for funding or review project proposals in a call for funding. It is also used for internal and external communication, and to less extent as a planning or decision-making tool.

1.3: TRL versus SRL/MRL (Q5, Q6)

Key findings

- 60% of all interviewees had never heard of SRL and 13% had only heard about them, without knowing details. Ca. 25% knew SRL scales, but nobody was using them.
- 53% of all interviewees had never heard of MRL and 17% did only hear about them. Ca. 30% knew the MRL scale, but nobody was using it.
- Some conclusions/remarks from the stakeholders that knew the SRL / MRL scale:
    - (from US stakeholders) SRL scale has no added value to TRL, as there is enough flexibility in the US DOE TRL scale to adapt the scale for complex systems (such as biorefineries, wind turbines, etc.);
    - MRL should be used next to and together with TRL, and not replace it;
    - SRL and MRL can be of added value, as TRL has some shortcomings with respect to assessing complex, integrated technologies and manufacturing issues (at higher TRL scales).

Main conclusions

- The general knowledge about SRL/MRL is very limited. The interviewees that have heard about them or know them, don't use them.
- The general knowledge on SRL and MRL was too low to make a quantitative comparison with TRL.
- There is no consensus between the stakeholders with respect to the advantages and disadvantages of SRL and MRL scales: some did not see any added value, others claimed the use of these scales is needed to compensate for the shortcomings of the TRL scale.

Table 6 Interview results for focus topic 1: TRL scales

Focus topic 2: Recommendations (Q7)

Key findings

- An important reason TRL scales are used is the need for a common language and metrics when talking about technology development. Unless every relevant person has the same understanding, there is no real benefit of the use of TRL scale.
- From literature, as well as from the interviews, it can be concluded that the TRL scale has some disadvantages:
    - it does not consider economic (cost) aspects, nor manufacturing aspects. This implies that there could be a benefit in introducing scales such as the MRL, SRL and CRL, although too little general knowledge was available amongst the interviewees to adequately address the potential and added value of these less common scales;
    - it focuses mainly on one technology, not on systems with integration issues;
    - it is not suitable as a management tool, as it is just a classification in levels, without decision-making steps in between;
    - it assumes a linear technology process design, which is not always the case since technology developers may have to start from scratch again;
    - its descriptions are not always very clear, leading to misunderstandings or misinterpretations. The TRL scale used by the EC for the Horizon 2020 program has

the disadvantage to be too general and is considered not descriptive enough, leading to interpretation. The lack of a specific guidance for determining the exact TRL also brings subjectivity into the projects' evaluation process.

- The following points give a summary of the main recommendations formulated by the interviewed stakeholders:
  - Some US stakeholders active in research explicitly focused on the drawbacks of TRL scales, e.g. saying that cost effectiveness is not considered in the current scale, which is a very important issue for renewable energy technologies (and much less for aerospace and military applications, which were the starting points for the development of the TRL scale by NASA and US DOD). Interviewees referred to a need for the addition of Technology Performance Levels (TPL) to be looked at simultaneously, together with the TRL dimension in a 2-dimensional matrix.
  - Other US stakeholders active in research had the opinion that the US DOE TRL is perfectly suited for their purposes and didn't report a need for the use of improved scales or additional scales. The Technology Readiness Assessment Guide of US DOE (2013) provides flexibility towards detailing TRL descriptions for different purposes. In each call for proposals (e.g. Funding Opportunity Announcement), the TRL is described in detail for the specific call (also including sizes of demonstrations or pilot scales), so the applicants know exactly what is expected with respect to the goals to be reached at the end of the project.
  - Most of the stakeholders mentioned that the existing Horizon2020 TRL scale is relevant from an evaluator point of view (compare the innovations and the progress foreseen in the different proposals) but it is quite easy for applicants to use the TRL so as to better position their innovations and access funding for a specific TRL range. It is not always easy to assess the real TRL of an innovation and therefore the reliability of the assessment is rather limited. Some stakeholders mentioned there should be precise explanations of the use of the TRL scale and the methodology to come up with a given level of maturity.
  - According to most industrial players, the TRL scale is rather well-suited for R&I purposes but not fully adapted to industrial developments. Some industrial players recommended the use of a TRL-like scale focused on the commercialisation of the products: at each stage, the development teams should follow a precise evaluation to avoid mistakes (manufacturing capability, costs of the final product, quality expected by the market). The focus of the evaluation should be the final market value of the product.
  - Many stakeholders made remarks regarding the limitations of the TRL scale in terms of system analysis (most of them were not aware of the SRL), such as the fact that The TRL scale should be able to handle complex systems (i.e. what is the TRL of a system which is composed of several technologies for which the TRLs are known?) and integration issues (i.e. what is the TRL of a component when it is integrated in a new system?).
  - Regarding the existence of several variants of the TRL scale, the stakeholders (research centres and funding agencies) recommended a generic and harmonised scale;
  - The addition of examples was considered as an added value.
- Other recommendations were the following.
  - To adapt the TRL scale to make it suitable as management/planning/communication tool. This would require big changes to consider cost effectiveness, business plans, etc.
  - The EC could promote the use of TRL in other occasions (e.g. incubation programs, SME instrument Business Academy, business coaching practices, etc.)
  - Better communication from the EC to the Member States shall be ensured about TRL scales and their use (e.g. within subsidy programs) and/or availability of a manual on TRL scales was recommended. This would allow Member States to do a similar assessment of technology's state of the art within subsidy programs and compare their situation to other Member States.
  - Not to add more levels on the scale, so as not to increase complexity.
  - To make clear that TRL scales are for technology developments and not for projects.
  - To encourage the use of only one general (non-technology-specific) scale (either DOE or Horizon2020 since they are rather similar, only the wording is slightly different), with a common interpretation shared by all the players.

