International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 15, No. 1, March 2024, pp. 530~539
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v15.i1.pp530-539

Evaluation of readiness to commercialize research results with the IRL framework: a case study of ORC turbines in Indonesia

Setyo Margo Utomo, Muizuddin Azka, Solichah Vichy Budiwati, Abdul Rahman, Hari Setiawan, Faisal, Pudji Hastuti, Aldrich Ilyas
National Research and Innovation Agency (BRIN), South Tangerang, Indonesia

Article Info

Article history:

Received Jun 30, 2023
Revised Sep 10, 2023
Accepted Sep 28, 2023

Keywords:

IRL
ORC turbine
Renewable energy
TRL
Waste management

ABSTRACT

Indonesia's commitment to reducing the use of fossil fuels for power generation has encouraged the exploration of biomass energy from waste materials. Organic Rankine cycle (ORC) turbine technology that converts waste into electrical energy can be an opportunity for the development of waste power plants. The developed ORC turbine has not been assessed for innovation readiness level (IRL). To address this gap, a comprehensive evaluation of the IRL and technology readiness level (TRL) of the ORC turbine is essential. This study uses qualitative and quantitative methods, combining the IRL and TRL frameworks. The results reveal that the ORC turbine market is ready, although the technology is still in the early stages of development (IRL 2). In order to achieve IRL 3 and be prepared to enter the decline stage as part of the market evolution phase, intellectual property protection, product testing, and certification must be carried out. The establishment of a product certification agency with testing facilities to ensure turbine performance is required. IRL and TRL approaches can be used to determine the stages of research activities that can be achieved by looking at the availability of resources needed at each level.

Corresponding Author:

Setyo Margo Utomo
National Research and Innovation Agency (BRIN)
South Tangerang, Indonesia
Email: sety003@brin.go.id

1. INTRODUCTION

The issue of energy transition towards new and renewable energy has attracted the attention of the global community, especially with regard to efforts to save the earth in the future and preserve the ecosystem of life [1]. Some of the renewable energies that are currently developing include wind, solar, geothermal, and water energy [2]–[4]. One of the problems with renewable energy sources is inconsistency over time. To overcome this, fuzzy logic control is needed in a system of renewable energy to maintain voltage stability and output frequency [5].

Currently, alternative energy is being developed utilizing biomass as a new and renewable energy source. Biomass energy that can be converted into electrical energy can potentially be generated from household waste by making waste processing for electric energy (WPEE). The development of WPEE has another benefit, it helps deal with the waste problem that is currently becoming an environmental issue, especially due to the limited landfills in some areas that are growing into big cities. In addition, the Indonesian government is committed to reducing the use of fossil energy in power generation and increasing the availability of national electricity supplies. WPEE with thermal technology can be developed in all regions with large waste volumes and waste emergencies to improve public health and hygiene [6]. Thermal technology is adopted with the aim of rapidly reducing the volume of waste, thereby overcoming the problems of land area.

One of the thermal technologies being developed for renewable energy applications is the organic Rankine cycle (ORC) turbine that can be utilized for WPEE. Today, ORC turbine technology is rapidly evolving to the point where waste heat that was once discarded now has the potential to generate electricity. ORC operates on the same principle as RC (Rankine cycle), but the working fluid is different. ORC can utilize heat sources with temperatures around 80 °C due to the low boiling point of organic liquids. The ORC cycle has the advantage of being able to operate at low temperatures. This utilization of waste heat has the potential to generate more electrical energy, increase efficiency, minimize the impact of waste heat on the environment, and save fuel.

Indonesia has considerable potential for the development of WPEE and household waste power generators (HWPG), which utilize new and renewable energy. This potential can be utilized through the mastery of ORC turbine design and manufacture by the domestic industry. It is expected that there will be an increase in the use of domestic products, and partners as users will find it easier to see the suitability of specifications, quality control, and routine maintenance when operating. This is an opportunity for the domestic industry to play a role in the supply of ORC turbine components so that it has an economic impact and creates jobs.

Currently, the National Research and Innovation Agency (BRIN) is conducting ORC turbine research at the Energy and Manufacturing Research Organization. This research activity began in 2007 with a literature review study on turbines, followed by the design and prototype of a 100-kW turbine in 2012. The prototype has only undergone functional testing, it has not been tested in the actual environment. In 2021, a study on the utilization of ORC turbines in WPEE was carried out, and in 2022, a design of an ORC turbine system integrated into WPEE was carried out. In 2023, a new ORC turbine was developed by making the cooling flow system and generator integrated with the turbine, called a hermetic type turbine, to avoid leakage of the turbine drive fluid. In 2024, it is planned to test the WPEE in a real environment by utilizing the WPEE made by industrial partners. The commercialization of research results might fail as a consequence of insufficient research or a lack of research facilities to proceed to the certification stage because researchers have not previously examined the availability of research facilities and market potential.

The problem investigated in this paper is whether ORC turbine research activities can produce proven designs and market potential that attract domestic industries with the IRL and TRL approaches. The IRL and TRL analyses were conducted to find factors that hinder the ORC turbine research stage, including technology development and market evolution that require the availability of human resources and research facilities consisting of software and hardware. The facilities are for verification and validation of the developed design so as to produce a commercially viable product. Using the analyses, it is possible to foresee the obstacles to research activities and prepare solutions from the start to overcome obstacles to achieving the commercialization of research results.

