Sustainable technology and Technology for sustainability: The paths towards Eco-innovation

Chiara Sandionigi
Univ. Grenoble Alpes, CEA, List
F-38000 Grenoble, France

Jean-François Berrée
Univ. Paris-Saclay, CEA, List
F-91120, Palaiseau, France

Maxime Péralta
Univ. Grenoble Alpes, CEA, List
F-38000 Grenoble, France

Ariane Piel
Univ. Paris-Saclay, CEA, List
F-91120, Palaiseau, France

Bénédicte Robin
Univ. Grenoble Alpes, CEA, List
F-38000 Grenoble, France

***Abstract*—Eco-innovation is an area of increasing concern for academics, practitioners and policy makers. Nevertheless, when referred to the technology domain, various concepts and terms with different definitions are used. This paper proposes a visual framework that helps to position and drive research projects and technology developments towards the final ambition of sustainable innovation. Via the study proposed in this paper, we also hope to contribute to the coherence of the related concepts, since we presume that significantly varying terms and definitions may eventually lead to confusion. Indeed, the proposed framework aims to offer guidelines to ensure sustainable goals and fulfill the ambition to eco-innovate.**

Keywords—Eco-innovation, Sustainability, Eco-design, Life Cycle Assessment.

I. INTRODUCTION

The analysis of the impact of technology on environment and society has gained momentum both among scholars and practitioners. It is commonly known that technology has a double and opposite impact: negative for its production, use and disposal; positive when exploited to solve sustainability issues. The negative impact must be minimized from the design phase of technology development, while the positive impact must be accurately evaluated and targeted to justify the appeal to technology. In this context, various concepts have risen: Green Tech, Tech for Green, Eco-design, Responsible design, Eco-innovation,... Nowadays all these terms are widely and wildly employed in the technology domain to indicate that the impacts on environment and society have been taken into account. Nevertheless, the concepts are still in development: they lack commonly recognized definitions and can mean many different things to different people. Such context makes it difficult to position and drive research projects and technology developments with the ambition to eco-innovate.

The aim of this work is to define a framework that helps to quickly position and simplify every activity linking technology and sustainability, by considering the three pillars of environment, society and economy. Another contribution of the framework is to create transparency regarding the current understandings of the concepts in this domain, based on a critical analysis of definitions of the most common terms.

Via this study, we have the ambition to provide a simple but efficient view to position the activities related to eco-innovation. The double involvement of technology in sustainable development translates into two main paths: Sustainable technology and Technology for sustainability. Each path is structured into steps towards eco-innovation. The steps constitute maturity levels in technology development from a point of view of sustainability, rather than incremental steps. Eco-innovation is the last step where the two paths meet. It is the ambition to develop sustainable technologies to solve sustainability issues.

The next section provides an analysis of the definitions found in the literature for the concepts related to eco-innovation and sustainable development in the technology domain. Section III presents the framework proposed to position activities linking technology and sustainability towards eco-innovation. Section IV applies the framework to a case study taken from the electronic field.

II. SUSTAINABILITY CONCEPTS AND ECO-INNOVATION DEFINITIONS

Sustainability and eco-innovation are contested concepts, with theories shaped by organizations and people influencing how issues are formulated and actions proposed. Because of the increase in the number of concepts linking technology and sustainability, the aim of this section is to provide an overview of the existing body of literature.

A. Sustainability in the technology domain

In the Brundtland report [1], commissioned by the United Nations, *Sustainability* is defined as the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainability implies limits, which are not absolute limits but limitations imposed by the present state of the environmental resources and by the ability of the biosphere to absorb the effects of human activities.

The Triple Bottom Line, coined by John Elkington in 1994, defines a framework for sustainability taking into account three lines: environment, society and economy [2]. Later, other works in the literature added other dimensions to sustainability. In [3], the individual dimension was added. Individual sustainability refers to the maintenance of the private good of individual human capital, which includes health, education, skills, knowledge, leadership and access to services. In [4], the technical dimension was added to sustainability. Technical sustainability has the central objective of long term usage of systems and their adequate evolution with changing surrounding conditions and respective requirements. We claim that individual sustainability can be considered as a subdimension of the social line, since individual and social capitals are related and constitute the society framework. As for technical sustainability, its objective is central for the environmental line in a perspective of durability of systems and circular economy strategies. Hence, in this paper, we consider three main pillars of sustainability: environment, society and economy.