Main conclusions

The most important recommendations proposed by stakeholders were: • A better clarification of the TRL scale is needed, so that the assessment can be done more objectively; • The inclusion of examples in the scale would be an added value; • An overall simplification of the scale would be recommended;

Table 7 Interview results for focus topic 2: Recommendations

Focus topic 3: Best practices (Q8, Q9)
Key findings
The question about best practices seemed the most difficult to answer for the stakeholders. • Most stakeholders considered the existing usages of the TRL scale as best practice: - The flexibility of the US DOE TRL scale was considered a best practice. The scale can be slightly adapted (mainly changing wording for detailed description) for different calls and purposes (e.g. in roadmaps); - NASA was mentioned to have the best methodology. Their scales, manuals and procedures are always comprehensive, updated and kept open to public. The use of TRL as stage-gate (management) process, with implementation of check points, to check if a certain level has been successfully reached is also considered a best practice.
Main conclusion
• For some stakeholders TRL was "only practice", i.e. using the scale in calls for proposals for funding. Most stakeholders considered this indeed as a good practice.

Table 8 Interview results for focus topic 3: Best practices

4.2.Task A2 – Review of the use of TRL for renewable energy in the US DoE calls

The following table summarizes the findings, intended to assess the quality of US DOE calls in terms of:

- clarity of TRL-related technical specifications; and
- requirements for each of the sector analysed.[12]

In general terms, we can say that:

- the TRL definitions were clearly stated in the majority of the calls;
- the TRL definitions were consistent among the different calls of the same technologies;
- the TRL addressed in the calls were generally comprised between TRL 2 and TRL 7, depending on the type of call;
- Specific calls addressing TRL 1 or TRL above 7 do exist in specific sectors (TRL 1 in bioenergy, TRL 8-9 in the wind sector).

Findings led to the conclusion that the calls from the US DOE addressed the TR levels the most consistently in the wind energy sector (consistency evaluated below at 56%); whereas, the RE Heating and Cooling sector was where a clear and consistent form of addressing the TRL was lacking the most, with a consistency score of 25% only.

The table below details the project team's assessment for each of the analysed sectors.

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[12] The project team could not retrieve information on 'Renewable alternative fuels' since this family of technologies is quite recent and no specific information on the documents analysed has been found. Moreover, some of the different technology families were coupled together, as the US calls covered more than one technology: 'bioenergy' refers to both biological and thermochemical pathways, 'water energy' includes hydropower as well as ocean and tidal energy and, finally, 'solar energy' includes both photovoltaics and concentrated solar power.

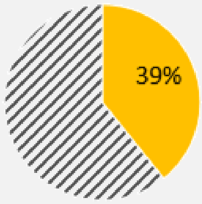
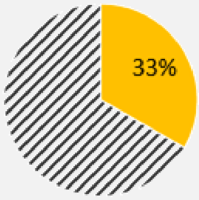
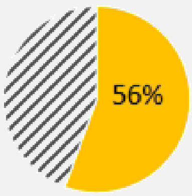
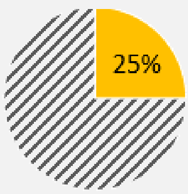
Sectors	Quality (% of consistent calls)	Comments
Bioenergy		• In 39% of the calls analysed the level of TRL was clearly defined or, alternatively, easy to assess from the documents of the call (in 47% of the overall cases). • The calls addressed TRLs from 1 to 7 and were particularly clear from TRL 6 and 7.
Geothermal Energy		• In 33% of the calls analysed the level of TRL was clearly defined or, alternatively, easy to assess. • The calls addressed TRLs from 2 to 7. • Only 29% of the calls clearly stated the TRL addressed, but in 43% of the cases this was easy to assess from the documents of the call.
Solar Energy		• In 28% of the calls analysed the level of TRL was clearly defined or, alternatively, easy to assess. • The calls addressed TRLs from 3 to 5. • Only 17% of the calls clearly stated the TRL addressed, but in 50% of the cases this was easy to assess from the documents of the call.
Water Energy		• In 33% of the calls analysed the level of TRL was clearly defined or, alternatively, easy to assess. • The calls addressed TRLs from 2 to 7. • Only 29% of the calls clearly stated the TRL addressed, but in 43% of the cases this was easy to assess from the documents of the call.
Wind Energy		• In 56% of the calls analysed the level of TRL was clearly defined or, alternatively, easy to assess. • The calls addressed TRLs from 2 to 7+. • 50% of the calls clearly stated the TRL addressed, and in 67% of the cases this was easy to assess from the documents of the call.
RE Heating and Cooling		• Only in 25% of the calls analysed the level of TRL was clearly defined or, alternatively, easy to assess. • The calls addressed TRLs from 2 to 7. • Only 25% of the calls clearly stated the TRL addressed, and only in 25% of the cases this was easy to assess from the documents of the call.

Table 9 Summary of our analysis

As an additional element to identify the most suitable set of useful references amongst the US DOE calls, the team compared the allocated budget to each of the TRL by the US DOE calls since 2013.

Figure 6 summarizes the results.