2. LITERATURE REVIEW

2.1. ORC turbine

The development of ORC turbine technology in binary cycle systems cannot be separated from the development of energy conversion technology with binary cycles. The development period of this technology can be divided into three main periods [7]. The first period, from 1967 to 1984, was the time when this technology was not widely used. The second period, from 1984 to 2000, was a period of development of binary cycle technology at a certain power capacity limit. Since 2000 and, especially, in recent years (the third period), there has been an active expansion of binary cycle power units applied to geothermal power plants with the application of ORC turbines of 2500 kW capacity units. There are two types of ORC turbines: the standard type and the hermetic type. The standard type is a type of turbine commonly used in rotary equipment where the turbine and generator are separated and coupled directly on one shaft (direct couple) or coupled with a gearbox. This type of turbine uses a mechanical seal that has the potential to cause leakage. The second type is the hermetic type turbine, a type of turbine that uses organic working fluid with the turbine rotor and generator rotor components connected directly (direct couple) in the same housing. Combining the turbine with the generator in one house is able to eliminate working fluid leakage.

The implementation and efficient operation of ORC (organic Rankine cycle) turbine systems is a major challenge due to heat source fluctuations that can be caused by various factors such as meteorological conditions, solar energy, and industrial waste heat irregularities. Such fluctuations, which include variations in temperature, flow rate, and frequency, can disrupt the stability and operational efficiency of ORC turbine systems, with potential negative impacts on the overall thermodynamic performance of the system. Currently, there are two technical approaches used to address this challenge: thermal buffering with thermal energy storage (TES) and adaptation to fluctuations with flow control. However, it should be noted that both of these approaches have certain drawbacks, such as potential energy loss from the heat source and insufficient energy utilization. As a solution, improving the performance of ORC turbines through the addition of instruments and the adjustment of turbine geometry is important to maximize the efficiency of ORC turbine systems when dealing with complex heat source fluctuations [8].

Additional instruments were adopted to improve the performance analysis of the cycle and its components. Increased sensor redundancy was used to further characterize the efficiency of the turbine by installing an extra flow meter at the front of the turbine and doubling the temperature and pressure probes at the turbine outlet. Pressure measurement points were also added on the turbine stator ring to characterize the supersonic expansion along the stator blade path, estimate trailing-edge shock losses, and assess how the expansion is shared between the stator and rotor during the experiment [9]. The geometry of the stator and rotor blades is altered to optimize the ORC turbine design. There are more than 50 optimized geometric parameters, including the parametric variables of stator and rotor profiles, rotor angle of rotation, circular tilt angle, and axial sweep, as well as the shape parameters of the end wall contours in the stator and rotor domains [10]. The combination of a gas turbine system with an ORC power plant has a positive impact since it raises the parameters of the geothermal brine flowing into the superheater, raising the ORC liquid's evaporation temperature [11]. By examining the impact of various geometric control parameters on turbine performance, it was discovered that some geometric control parameters can be modified to increase turbine performance [12]. Testing ORC turbine refers to the evaluation and analysis of the performance of turbines in organic Rankine cycle (ORC) systems. The design of ORC turbines is crucial for system efficiency and cost. Several abstracts discuss the design and performance prediction of ORC turbines [12]–[14]. Experimental campaigns and numerical simulations are used to validate and improve the design of ORC turbines [15]. Time choice of working fluid also affects turbine performance, with different fluids showing varying degrees of matching with the heat source [13]. Additionally, the use of partial admission and adaptable turbine geometry can enhance the efficiency of ORC turbines [16], [17]. Overall, these studies provide insights into the design, performance, and optimization of turbines in ORC systems.

2.2. Technology readiness level

Technology readiness level (TRL) is defined as a systematic measurement that objectively assesses the level of readiness of a technology [18]. NASA originally used TRL in the middle of the 1970s to evaluate the development stage of new technologies [19]. Furthermore, NASA, the United States Air Force, and the Department of Defense collaborated to refine and generalize TRL [20]. Technology readiness levels (TRL) are characterized as an assessment metric, to evaluate the maturity of technology [21]. It is used to determine the availability of new technologies [22].

Currently, the TRL consists of nine levels out of seven levels previously introduced by NASA, which were subsequently adopted by the US Department of Defense and have been adapted to the needs [23]. The nine-stage TRL refined and implemented by the US Department of Defense is the most often used definition of TRL [21]. TRL can also be adapted to support an understanding of the capabilities and resources required to develop technologies at different stages of development [24]. The nine TRL stages above can be grouped based on the stages of the validation environment where the innovation product is developed: i) In the first four levels (TRL 1–4), the technology validation environment is in the laboratory; ii) In levels 5 and 6, the technology is being validated in an environment with characteristics similar to the real environment; and iii) The last three levels (TRL 7–TRL 9) deal with the testing and validation of the technology in a real environment [25].

In addition, TRL can also be grouped based on the type and size of the entity that is developing the technology. Technologies that have only been developed at the academic or research level have a low TRL. Medium to high-range TRL refers to small and medium-sized companies with prototypes or ready technology that can be successfully scaled up. Technologies developed by large companies with significant R&D resources and opportunities to explore economies of scale have the highest TRL [26]. Technology readiness level (TRL) is a framework that has been used in many industries to provide a measurement of technology maturity from idea generation to commercialization [27]. For example, TRL is used to measure the technological readiness of innovative products in various sectors, such as biomass electricity, the chemical industry, and food processing [20], [21], [28].

2.3. Innovation readiness level

Technology is a key driver of innovation and long-term business growth; hence, both the private and public sectors invest heavily in research and development. An approach to increasing the efficiency of this huge investment would reap major benefits in the form of the creation of cutting-edge technologies with a more focused impact that would fulfill market demand and promote improved, sustainable company growth [29]. The concept of technology readiness levels (TRLs) has been developed as a tool to assist in monitoring technology development and is now very familiar in the innovation lexicon [30]. The term originated with NASA in the 1980s in order to help management make decisions concerning the development and transitioning of technology [31]. The original definition of TRL included seven levels, but in the 1990s NASA adopted a nine-level scale that subsequently gained widespread acceptance [23].