The literature presents different visions of the positioning of sustainability with respect to the three pillars. Two main visions can be identified, called weak and strong sustainability. In weak sustainability, sustainability is presented as the intersection between environment, society and economy. In this vision, the three pillars are conceived as separate entities. The economy is often given priority in policies, and the environment is viewed as apart from humans. In strong sustainability, the three pillars are interconnected, with the economy dependent on society, and both on the environment [5].

When coming to technology, in the literature, various words are employed to refer to concepts linked to each pillar. For the environmental pillar, *Green* is often used. In the technology domain, it is usually linked to concepts like *Green Tech* or *Tech for Green*. *Eco* is another term usually employed in the literature to refer to a reduced negative impact on the environment. When used in *Eco-innovation,* the notion can be larger than the environmental pillar, as explained in Section B. For the social pillar, research on the field is still in its infancy, especially when coming to the technology domain. A proof of this statement is the lack of consensus and clear definitions about the concept of *social* versus *societal*. Since this paper is positioned on global sustainability and not on a single pillar, we employ the concepts of *Sustainable technology* and *Technology for sustainability*.

B. The objective of eco-innovation

The other concept investigated is eco-innovation, considered as the final ambition of research projects and technology developments linked to sustainability. Etymologically, the word *eco* derives from the Greek οικος, literally meaning home but also, in a wider sense, family or planet. *Innovation* descends from the Latin *in novare,* as in to make something new, or to change something already existing.

The work presented in [6] analyzes various definitions of eco-innovation. The analysis focuses on the discipline of Social Sciences and Humanities, but it can be easily adapted to the technology domain. The authors identify two ways to define eco-innovation: by its effect on the environment, hence focusing on the environmental result, or by the intention of the innovator, meaning the environmental motivation.

According to [7], *Sustainable innovation* is the term that must be employed to indicate innovation implementing economic, environmental and social aspects, while *Eco-innovation* includes only economic and environmental aspects. The authors analyzed various definitions of *Eco-innovation* appeared in literature between 1996 and 2010. For the economic aspect, they identified two market orientations: the response to needs and the objective of being competitive on the market. For the environmental aspect, the objective is to reduce the negative impact, with an optimum of zero impact. Other notions largely used synonymously to *Eco-innovation* are *Green*, *Ecological* and *Environmental innovation*. The notion of *Sustainable innovation* broadens the concept by including the social dimension.

Although such notion of *Sustainable innovation* well describes the final aim of the framework proposed in this paper, *Eco-innovation* is the term employed by the European Commission. Indeed, we analyzed the definition of *Eco-innovation* provided by the European Commission to verify that the three pillars of sustainability are addressed. From our search, it seems that the definition changed in the last years. As pointed out in [8], which explores how the discourse of eco-innovation has been framed by the EU research funding programs Horizon 2020 since the introduction of the 2011 EcoInnovation Action Plan, the notion of eco-innovation is far from being a stable and monolithic concept. A selection of the main definitions that we found are shown in Table 1. In the first definition, the only focus is on the environmental pillar of sustainability, with the main objectives of reducing the impacts on the environment and resource efficiency. Only later is the economical pillar addressed by introducing the objective of business opportunity. The most recent definition, which is the one considered for the framework of this work, addresses the three pillars.

Year	**Definition**
2006 **[9]**	Any form of innovation aiming at significant and demonstrable progress towards the goal of sustainable development, through reducing impacts on the environment or achieving a more efficient and responsible use of natural resources, including energy
2011 **[10]**	Any innovation that reduces impacts on the environment, increases resilience to environmental pressures or uses natural resources more efficiently
2012 **[11]**	All forms of innovation – technological and non-technological – that create business opportunities and benefit the environment by preventing or reducing their impact, or by optimizing the use of resources
2023 **[12]**	Powerful instrument to protect the environment with a positive impact on the economy and society

Table 1: Definitions of *Eco-innovation* by the European Commission

III. ECO-INNOVATION FRAMEWORK

Without clear guidelines, misleading information can be given about the environmental or social impacts of technologies with the risk of *greenwashing* or *social washing*. Guidelines allow identifying how impacts are evaluated, including potential rebound effects. To position research activities and technology developments towards eco-innovation at the earliest stage of their development, we propose the visual framework shown in Figure 1.