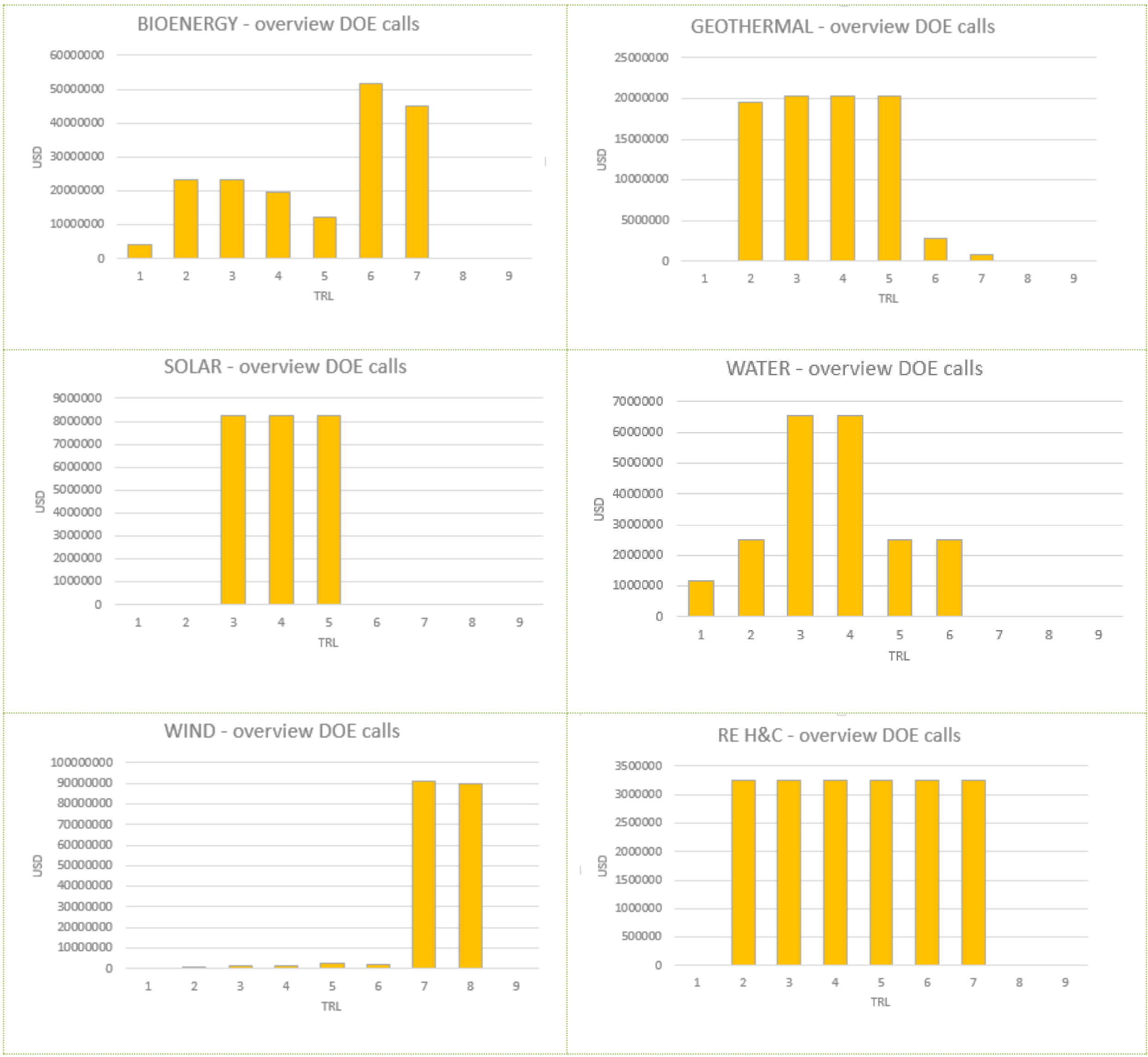


Figure 6 Comparison of allocated budget by TRL levels for each sector in the US DOE calls

Assessing the budget allocated to each TRL in the US DOE calls helped identify the actual level of investment and, therefore, the actual level of perceived technology development by the US DOE. Water and (partially) solar technologies had a higher budget at low TRL compared to the other technologies, while wind had a dedicated high budget on high TRL. The budget allocated to bioenergy was quite distributed among the different TR Levels.

By combining an assessment of the quality of TRL references in the US DOE calls with a comparison of the budget allocated to each TRL per sector, the team gained a quantification of potential number of inspirational cases for the specific sector and TR level, as depicted in Table 11.

Sector	Quality of the calls	Budget TRL								
		1	2	3	4	5	6	7	8	9
Bioenergy	M	L	M	M	L	L	H	M	*na*	*na*
Geothermal	M	*na*	L	M	M	M	L	L	*na*	*na*
Solar	L	*na*	*na*	L	L	L	*na*	*na*	*na*	*na*
Water	M	L	L	L	L	L	L	*na*	*na*	*na*
Wind	H	L	L	L	L	L	L	**H**	**H**	*na*
RE H&C	L	*na*	L	L	L	L	L	L	*na*	*na*

Table 10 Quality and Budget of US DOE Calls

Quality ranges: high (H) = > 40%; medium (M) = 30%-40%, low (L) =< 30%

Budget range: high (H) = > 50M; medium (M) = 20M-50M, low (L) =< 20M

Overall, the analysis conducted led to assess that the use of TRL scale in the US DOE calls was consistent among the different technologies, and differences were related to the use of single words, without the addition of any element specifically linked to a technology.

The team considered as best practice the Geothermal sector funding calls, in which the definitions of the different TR levels are complemented by practical examples and/or specification related to this specific energy technology family.

4.3.Task A3 – Evaluation on how TRL is currently used in the energy research and development programmes and in industrial and commercial programs

The project team reached out to almost 1100 stakeholders, ensuring a good balance of representativeness among stakeholders from industry (31%), research institutes (48%), universities (7%), governmental organizations (13%) and stakeholder associations (1%). The response rate was 7,5%.

The main conclusion from the analysis of the eSurvey results was that the assessment of TRL done by the stakeholders for the 10 different renewable technology sectors was not very consistent, as they had a different idea about which TRL to appoint to a given technology description. The spread in assessment seemed bigger for the technologies for which a larger sample size of stakeholders finished the eSurvey.

There seemed to be no link between the clarity of the technology description and the consistency of the TRL assessments done by the different stakeholders, as the spread in assessment of TRL can be attributed to a lack of detailed guidelines.

Therefore, the main conclusion to be drawn is that the results of the survey clearly indicated the need for good guidance documents on the TRL scales for the different technologies, so that the TRL assessment can be done more consistently.