Based on the concept of technology readiness levels (TRLs), it introduced innovation readiness levels (IRLs) as a more holistic systems approach. This approach recognizes that successful and sustained innovation involves challenges rooted in technological uncertainties, ambiguous market signals, and embryonic competitive structures [32]. It is used to assess or evaluate the degree to which an enterprise is ready to adopt and implement innovative ideas and practices [33].

IRL aims to provide better monitoring and control based on a framework that shows how innovation develops over its lifecycle. Technology, market, organization, partnership, and risk were recognized as the five major components of innovation that have the most influence on how well ideas are implemented at different stages of the innovation life cycle [34]. Of these five key aspects identified, two are key drivers of innovation, namely technology and the market, while the other three are modifying and constraining variables to their exploitation: risk, organization, and partnership [32]. The risk considered by Tao and colleagues is "technology risk," i.e., the probability of science and engineering being able to deliver a technological solution to a particular problem. In terms of TRL, since it focuses on the technical maturity of a technology, it can be utilized to measure the first key aspect of the innovation readiness level, i.e., the technology aspect. TRL is equivalent to IRL 1 to IRL 3 for concept (TRL 1-3), component (TRL 4-6), and completion (TRL 7-9) of technological development [32].

3. METHODS

Data collection was conducted using surveys and interviews with ORC turbine research team leaders and members. This research uses qualitative and quantitative methods to determine the level of innovation readiness (IRL) and technology readiness level (TRL). In the first stage, an analysis was conducted using the IRL framework. This method is used to assess the level of innovation readiness of ORC turbines. The IRL framework evaluates five different aspects. The assessment will reveal areas that still need improvement and those that have been reinforced by research activities. The purpose of this study is to provide an overview of what aspects need more attention in order to master the design and manufacture of ORC turbines. The results of the analysis were then discussed and verified with the lead researcher and his members.

In the second stage, the analysis was conducted using the TRL framework. This method is used to evaluate the technological readiness of ORC turbine research results. This TRL analysis will identify the stages of research that must be carried out and the necessary resource requirements. The analysis result will reveal resources not yet available, and solutions to overcome the problem can be prepared. The analysis is carried out by compiling a table of research activities at each stage of technological readiness (TRL), resource requirements, and availability.

4. RESULT AND DISCUSSION

Based on information from ORC turbine researchers at the Process and Manufacturing Industry Technology Research Center (BRIN) in 2023, a new ORC turbine prototype, a hermetic-type turbine, will be constructed and tested at the WPEE pilot plant in 2024 to be evaluated in a real environment. The WPEE has a household waste treatment capacity of 30 tons per day. The following are the results of the ORC turbine product IRL assessment, with five aspects in IRL and an explanation of each aspect.

4.1. Technology aspect

The design in ORC turbine research has been supported by personnel who are experts in turbine technology and the numerical analytical software required to validate the concept. The human resources consist of three groups: i) Energy conversion experts who analyze thermodynamics and fluid dynamics to determine the pressure, temperature, and fluid mass flow parameters required to obtain the planned power; ii) Structural experts for design and structural strength analysis and material selection; and iii) Manufacturing experts for production process planning and quality control.

The design software owned is computer aided three-dimensional interactive application (CATIA) and SolidWorks, which have the ability to design 3D-based components, 3D design assemblies, and make engineering drawings. ANSYS mechanical is used for structural strength analysis of components, while ANSYS fluent, or NUMECA, is used for computational fluid analysis. The design and its analysis begin with the manufacture and assembly of components using CATIA or SolidWorks software. ANSYS mechanical is also used to assess the components for structural strength and mechanical characteristics. The design data and attributes are then used in ANSYS Fluent or NUMECA software for fluid and power analysis. The ORC turbine design analysis reveals that numerous materials may be utilized to produce the ORC turbine. It is feasible to employ materials produced by domestic industries, such as stainless steel for the rotor and stator, and carbon steel plate for the turbine casing, to lower material costs and boost local content in the ORC turbine.

The above conditions indicate that research activities for both types of ORC turbines to identify potential technology or product improvements and technological feasibility can be carried out due to adequate human resources and research facilities. As a result, the technological element required in IRL 1 can be met. To satisfy the objective of IRL 2, the design must be created in the form of a prototype and tested in a laboratory. The rotor, stator, casing, and shaft are prototypes of ORC turbine components that are being manufactured. The prototyping was conducted by the domestic industry, which became the partner for ORC turbine design development. In compliance with API 611 specifications, the balance of both ORC turbine prototypes was checked on the rotor and stator using a balancing test tool. Testing was carried out in a manufacturing industry with balance test facilities. To ascertain the presence of leaks, a hydrostatic test was also performed. Both ORC turbine prototypes were tested using water vapor, and the findings indicated that the standard type turbine leaked at 3000 rpm, while the hermetic type turbine did not leak until 6000 rpm. Testing is carried out in manufacturing industries that have hydrostatic test facilities.