4.4.Task A4 – Identification of best practices

From the work performed in Task A1, A2 and A3, best practices were selected and described, according to the following criteria:

- Best practices that didn't concern the energy field were not selected;
- Only best practices related to TRL's of specific renewable energy technologies were taken into account;

4.4.1. Selected best practices arising from desk research and literature review.

Since the objective of this project was to define TRL scale descriptions for different renewable energy technologies, it was interesting to look at two different technology-specific TRL scales, which were considered by the project team as a best practice:

1. Technology-specific TRL scale for wave and ocean energy, as developed by ESBI

ESB International has developed its own TRL scale for wave power conversion systems. This 9-level TRL scale is described very detailed by ESBI with respect to functional readiness and lifecycle readiness, and contains an ESBI Verification Checklist and indicative information on costs. It can be found at the following link: https://www.seai.ie/Renewables/Ocean-Energy/Prototype-Development-Fund/ESB-Technology-Readiness-Levels-for-Supply-Chain-Study-for-WestWave-.pdf

The idea of checkpoints at each TRL level was taken up by the project team in the development of the Guide of Guides.

2. Technology-specific TRL scale for geothermal energy in US DOE calls

Although the US DOE calls mainly use general TRL scales (see recommendations below), for geothermal energy a further technology-specific detailing was found. The use of specific descriptions that are clear an verifiable was considered highly relevant. Although the description was perceived as too elaborate and the continuous text seemed not structured enough in its presentation, the descriptive parts were however providing clear formulations that could be used in the refinement of the descriptions for each TRL and the identification of the checkpoints.

Below are examples of US OE TRL for geothermal energy, where constituting elements of each level are in red (as issued by the US DOE).

TRL for geothermal energy (Source: US DOE calls DE-FOA-0000522 and DE-FOA-0000842)	
TRL 1	**Basic principles observed and reported:** This is the lowest level of technology readiness. *Scientific research begins to be translated into applied R&D*. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology. A specific example in GTP might be a paper study analyzing the technological barriers in developing an Enhanced Geothermal System. *Intersection of BES and applied research.*
TRL 2	**Technology concept and/or application formulated:** Once basic principles are observed, *practical applications can be invented*. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 *moves the ideas from basic to applied research*. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work. An example in GTP might be application of a new concept to the development of a high temperature logging tool or development of a numerical model.
TRL 3	**Analytical and experimental critical function and/or characteristic proof of concept:** Active research and development (R&D) is initiated. This includes *analytical studies and laboratory-scale studies to physically validate the analytical predictions* of separate elements of the technology. Examples include components that are not yet integrated. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected. Components of the technology are validated, but there is no strong attempt to integrate the components into a complete system. Modelling and simulation may be used to complement physical experiments. Examples in GTP would include laboratory testing and analysis of insulation materials for down-hole tools, and preliminary engineering design development.
TRL 4	**Component and/or system validation in laboratory environment**: The *basic technological components are integrated* to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function. An example in GTP might include the operation and laboratory testing of innovative components in an improvised (e.g., small-scale) electronic submersible pump at room temperature/pressure. The goal of TRL 4 should be the *narrowing of possible options in the complete system*.
TRL 5	**Laboratory scale, similar system validation in relevant environment:** The basic technological *components are integrated* so that the system configuration is similar to (matches) the full application in almost all respects. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/ environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical. An example in GTP might be laboratory testing of newly developed packer components in a high temperature/high pressure environment. *Scientific risk should be retired at the end of TRL 5*. Results presented should be statistically relevant.
TRL 6	**Engineering/pilot-scale, similar (prototypical) system validation in relevant environment:** *Engineering-scale* models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include fabrication of the device on an engineering pilot line. Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the *step up from laboratory scale to engineering scale* and the determination of scaling factors that will enable design of the final system. An example in GTP might be the development of prototype drilling bits

	subjected to high temperatures and pressures for long, continuous periods of time. The engineering pilot scale demonstration should be capable of performing all the functions that will be required of a full manufacturing system. The operating environment for the testing should closely represent the actual operating environment. *The goal while in TRL 6 is to reduce engineering risk*. Results presented should be statistically relevant.
TRL 7	**Full-sale, similar (prototypical) system demonstrated in relevant environment:** This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. An example in GTP might be field testing of a prototype downhole pressure monitor in a geothermal well. Significant amount of automation is expected at the completion of this phase if the cost model for full scale ramp requires it. *24 hour production* (at least for a relevant duration) is expected to discover any unexpected issues that might occur during scale up and ramp. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete. The goal of this stage is to *retire engineering and manufacturing risk*. To credibly achieve this goal and exit TRL 7, scale is required as there are many significant engineering and manufacturing issues can surface during the transition between TRL 6 and 7.
TRL 8	**Actual system completed and qualified through test and demonstration:** The *technology has been proven to work in its final form* and under expected conditions. In almost all cases, this TRL represents the end of true system development. An example in GTP might be the demonstration of a new tool/method for integrating seismic and resistivity datasets from an operating geothermal field to more effectively model a reservoir, including comparison of observed performance data relative to the previous state-of-the-art. Product performance delta to plan needs to be highlighted and plans to *close the gap* will need to be developed. The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Product performance delta to plan needs to be highlighted and plans to close the gap will need to be developed.
TRL 9	**Actual system operations:** The technology is in its final form and operated under the full range of operating conditions. Examples include the actual commercial operation of newly developed logging tools, casing designs, remote sensing techniques, etc. in a geothermal system in their final forms. Emphasis shifts toward statistical process control.

Table 11 Example of US DOE TRL scale for geothermal energy

5. RESULTS FROM TASK B

5.1. Main issues arising from the interaction with stakeholders

The methodological approach proposed, entailing sequential steps of involvement was very appropriate to get stakeholders' contribution and buy-in.

- The preparatory work of commenting the draft documents through an eSurvey before the actual discussion proved to be beneficial in terms of acculturation with the objective, the scope and the content of the related workshop.
- The proposed interactive roundtable managed by a lead expert (for the energy field at hand) accompanied by a moderator (involved horizontally along the ten sectors) was well appreciated and useful to manage the strict timings of one day for each discussion.

The main challenge was to clarify and get alignment on the overall purpose of the exercise and the project team managed to convey the message that the document at hand was not to replace the existing definitions of TRL used by the EC in the Horizon2020 calls, but rather to help project developers understand what it means to be at a certain TRL in their technological field.[13]

Some outstanding issues and concerns raised by stakeholders and common to all workshops are presented in the table below, where we also describe the way we addressed them. The table provides some recommendations to be taken into account should other guidance documents in other renewable energy fields be drafted.

Main issues raised by stakeholders	How the project team addressed them	Recommendations for future guidance documents
Sector delimitations		
Boundaries and potential overlap across the ten guidance docs (e.g.: renewable heating and cooling vs. geothermal) were sources of confusion.	Specific introduction was needed to clarify the boundaries and definitions of the technologies under analysis, and how the technologies differed from one another.	Develop a different set of boundaries across the sectors for the different guidance documents, e.g. with focus on the application.
Object of the TRL assessment		
The use of the guidance along the different levels to describe the development of a material (or a component or an entire plant) requires the introduction of variations.	The terminology used in the guidance has been made applicable to different dimensions, such as new materials, sub-components (e.g. wind turbine blade coating) or complete systems (e.g. new cycles in CSP).	Propose a different approach in which some objects that differ from the common "plant" shall be evaluated at different TRL level (e.g. biomass).
Soft vs. hard technology		
Possible use of the guidance documents to describe software products instead of "hardware" technologies.	Since in certain technologies the software development can be a crucial area where technological innovation can advance, this was included in the specific guide as a possible key of reading (i.e.: referring to the development of a software).	Exclude the software objects from this evaluation and refer to another guidance specifically tailored for this scope.
Non-technological parameters		

[13] The titles of the nine TR levels are the same for every technology and correspond to the Horizon2020 TRL definition (2017 edition). During the drafting of the guides and the workshops, the 2014 version was used as well. In this way we tried to maximize the acknowledgment of the basic fundamentals, in general terms, of each level, by considering the various experiences in recent years gained by the different stakeholders.

Although a TRL scale must be focused only on technological development (and from levels 6/7 also on manufacturing) other parameters were required to be taken into account: - economic analysis (costs, business model and plan, feasibility, marketing and commercial aspects) - sustainability and risks mitigation - social acceptance.	These factors identified by stakeholders influence the design, the development process and the final intended scale of the technology; as their inclusion was consensually asked for during the review process and the workshops, they project team accommodated it to some extent.	Include the necessary parameters at the relevant TRL in a non-binding formulation.
Prescriptiveness		
When formulating the guidance documents, the end result may turn too prescribing: if TRL definitions are too prescriptive, there may be the risk to make financing conditional to the complete fulfilment of the TRL definition and exclude new ideas, whereas one of the main purposes of better TRL definitions is to improve the current situation in terms of transparency and inclusiveness.	Not too many specific details related to technologies were inserted at low TRL levels so as not to exclude any new ideas. Applications were presented as examples, not as parameters to be fulfilled. Following participants' suggestions, the use of a clear definition for the product scale development was adopted: • from proof of concept at readiness levels 2 – 3 • small scale prototype at level 4, large scale prototype at level 5 • pilot at level 6 • demonstrator at level 7 to commercial system as of level 8.	Provide sets of examples for each TRL to offer concrete applications while making sure they are not understood as restrictive checkpoint to be completed to reach a given TRL.

Table 12 Issues raised by stakeholders during the review process

5.2.TRL-related issues

5.2.1. Common trends identified

The following table describes, per each TR Level, the main features and milestones that are common to all sectors and each technology interpret them.

Table 13 Observed milestones in each sector

TRL	Milestones					
	Common to all sectors	**PV**	**CSP**	**Hydro**	**Wind**	**RE alt. fuels**
1	Identification of new concept, applications and barriers	Identification of technology and materials , applications and benefits	New concept and design (collectors, receivers, HTF) identified	New concept (materials and technology) identified	New concept identified	New concept identified, benefits and technological gaps identified
2	Definition of application, consideration of interfaces and commercial offer	Identification of materials, interfaces, prototyping approach, preliminary feasibility	Identification of materials/technology/process, statement of interfaces, preliminary risk analysis	Identification of sample prototyping approach	Identification of materials, sample prototyping approach, preliminary feasibility	Definition of the proof of concept, first indications of fuel properties
3	Proof of concept prototype ready: concept is laboratory tested	Evaluation of integration of components	Evaluation of the plant and subcomponents through simulation	Identification of prototype / numerical model for laboratory tests	Identification of prototype strengths and weaknesses	Proof of concept verified through simulation
4	Integrated small-scale prototype with auxiliary systems laboratory validated	PV cell/technology prototype validated	Integrated small-scale prototype laboratory tested and validated	Reduced scale prototype tested and validated	Integrated prototype with auxiliaries tested and validated	Fuel/process tested and validated at laboratory scale (small-scale prototype/simulation model)
5	Large-scale prototype completed with auxiliaries, refined commercial assessment	Large-scale prototype completed and tested in relevant environment	Large-scale prototype integrated with auxiliaries and tested in relevant environment	Large-scale prototype integrated with auxiliaries and tested in relevant environment	Large-scale prototype validated in relevant environment	Large-scale prototype realized
6	Technology pilot demonstrated in relevant environment, manufacturing strategy defined	Technology demonstrated in relevant environment, manufacturing approach investigated	Integrated pilot installed in field, manufacturing approach investigated	Full-scale pilot operated in field	Pilot built and demonstrated	Pilot scale prototype fine-tuned in field
7	Pilot demonstrated in operational environment, manufacturing approach demonstrated	PV full-scale pilot system demonstrated in operational environment	Full-scale demonstrator connected to grid for testing	System verified in operational environment	Full-scale built and demonstrated in field	Fuel qualification completed
8	Technology in its final form, low-rate production	Technology in its final form, low-rate production, certifications completed	Technology in its final form, connected to the grid	Technology in its final form, mandatory standards fulfilled	Technology in its final form, manufacturing process and logistics issues completed	System certified for market application, compliance with legal obligations
9	System fully operational and ready for commercialization	PV power system fully operational, scale-up production optimized	System fully operational, full-rate production	New technology fully operational, full-rate production ready	New technology fully operational, full-rate production ready	New technology fully operational and market available, full-rate production ready