In 2022, intellectual property has been filed in the form of a turbine industrial design, and it is expected that the industrial design certificate can be obtained in 2023. Then, in 2023, a patent will be filed for the developed hermetic-type ORC turbine. Thus, the technological aspect requirements in IRL 2 have been met, but the turbine component test facilities are still dependent on the industry. This condition forces turbine research activities to cooperate with the industry for prototyping and testing. Hydrostatic test facilities in industrial businesses are used to conduct testing. Intellectual property in the form of a turbine industrial design was filed in 2022, and it is anticipated that the industrial design certificate will be available in 2023. The designed hermetic-type ORC turbine will then have a patent application made for it in 2023. As a result, IRL 2's technological aspect criteria have been satisfied, but the turbine component test facilities are still dependent on the industry. This condition requires turbine research activities to collaborate with the industry for testing and development.

Requirements to achieve IRL 3 are actual system demonstrated, external tests completed, and intellectual property protected. There are currently no testing facilities available to validate the design; therefore, evaluating the turbine's performance in an actual working environment is not possible. IRL is classified into two categories: technology development and market evolution. The technology development category is divided into three stages: concept (IRL 1), component (IRL 2), and completion (IRL 3). Based on the technical aspects discussed above, the stages of technology development in IRL can be achieved if there are experts in their fields, software for numerical analysis and modeling, manufacturing facilities for prototyping, testing facilities for design verification and validation, as well as product certification. Thus, we can determine from the start whether the technological development stage is achievable by looking at the availability of the required resources.

4.2. Market aspect

The need for ORC turbines by a research partner, a private waste processing enterprise, drives the development of innovative products. Market demand and needs are identified through the planned installation of ORC turbines in waste processing units in a number of locations, including Soreang, West Java (5 units), Morowali (3 units), Yogyakarta (5 units), South Tangerang (3 units), and Tebet DKI (5 units). As a result, the market aspect requirement in IRL 1, which calls for doing market research with industry partners to identify the demand for ORC turbines, is fulfilled.

In addition, the assessment for IRL 2 requires market identification and the establishment of a product launch plan. According to presidential regulation of the Republic Indonesia Number 35 of 2018 concerning the acceleration of the Development of Waste Processing Installations into Electrical Energy Based on Environmentally Friendly Technology (WPEE), it is necessary to accelerate the development of WPEE, in the waste management sector by setting targets in 12 regions (1 province and 11 cities). The designated areas can then be recognized as prospective target markets.

In partnership with a waste-to-energy firm, the ORC turbine will be examined for performance this year by integrating it with a waste-to-energy company in Bandung. If the ORC turbine operates as expected at the WPEE in Bandung, it will be implemented at other WPEEs in collaboration with the local government. Furthermore, other potential markets were identified based on discussions with researchers and industry partners, including a number of user industries, such as PLN, which uses ORC turbines for PLTP, as well as process and biomass industries that use ORC turbines to meet electricity needs in production facilities. The market aspect of IRL 2 has been met based on the aforementioned requirements, which include the identification of possible target markets and a product launch strategy.

IRL 3 requires the identification of customer-specific needs to meet community demands and address identified problems. In order to generate heat for the ORC turbine system, the customer required a small-scale ORC turbine with a capacity range of 100–300 kW. Through a feasibility analysis, ORC turbine capacity and market share were estimated. The product price is more competitive than that of imported goods. The market price for imported goods is 2.5 M (IDR) for 100 kW, whereas the price for domestic goods is 1.1 M (IDR) for 100 kW. As a result, the market aspect of IRL 3 has been fulfilled.

The product already has a strong market position, with the price projected to be 50% lower than imported goods, and local industries are ready to produce it. The established business model involves BRIN, the turbine manufacturing industry, the waste treatment equipment manufacturing industry, and the local government that will use the WPEE in its territory. Users who will use ORC turbines in the WPEE under construction have provided feedback. There is currently no domestic industry producing ORC turbines; hence, there is no domestic industry competitor. To accommodate demand at the moment, more expensive imported ORC turbines are used. Partnerships have been made with industry in collaboration with local governments to enter the ORC turbine market. As a result, the market component of IRL 4 is fulfilled. Currently, all aspects of IRL 5, which include products differentiated, services and solutions provided, periodic review conducted, business model refined, and partnership as an option to compete, have not been met.

4.3. Organizational aspect

BRIN, as a research institution, has appointed the Energy and Manufacturing Research Organization to develop strategies and conduct ORC turbine research. The required research resources, especially from LPDP, BRIN Program Houses, and collaborators, have been determined, allowing the organizational components of IRL 1 to be met. A business plan and analysis have been developed with partners, as well as the involvement of key individuals, including the leader of team research from BRIN and partner representatives, both users and producers. It fulfills the organizational aspects of IRL 2 and IRL 3. The IRL 4 aspect has not been met since the formalizing organization has not been established, particularly in terms of the organization's ability to anticipate a dead valley or chasm.

4.4. Partnership aspect

Potential partners for ORC turbine research activities have been identified, and collaborations with the industry have been established appropriately. Hence, the partnership aspect of IRL 1 has been fulfilled. PT. Bumi Resik Nusantara, the ORC turbine research partner, is capable of designing and integrating a waste processing system that will be combined with the ORC turbine system to produce a waste processing system that creates electrical energy. Therefore, the partnership aspect of IRL 2 has been met. Nevertheless, the partnership requirement of IRL 3 has not been fulfilled because the collaboration has not been formalized.

4.5. Risk aspect

Technological risk studies have been taken into consideration at each stage of the research, and the technical feasibility of making turbines has been based on API 611 and SNI ISO 10437 2017 standards. The materials for producing ORC turbine components can be obtained through imports or from domestic industry, and the manufacturing process can be done domestically. The risk aspect of IRL 1 has been fulfilled. However, the testing process has yet to begin because it requires an accredited turbine testing facility. As a result, the risk aspect of IRL 2 has not been met.