TRL	Milestones					
	Common to all sectors	**Ocean**	**Geothermal**	**RE Heating and cooling**	**Bioenergy - Biological pathway**	**Bioenergy - Thermochemical pathway**
1	Identification of new concept, applications and barriers	Identification of principles and interfaces	Theoretical concept identified, applications and barriers identified	Identification of innovative concept, evaluation of benefits, gaps and risks	Identification of new concept, benefits and barriers	Identification of new concept, benefits and barriers
2	Definition of application, consideration of interfaces and commercial offer	Identification of challenges, consideration of commercial offer	First simulation of model	Identification of material and design procedures, definition of prototyping approach and preliminary technical specifications	Definition of proof of concept, identification of interfaces	Definition of proof of concept, identification of interfaces
3	Proof of concept prototype ready: concept is laboratory tested	Validation of concept through laboratory tests	Concept validated through simulation	Verification of proof of concept through simulation	Verification of proof of concept through validation	verification of proof of concept through validation
4	Integrated small-scale prototype with auxiliary systems laboratory validated	Ocean concept/technology laboratory validated	Prototype ready for testing	Integrated small-scale prototype laboratory tested and validated	Small-scale prototype is designed, integration is analysed at laboratory level	Small-scale prototype is designed, integration is analysed at laboratory level
5	Large-scale prototype completed with auxiliaries, refined commercial assessment	Prototype tested and validated in relevant environment	Prototype tested and auxiliaries integrated	Large-scale prototype integrated with auxiliaries tested and validated in intended environment	Small-scale prototype is tested and validated	Small-scale prototype is tested and validated
6	Technology pilot in relevant environment, manufacturing strategy defined	Pilot scale prototype fine-tuned in field	Full-scale prototype demonstrated	Integrated pilot fine-tuned in field	Pilot-scale prototype fine-tuned	Pilot-scale fine tuned
7	Demonstrator in operational environment, manufacturing approach demonstrated	Concept demonstrated and validated, economic and manufacturing issues completed	Full-scale demonstrator installed and connected	Technology demonstrated in relevant environment	Technology demonstrated in relevant environment	Concept demonstrated and validated, economic and manufacturing issues completed
8	Technology in its final form, low-rate production	Pilot scale device tested in a natural site	Technology in its final form, economic and financial issues fixed, marketing operations on-going	Technology in its final form, compliance with certifications	Technology in its final form, low-rate production	Technology in its final form, compliance with legal obligations
9	System fully operational and ready for commercialization	New technology fully operational	Concept fully operational from the productive, commercial, market point of view	Technology available on market, full-rate production	Technology available on market	Technology available on market

5.2.2. The update of the Guide of Guides

Throughout the execution of the project, the GoG has evolved into a living document, as it was amended with the integration of up-to-date information coming from the interaction with stakeholders in the 10 RE fields.

The homogenisation of common trends faced challenges when addressing readiness levels which diverge from one technology to another. As matter stands, technology development processes do not follow the same path depending on their particularities (interface with environment, manufacturing readiness, testing and validation steps, etc.). This means that the definition of the common trends should be robust enough in order to comply with all technology readiness levels. It is assumed that examples are valuable information in terms of acceptability towards future users of the GoG. In this context, the provision of examples should be encouraged in the guidance documents.

The following table provides an overview of the common trends identified.

TRL 1: Basic principles observed
• Identification of the new concept • Identification of the integration of the concept • Identification of expected barriers • Identification of applications • Identification of materials and technologies based on theoretical fundamentals/literature data • Preliminary evaluation of potential benefits of the concept over the existing ones

TRL 2: Technology concept formulated
• Enhanced knowledge of technologies, materials and interfaces is acquired • New concept is investigated and refined • First evaluation about the feasibility is performed • Initial numerical knowledge • Qualitative description of interactions between technologies • Definition of the prototyping approach and preliminary technical specifications for laboratory test

TRL 3: Experimental proof of concept
• First laboratory scale prototype (proof-of-concept) or numerical model realized • Testing at laboratory level of the innovative technological element (being material, sub-component, software tool, …), but not the whole integrated system • Key parameters characterizing the technology (or the fuel) are identified • Verification of the proof of concept through simulation tools and cross-validation with literature data (if applicable).

TRL 4: Technology validated in lab
• (Reduced scale) prototype developed and integrated with complementing sub-systems at laboratory level • Validation of the new technology through enhanced numerical analysis (if applicable). • Key Performance Indicators are measurable • The prototype shows repeatable/stable performance (either TRL4 or TRL5, depending on the technology)

TRL 5: Technology validated in relevant environment

- Integration of components with supporting elements and auxiliaries in the (large scale) prototype
- Robustness is proven in the (simulated) relevant working environment
- The prototype shows repeatable/stable performance (either TRL4 or TRL5, depending on the technology)
- The process is reliable and the performances match the expectations (either TRL5 or TRL6, depending on the technology)
- Other relevant parameters concerning scale-up, environmental, regulatory and socio-economic issues are defined and qualitatively assessed

TRL 6: Technology pilot demonstrated in relevant environment

- Demonstration in relevant environment of the technology fine-tuned to a variety of operating conditions
- The process is reliable and the performances match the expectations (either TRL5 or TRL6, depending on the technology)
- Interoperability with other connected technologies is demonstrated
- Manufacturing approach is defined (either TRL6 or TRL7, depending on the technology)
- Environmental, regulatory and socio-economic issues are addressed

TRL 7: System prototype demonstration in operational environment

- (Full scale) pre-commercial system is demonstrated in operational environment.
- Compliancy with relevant environment conditions, authorization issues, local / national standards is guaranteed, at least for the demo site
- The integration of upstream and downstream technologies has been verified and validated.
- Manufacturing approach is defined (either TRL6 or TRL7, depending on the technology)

TRL 8: System complete and qualified

- Technology experimented in deployment conditions (i.e. real world) and has proven its functioning in its final form.
- Manufacturing process is stable enough for entering a low-rate production.
- Training and maintenance documentation are completed.
- Integration at system level is completed and mature.
- Full compliance with obligations, certifications and standards of the addressed markets

TRL 9: Actual system proven in operational environment

- Technology proven fully operational and ready for commercialization
- Full production chain is in place and all materials are available
- System optimized for full rate production

Table 14 Common trends observed in all guidance documents

5.2.3. Technology-related specificities

Here below we summarize the main issues that emerged from the discussion with stakeholders during the workshops, characterizing the technological development of each renewable energy field and that were drivers of possible enrichments or deviations from the horizontal approach initially given by the GoG.

Photovoltaics

Photovoltaics is a relatively mature technology with modular elements, hence the TRL guidance document is focused on the "upscale" concept, starting from the study of the photovoltaic cell up to the series of modules.

- TRL 8 is not conceived as "first of a kind" or "low rate production", but instead as limited and stable production of the modules' system.
- For this sector it is possible to consider a "mass production" at TRL 9.

CSP

CSP does not entail mass/serial production at plant level (such as, for example, PV technology) since specific conditions of the site influence the specific engineering practice.

- The project team faced for the first time the issue of dimensions: the guidance document should be applicable to either subcomponents or a complete system (CSP plant).

Hydropower

- The stakeholders stressed the need of potential application of this guidance for both physical systems and software tools related to hydropower energy conversion schemes. This issue has been dealt with by including a set of different examples of applications and by providing the possibility to refer to the different objects of the evaluations in the definitions (e.g. "a first lab scale prototype or appropriate numerical model is realized").
- With regard to dimensions, it has been noted that reference to 1:1 scale should be avoided, by using more flexible definitions such as small scale, large scale, full scale. Instead, a specific mention of KPIs has been considered useful to detail the definitions along the technological development.

Wind

- As in the case of the hydropower sector, stakeholders stressed the need to include new software developments among the possible objects to be evaluated with the TRL scale. Therefore, the respective requirements for physical technologies or software were specified when relevant.
- Moreover, specific mention of KPIs was considered as relevant, as already emerged while drafting the guidance document for the hydropower sector.
- The concept of "producibility", originally present in the GoG, was considered misleading by the wind energy stakeholders, so it was excluded from the checkpoints. Instead, for the first time along the sequential development of the different guidance documents, reference to standardization framework was considered a key point for advanced levels of the scale.

RE H&C

Stakeholders highlighted that "Renewable Heating & Cooling" is not a technological sector but it is an application sector, which rely on three different types of technology (geothermal, solar, biomass).

For this reason, the developed guidance document was conceived as a more general guide And, as a consequence, the evidence of the three technologies is visible in the reported examples, crucial for the development and use of the guide.

Geothermal

- Owing to the fact that geothermal sector in general embraces not only electricity generation but also heating and cooling production, the stakeholders stressed the need of an introductory part to clarify the scope of this guidance.
  Moreover, an indicative and non-exhaustive summary of the geothermal activities possibly covered by this guidance was generally depicted.
- In particular the following sentence was the result of intense discussion to explain the scope of the document: "*The geothermal RE sector devoted to production of electric energy includes many different matters, activities and scientific/technologic aspects. In brief the whole life of every geothermal program/ project comprehends and requires the fulfilment of six basic phases: site identification; surface exploration; deep exploration; tests/field models/evaluation; plant/field engineering; plant construction/installation/management. Consequently a very large number of different kinds of arguments/ideas/solutions can be proposed. Accordingly, the expression concept indicates the whole of conceptual/laboratory, design/realization aspects of the proposal which can concern one or more of the six phases as above*".

- The reference to key performance indicators was kept in the approach and, in particular, repeatable results were associated to TRL 5 whilst evaluation of performance towards expected conditions was introduced at TRL 6.

RE Alternative Fuels

- The guidance document for renewable alternative fuels (that includes artificial photosynthesis, metal fuels and other potential unknown technologies for alternative fuel production) was conceived as a more general guide, open to new technologies not yet available. The reported examples are crucial for the development and use of the guide.
- For the same reasons, the social acceptance of the technology was touched upon during the discussion on readiness levels 5, 6 and 7. On one hand it was argued that social acceptant should be evaluated as of level 5 or even earlier, to secure this risk as early as possible. On the other hand, as presenting an early version of the product may confuse the target audience, it was agreed to evaluate social acceptance as of level 6, when a pilot is available and may be presented to the target audience.

Ocean

- Preliminary concerns were raised by stakeholders over the scope of the technology covered by the guidance document: whether it was applicable to the system or subsystem and which technologies were included. It was agreed that the guidance covered the full concept of technology producing energy from wave and tidal current, including new ocean energy technology such as ocean thermal energy conversion, currents, salinity gradient-based technologies or other ones that have not emerged yet.
- Finally, agreement over the scaling was achieved by establishing a scale applicable to all type of ocean energy technologies, regardless of their size or the type of the sea it is intended for. Stakeholders argued against including specific scale ranges but rather use the formulation "appropriate scale", with the full scale being referred to as the "final intended scale".

Bioenergy – biological pathway

In contrast to other types of renewable fields, where research is mostly directed to the development of new technologies for the conversion/processing of wind/light/waves (etc.) into energy, the production of bioenergy from biomass requires innovation on both the establishment of better conversion/processing technologies and on the development (and cultivation) of dedicated feedstocks. Given the great relevance of both aspects in the development of feasible bioenergy concepts, they have been both considered in the definition of TRLs for biological pathways. Hence, from TRL 5 to TRL 9 the distinctions needed to refer to feedstock object are highlighted in italics in the developed guidance document.