IRL measurements of ORC turbines reveal that they are at IRL 2. However, one indicator, intellectual property protection, has not been met. It demonstrates that the ORC turbine innovation product is still in the technology development phase. Figure 1 depicts the findings of the assessment of the five IRL framework components.

The assessment result shows that the product is in TRL 6, which indicates that the steps of design, engineering analysis, validation, and testing of components and/or product prototypes in a laboratory environment have been performed. The existing testing laboratory, however, can only evaluate rotation and power by using steam from the boiler as a working fluid. Such testing laboratory facilities still require improvement. For example, the ORC turbine prototype was tested at the University of Hannover using an ORC test bench capable of testing various ORC fluids and components with the purpose of validating numerical calculations and the design [35]. To test the ORC turbine, an ORC system with a preheater and superheater was developed [36].

To achieve TRL 9, the following steps need to be taken: i) The performance is demonstrated in an operational environment; ii) A representative model that fully reflects all aspects of the design has been built and tested with adequate safety limits to demonstrate performance in the actual environment (TRL 7); iii) The model is qualified, integrated, and functionally tested (TRL 8); iv) The technology is mature; v) The system has been operated under all conditions, extents, and ranges; and vi) The element is operating successfully for the designated application in the actual operating environment (TRL 9).

The ORC turbine system industrial design has been registered. In addition, the ORC turbine design is being optimized for patenting to fulfill the requirements for achieving IRL 2. Then, to attain IRL 3, it is necessary to complete the stages of technology development from TRL 6 to TRL 9, as described above. The development of this technology requires a waste processing for electric energy (WPEE) pilot plant to test the ORC turbine, with a turbine capacity below 500 kW (in accordance with the capabilities of the domestic manufacturing industry in developing waste processing).

To achieve TRL 9 or IRL 3, testing under actual conditions is required, as well as certification from an external party (an accredited testing organization). However, there is currently no accredited testing institution in Indonesia. The current test is carried out by making a prototype that is installed on an existing generating system. According to the technology readiness assessment, the ORC turbine is at TRL 6, where the TRL intersects the IRL section, as shown in the Figure 2.

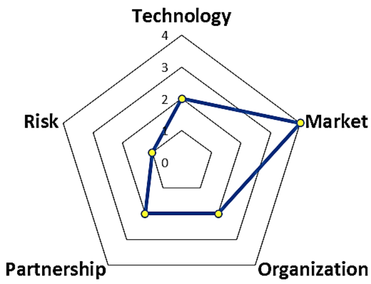

Figure 1. The five aspects of IRL for ORC turbine

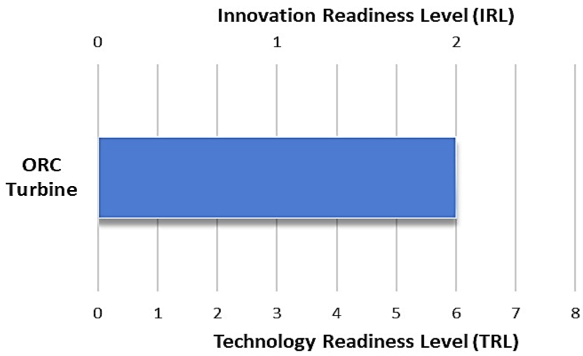

Figure 2. TRL-IRL ORC turbine

Based on the stages of ORC turbine research that have been completed and those that must be completed, the issues encountered in achieving TRL 9 may be summarized by stating the research activities that must be completed and the resources required, as indicated in Table 1. The table shows that a performance testing facility is required to reach TRL 8 in order to continue ORC turbine research. Furthermore, to achieve TRL 9, a certification agency must be available to ensure the quality of the ORC turbine in accordance with the reference standard. The commercialization of ORC turbine research results is not possible without these testing facilities and certification agency.

Table 1. Resources availability for TRL ORC turbine

TRL	Target activity	Resources	Resources Availability
1	Basic principles of the technology have been observed and reported	1. Turbine expert 2. Literature	Available
2	Concept formulation and/or formulation application	1. Turbine expert 2. Software simulation	Available
3	Analytical studies on separate elements of the technology. Laboratory based trials that show the feasibility of the predictions	1. Turbine expert 2. Software simulation 3. Turbine modelling laboratory	Available
4	Basic technological components integrated together to show that they work together. At this point, durability is not yet important	1. Turbine expert 2. Component turbine testing facility 3. Workshop	Available
5	Basic technological components integrated within realistic context under a fully controlled environment in or outside the lab	1. Turbine expert 2. Component turbine testing facility 3. Workshop	Available
6	A functional version of the product working on a realistic environment able to draw conclusions on the technical and operational capabilities of the product	1. Turbine expert 2. Functional turbine testing facility 3. Workshop	Available
7	A manufacturable version of the product working in an environment that addresses all the operational requirements for the product	1. Turbine expert 2. Turbine manufacturing facility 3. Performance turbine testing facility	Performance turbine testing facility is not feasible
8	Product in its final design working in full mode under expected conditions and periods	Turbine expert	Available
9	Product in its final design under full commercial deployment	Certification agencies	Not available

5. CONCLUSION

The two phases of the IRL are technological development and market evolution. The analysis results show that the ORC turbine market is ready, but the technology is still in the early stages of development (IRL 2). Intellectual property protection, product testing, and certification must be completed in order for a product to reach IRL 3 and be prepared to enter the brink stage as part of the market evolution phase.