Bioenergy – thermochemical pathway

- The guidance document was conceived as very similar to the one related to biological pathway. Nevertheless, in this case, biomass and other bio-based feedstocks were considered as potential fields for new concepts.
- The TRL scale up to commercialization was finally described with focus on the energy generation technologies.

The following table highlights how specific technical issues were addressed at different TR Levels in the renewable fields under our analysis.

TOPIC	TRL								
	1	2	3	4	5	6	7	8	9
Stable Performances				PV	GEOTHERMAL				
				CSP	BIO - BW				
				HYDRO	BIO - TW				
				RE H&C					
				WIND					
				RE AF					
Expected Performances					WIND	RE AF			
					PV	BIO - BW			
					CSP	BIO - TW			
					HYDRO				
Manufacturing approach		OCEAN				PV	HYDRO		
						CSP	RE H&C		
						WIND	RE AF		
							BIO - BW		
							BIO - TW		
Standardization						WIND	CSP	PV	
						OCEAN	HYDRO	RE H&C	
							BIO - BW		
							BIO - TW		
Market, costs and business			RE H&C			PV			
	GEOTHERMAL	GEOTHERMAL	GEOTHERMAL	GEOTHERMAL	GEOTHERMAL	GEOTHERMAL	GEOTHERMAL	BIO - BW	
			OCEAN					BIO - TW	
Sustainability		HYDRO			WIND	BIO - TW	OCEAN		
					RE AF				
					BIO - BW				
	RE H&C	RE H&C	RE H&C	RE H&C	RE H&C				
Risk Analysis	RE AF	CSP	RE H&C	GEOTHERMAL					
			OCEAN						
Simulation/numerical models		CSP	RE H&C						
		HYDRO							
		WIND							
		GEOTHERMAL							
		RE AF							
		OCEAN							
		BIO - BW							
		BIO - TW							
SW included	HYDRO	OCEAN				GEOTHERMAL			

Table 15 Technical specific issues

6. CONCLUSIVE REMARKS

6.1. General comments

As a result of an analytical comparison at a high level, i.e. without considering technology-specific features, it appears that the common trends obtained from the 10 guidance documents are compatible with all the technologies considered. This means that it makes sense, in a first approach, to take into consideration the common trends and the associated checkpoints to get an overview of every technology readiness levels with accuracy. This statement is roughly verifiable from TRL 1 to TRL 4-5. From TRL 6 to TRL 8, some differences from one TRL to another are observable between technologies, especially regarding commercialization, manufacturing approach, standardization and in-field integration issues. At TRL 9, a global consistency is verifiable again between technologies.

Also, when considering the technology specific features, some differences are observable, especially regarding prototype and pilot production trajectories to validate the product and simulation approaches with numerical tools. This is also true for technologies such as marine technologies for which there is a strong dependency of the technology development process on the operational environment (geographical, geological, climate, etc. constraints).

In the present work, it has been shown that the dependence of readiness level on the operational environment is a differentiating factor which could allow to categorize groups of TRL scales. The following categories (see table below) can be obtained:

Categories of TRL scales: closeness to the operational environment	
Increasing dependency of the readiness level on the operational environment ↓	RE alternative fuels
	Bioenergy technologies
	Solar and heating/cooling technologies (PV, CSP and RE heating and cooling technologies)
	Hydro, Geothermal, Ocean , Wind

6.2. Lessons learnt towards replicability

The outputs of the ten guidance documents obtained from the workshops show that the gathering of features to build the GoG made up a robust framework allowing the characterization of the different TRL of the several technologies. Therefore, it is assumed that the approach carried out during the project is actually replicable to other technologies. With this in mind, it might be possible that, when integrating additional technologies to the existing TRL framework, some features could be slightly modified until reaching an asymptote. As a result, a common GoG framework, made up from a bottom up approach, should be obtained.

6.3. To go further

Ten technologies have been considered in our study. However, it is possible to include other technologies in the existing framework. Hence, should several other technologies be included into the GoG framework in the future, it would be then conceivable to design a mapping approach in order to get a clear identification of each couple {technology, readiness level} towards users.

This could be done on what has been designed at smart grids level with the Smart Grid Reference Architecture Model (SGAM) framework by the CEN-CENELEC-ETSI Smart Grid Coordination Group[14]. As matters stand, carrying out a similar mapping approach would be useful in order to identify the uniqueness of a couple of data relative to both technology and readiness level among the development process. In this context, it should be conceivable to design a Technology

[14] The SGAM Framework aims at offering a support for the design of smart grids use cases with an architectural approach allowing for a representation of interoperability viewpoints in a technology neutral manner, both for current implementation of the electrical grid and future implementations of the smart grid.

Readiness Reference Architecture Model or “TRAM” in order to characterise and categorize, in a user friendly and illustrative way, TRLs of several technologies.

ANNEX: FINAL GUIDANCE DOCUMENTS

Please refer to the document attached to this report

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The European Union's research framework programme Horizon2020 uses the concept of Technology Readiness Level (TRL) to describe the scope of its calls for proposals; yet the definitions provided are meant as an overall guidance and do not refer specifically to renewable energy technologies.
This study was meant to firstly assess the use of TRL in the energy field at European level: a desk research, complemented by surveys and interviews with relevant stakeholders, led to the conclusion that there is still a lack of common understanding around the concept of TRL and further guiding principles would be needed.
A Guide of Guides (GoG) was conceived to be the backbone for any technology-specific definition and, based on its instructions, 10 guidance documents in different renewable energy fields were produced and validated by stakeholders in a two step-approach: first through an online survey and then during a one-day workshop. An external reviewer ensured the documents produced were consistent to update the GoG; its analysis identified technology-specific issues as well as a set of common trends for each TRL that may serve as a reference to develop guidance documents in any other energy technology field.

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