Product commercialization is only possible when IRL 3 or TRL 9 have been reached, which occurs after product performance feasibility testing. Only a product certification agency, which is currently unavailable in Indonesia, may undertake these tests. As a result, this study will not be successful in entering the commercialization stage. To ensure the success of ORC turbine research, it is required to establish a product certification agency with testing capabilities to ensure the turbines performance. To achieve the commercialization goal of ORC turbine research results, it will take some time until turbine certification is available. Using the IRL and TRL approaches, it is possible to determine at what stage research activities cannot be continued due to factors such as the availability of human resources, numerical analysis software, prototyping facilities, testing facilities in the actual environment, and a research product certification agency.

From the experience of the ORC turbine research conducted since 2007 to the present day, it is impossible to commercialize the results of the research. This is because no test labs are available to determine the design performance of the ORC turbine. Once the test lab is available, it turns out there is no certification agency for turbines to reach TRL 9 as a condition for moving to the commercial phase. This time-consuming research process would not have happened if we had previously analyzed the resource requirements for each stage of research, or TRL.

ACKNOWLEDGEMENTS

We express our gratitude for the support of the Process Industry and Manufacturing Technology Research Center, the Manufacturing Energy Research Organization, and the National Research and Innovation Agency of the Republic of Indonesia, which has funded this research.

REFERENCES

[1] G. Gorel and I. Fadhil, "Control technique for power quality improvement of isolated wind power generation system," *Bull. Electr. Eng. Informatics*, vol. 12, no. 4, pp. 1881–1892, 2023, doi: 10.11591/eei.v12i4.5082.

[2] A. Tarraq, F. El Mariami, and A. Belfqih, "New typical power curves generation approach for accurate renewable distributed generation placement in the radial distribution system," *Int. J. Electr. Comput. Eng.*, vol. 13, no. 5, p. 4909, 2023, doi: 10.11591/ijece.v13i5.pp4909-4918.

[3] Y. Niu, A. M. Merza, S. I. Kadhem, J. F. Tawfeq, P. S. JosephNg, and H. M. Gheni, "Evaluation of wind-solar hybrid power generation system based on Monte Carlo method," *Int. J. Electr. Comput. Eng.*, vol. 13, no. 4, pp. 4401–4411, 2023, doi: 10.11591/ijece.v13i4.pp4401-4411.

[4] R. Mohamed, M. Helaimi, R. Taleb, H. A. Gabbar, and A. M. Othman, "Frequency control of microgrid system based renewable generation using fractional PID controller," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 19, no. 2, pp. 745–755, 2020, doi: 10.11591/ijeecs.v19.i2.pp745-755.

[5] O. Feddaoui, R. Toufouti, L. Jamel, and S. Meziane, "Fuzzy logic control of hybrid systems including renewable energy in microgrids," *Int. J. Electr. Comput. Eng.*, vol. 10, no. 6, pp. 5559–5569, 2020, doi: 10.11591/ijece.v10i6.pp5559-5569.

[6] M. M. Sari *et al.*, "Prediction of recovery energy from ultimate analysis of waste generation in Depok City, Indonesia," *Int. J. Electr. Comput. Eng.*, vol. 13, no. 1, pp. 1–8, 2023, doi: 10.11591/ijece.v13i1.pp1-8.

[7] G. V. Tomarov, A. A. Shipkov, and E. V. Sorokina, "Investigation of a binary power plant using different single-component working fluids," *Int. J. Hydrogen Energy*, vol. 41, no. 48, pp. 23183–23187, 2016, doi: 10.1016/j.ijhydene.2016.09.165.

[8] X. Li, B. Xu, H. Tian, and G. Shu, "Towards a novel holistic design of organic Rankine cycle (ORC) systems operating under heat source fluctuations and intermittency," *Renew. Sustain. Energy Rev.*, vol. 147, no. September, 2021, doi: 10.1016/j.rser.2021.111207.

[9] A. Uusitalo, M. Zocca, and T. Turunen-Saaresti, "Measurement System of Small-Scale High Expansion Ratio ORC Turbine," *ERCOFTAC Ser.*, vol. 28, pp. 114–122, 2021, doi: 10.1007/978-3-030-69306-0_12/COVER.

[10] Witanowski *et al.*, "Optimization of an axial turbine for a small scale ORC waste heat recovery system," *Energy*, vol. 205, 2020, doi: 10.1016/j.energy.2020.118059.

[11] Z. Wang, B. Xie, X. Xia, L. Luo, H. Yang, and X. Li, "Entropy production analysis of a radial inflow turbine with variable inlet guide vane for ORC application," *Energy*, vol. 265, no. November 2022, p. 126313, 2023, doi: 10.1016/j.energy.2022.126313.

[12] W. Li, Q. Ni, and X. Ling, "Investigations on ORC radial inflow turbine three-dimensional geometry design and off-design performance prediction," *Case Stud. Therm. Eng.*, vol. 44, no. November 2022, p. 102893, 2023, doi: 10.1016/j.csite.2023.102893.

[13] W. Li and X. Ling, "A novel analysis framework for the organic Rankine cycle waste heat recovery system: From the viewpoint of turbine design," *Case Stud. Therm. Eng.*, vol. 32, no. December 2021, p. 101830, 2022, doi: 10.1016/j.csite.2022.101830.

[14] L. Zanellato, M. Astolfi, A. Serafino, D. Rizzi, and E. Macchi, "Field performance evaluation of geothermal ORC power plants with a focus on radial outflow turbines," *Renew. Energy*, vol. 147, pp. 2896–2904, 2020, doi: 10.1016/j.renene.2018.08.068.

[15] M. Manfredi, G. Persico, A. Spinelli, P. Gaetani, and V. Dossena, "Design and commissioning of experiments for supersonic ORC nozzles in linear cascade configuration," *Appl. Therm. Eng.*, vol. 224, no. February 2022, p. 119996, 2023, doi: 10.1016/j.applthermaleng.2023.119996.

[16] J. Krail, G. Beckmann, F. Schittl, and G. Piringer, "Comparative thermodynamic analysis of an improved ORC process with integrated injection of process fluid," *Energy*, vol. 266, no. October 2022, p. 126352, 2023, doi: 10.1016/j.energy.2022.126352.

[17] P. Klonowicz, Ł. Witanowski, T. Suchocki, Ł. Jędrzejewski, and P. Lampart, “Selection of optimum degree of partial admission in a laboratory organic vapour microturbine,” *Energy Convers. Manag.*, vol. 202, no. July, p. 112189, 2019, doi: 10.1016/j.enconman.2019.112189.
[18] J. Mankins, “Technology readiness levels – A white paper,” 1995.
[19] J. C. Mankins, “Technology readiness assessments: A retrospective,” *Acta Astronaut.*, vol. 65, no. 9–10, pp. 1216–1223, 2009, doi: 10.1016/j.actaastro.2009.03.058.
[20] G. A. Buchner, K. J. Stepputat, A. W. Zimmermann, and R. Schomäcker, “Specifying Technology Readiness Levels for the Chemical Industry,” *Ind. Eng. Chem. Res.*, vol. 58, no. 17, pp. 6957–6969, 2019, doi: 10.1021/acs.iecr.8b05693.
[21] F. B. Dovichi Filho, Y. Castillo Santiago, E. E. Silva Lora, J. C. Escobar Palacio, and O. A. Almazan del Olmo, “Evaluation of the maturity level of biomass electricity generation technologies using the technology readiness level criteria,” *J. Clean. Prod.*, vol. 295, 2021, doi: 10.1016/j.jclepro.2021.126426.
[22] E. Sandberg and A. Krook-Riekkola, “The impact of technology availability on the transition to net-zero industry in Sweden,” *J. Clean. Prod.*, vol. 363, no. November 2021, p. 132594, 2022, doi: 10.1016/j.jclepro.2022.132594.
[23] Jim Banke, “Technology Readiness Levels Demystified,” 2017, Accessed: Sep. 10, 2023. [Online]. Available: http://www.nasa.gov/topics/aeronautics/features/trl_demystified.html
[24] J. Rybicka, A. Tiwari, and G. A. Leeke, “Technology readiness level assessment of composites recycling technologies,” *J. Clean. Prod.*, vol. 112, no. January, pp. 1001–1012, 2016, doi: 10.1016/j.jclepro.2015.08.104.
[25] F. Martínez-Plumed, E. Gómez, and J. Hernández-Orallo, “Futures of artificial intelligence through technology readiness levels,” *Telemat. Informatics*, vol. 58, no. June 2020, 2021, doi: 10.1016/j.tele.2020.101525.
[26] M. Solis and S. Silveira, “Technologies for chemical recycling of household plastics – A technical review and TRL assessment,” *Waste Manag.*, vol. 105, pp. 128–138, 2020, doi: 10.1016/j.wasman.2020.01.038.
[27] H. Nakamura, Y. Kajikawa, and S. Suzuki, “Multi-level perspectives with technology readiness measures for aviation innovation,” *Sustain. Sci.*, vol. 8, no. 1, pp. 87–101, 2013, doi: 10.1007/s11625-012-0187-z.
[28] A. A. R. Setiawan, A. Sulaswatty, Y. Meliana, and A. Haryono, “Innovation Readiness Assessment toward Research Commercialization: Case of Surfactants for Food Processing,” *Int. J. Innov.*, vol. 6, no. 2, pp. 180–193, 2018, doi: 10.5585/iji.v6i2.291.
[29] D. Dent and B. Pettit, “Technology and Market Readiness Levels,” *Dent Assoc. Sci. Bus.*, 20111.
[30] Sujit Bhattacharya, V. Kumar, and S. N. Nishad, “Technology Readiness Level: An Assessment of the Usefulness of this Scale for Translational Research,” *Productivity*, vol. 62, no. 2, pp. 106–118, 2022, doi: 10.32381/prod.2021.62.02.2.
[31] S. R. Sadin, F. P. Povinelli, and R. Rosen, “The NASA technology push towards future space mission systems,” *Acta Astronaut.*, vol. 20, no. C, pp. 73–77, 1989, doi: 10.1016/0094-5765(89)90054-4.
[32] L. Tao, D. Probert, and R. Phaal, “Towards an integrated framework for managing the process of innovation,” *R&D Manag.*, vol. 40, no. 1, pp. 19–30, Dec. 2009, doi: 10.1111/j.1467-9310.2009.00575.x.
[33] A. Benaim, A. Larsson, T. Larsson, and J. Elfsberg, “Becoming An Innovative Company: Assessing An Organization’s Innovation Capability From The Perspective Of A Team,” *15th Int. CINet Conf.*, 2014.
[34] E. K. Zervoudi, “Fourth Industrial Revolution: Opportunities, Challenges, and Proposed Policies,” *Ind. Robot. - New Paradig.*, pp. 1–25, 2020, doi: 10.5772/intechopen.90412.
[35] H. K. J R Seume, M Peters, “Design and test of a 10kW ORC supersonic turbine generator,” *J. Phys. Conf. Ser.*, vol. 755, no. 1, 2017, doi: 10.1088/1742-6596/755/1/011001.
[36] Y. Gou, L. Li, and H. Min, “Design and performance experiment of radial inflow turbine expander for organic Rankine cycle system,” *Int. J. Low-Carbon Technol.*, vol. 16, no. 4, pp. 1202–1209, 2021, doi: 10.1093/ijlct/ctab043.

BIOGRAPHIES OF AUTHORS

Setyo Margo Utomo is a researcher at the Research Center for Process and Manufacturing Industry in the National Research and Innovation Agency, Indonesia. He received his Ir. degrees from Brawijaya University, Malang, Indonesia, in 1993, and his M.Eng. degrees in system engineering from Nagoya Institute of Technology, Japan, in 2001. He has been a researcher at the National Research and Innovation Agency, Indonesia, since 2006. He is currently the Chief Researcher of the Supply Chain and Local Content of the ORC Turbine Research Group. His research interests include the fields of technology readiness level, inovasion readiness level, manufacturing readiness level, supply chain, value chain, industry development, local content calculation, cost modeling, and the ecosystem of industry. He can be contacted at email: sety003@brin.go.id.

Muizuddin Azka is a researcher at the Research Center for Process and Manufacturing Industry in the National Research and Innovation Agency, Indonesia. He received his S.T. degrees in Mechanical Engineering from Sebelas Maret University, Surakarta, Indonesia, in 2005, his M.T. degrees in Mechanical Engineering from the University of Indonesia in 2012, and his Dr.Eng. degrees in Mechanical System Engineering from the Hiroshima University, Japan, in 2020. He has been a researcher at the National Research and Innovation Agency, Indonesia, since 2008. He is currently the Leader of the Rotating Equipment Research Group. His research interests include the fields of manufacturing technology, CAD/CAM&CAE, complex surface machining, vibration analysis, manufacturing readiness level, supply chain, and industry development. He can be contacted at email: muizuddin.azka@brin.go.id.

Solichah Vichy Budiwati is a researcher at the Research Center for Process and Manufacturing Industry in the National Research and Innovation Agency, Indonesia. She received her S.T. degrees in industrial engineering from Islamic University of Indonesia, Yogyakarta, Indonesia, in 1999, and her M.E. degrees in Master in Planning and Public Policy from University of Indonesia in 2015. She has been a researcher at the National Research and Innovation Agency, Indonesia, since 2002. She is one of the researchers in the supply chain and local content of ORC Turbine Research Group. Her research interests include the field of industrial policy such as assessments and measurements of: technology readiness level, innovation readiness level, manufacturing readiness level, supply chain, value chain, cluster of industry development, level of local content, and also assessment of the ecosystem of industry. She can be contacted at email: soli006@brin.go.id.

Abdul Rahman is a researcher at the Center for Sustainable Production Systems and Life Cycle Assessment at the National Research and Innovation Agency, Indonesia. He received an S.T. in Bachelor of Industrial Engineering from Krisnadwipayana University, Indonesia, in 2018, He has been a researcher at the National Research and Innovation Agency, Indonesia, since 2008. Research activities he has participated in include policy studies on charging stations, or SPKLU, the development of the oil and gas industry, the development of the power industry solar energy, and life cycle engineering. His research interests include manufacturing technology, manufacturing readiness level, supply chain, industrial development, life cycle assessment, and sustainability. He can be contacted at email: abdul.rahman.1@brin.go.id.

Hari Setiawan has been a researcher at the National Research and Innovation Agency (BRIN) since 2020. He completed his bachelor's degree in industrial engineering at Telkom University in 2019. Currently, he is at the Research Center of Process Industry Technology and Manufacturing (PR TIPM) at BRIN. The research activities in which he has participated include policy studies on charging stations, or SPKLU, the development of the oil and gas industry, the development of the solar power industry, and the development of the medical equipment industry. His research interests include dynamic systems, production process, automation, and technical drawings. He can be contacted at email: hari045@brin.go.id.

Faisal is researcher at the Research Center for Process and Manufacturing Industry in National Research and Innovation Agency, Indonesia. He received his S.T. degrees in civil engineering from Muslim University of Indonesia, Makassar, Indonesia, in 2002, and his M.T. degrees in industrial engineering from University of Indonesia, Jakarta, in 2017. He has been a researcher in National Research and Innovation Agency, Indonesia, since 2010. He is currently an Researcher of the Supply Chain and Local Content of ORC Turbine Research Group. His research interests include the fields of technology readiness level, innovation readiness level, manufacturing readiness level, supply chain, value chain, industry development, local content calculation, cost modeling, and ecosystem of industry. He can be contacted at email: fais002@brin.go.id.

Pudji Hastuti is a researcher at the Research Center for Process and Manufacturing Industry in the National Research and Innovation Agency, Indonesia. She received her bachelor’s degree in financial management from Universitas Indonesia in 1995. She has been involved in some studies in the areas of technological capabilities, innovation systems, value chains, industry clusters, innovation diffusion, technology readiness levels, manufacturing readiness levels, innovation readiness levels, and technology foresight. She can be contacted at email: pudj002@brin.go.id.

Aldrich Ilyas is a researcher at the Research Center for Process and Manufacturing Industry in the National Research and Innovation Agency, Indonesia. He received his S.T. degree from Darma Persada University, Jakarta, Indonesia, in 2009, and his M.P. degree in the field of Professional Masters in Small and Medium Industries from the Bogor Agricultural Institute, West Java, in 2016. He has been a researcher in National Research and Innovation Agency, Indonesia, since 2011. His research interests cover the areas of technology readiness level, innovation readiness level, manufacturing readiness level, supply chain, value chain, industrial development, and industrial ecosystem. He can be contacted at email: aldr001@brin.go.id.