We identify two approaches, defined as paths or arrows towards eco-innovation and based on different focuses of sustainable development. In the *Sustainable technology* path, the focus of sustainable development is on the technology itself. In the *Technology for sustainability* path, the focus is on the application.

For each path we identify three levels, with the third level common to the two paths and corresponding to eco-innovation. The three levels are not incremental steps, but rather levels of maturity in taking sustainability into account. As in this paper we adopt the strong sustainability model, for each level at least the environmental pillar must be addressed.

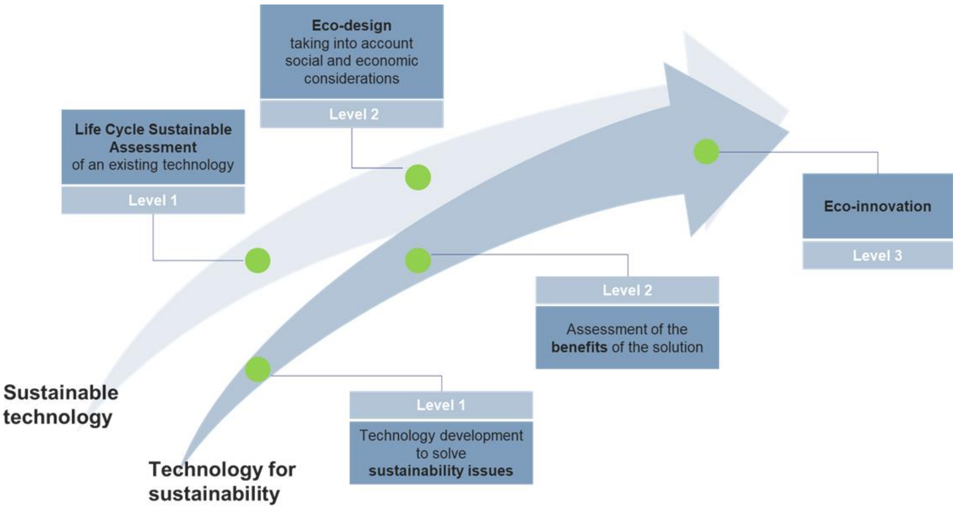

Figure 1: Eco-innovation framework

The two paths and the different levels are detailed in the following.

A. Sustainable technology

Developing Sustainable technology means focusing on reducing the direct impacts generated by the technology itself and its own value chain. These are referred to as *first-order impacts* (see Figure 2:).

Maturity level 1 of Sustainable technology consists in assessing the environmental impacts of an existing technology. In a global approach towards sustainability, the social and economic impacts can be assessed as well. A recommended method is Life Cycle Assessment (LCA), as it is a proven evaluation method which avoids impact transfer by considering all phases of a system's life and different impact categories. The LCA method has originally been proposed to evaluate environmental impacts; analogous methods exist to evaluate social impacts (Social Life Cycle Assessment) and economic impacts (Life Cycle Costing or Life Cycle Cost Analysis). One difficulty to evaluating the impacts of a technology at the early stages of design is that all design parameters, as well as the use-case may not yet be fully defined. In such a case, a parametric LCA can help project the impacts of the system under several scenarios and under different hypothesis. In addition, secondary data, generic data from different databases, is likely to be used as manufacturing information can be missing. Such a preliminary LCA is referred to as screening LCA.

Maturity level 2 involves taking into account the technology's impacts during its design, until the final version of the system. Design choices should be made to minimize their negative impacts, which requires having a design workflow including impact computation alongside other usual Key Performance Indicators (KPIs). The more details are known about the final application, the narrower the design research space can be, allowing to formulate more precise eco-design recommendations.

B. Technology for sustainability

A Technology for sustainability is a technology designed or implemented to tackle at least environmental issues during the technology lifespan. This article focuses on assessing the environmental impacts of an application and not on defining characteristics to classify applications as sustainable.

Assessing the sustainability of a technology for its application requires evaluating the *indirect impacts* of the technology, i.e. the positive or negative impacts that occurs outside the technology value chain but resulting from its use.

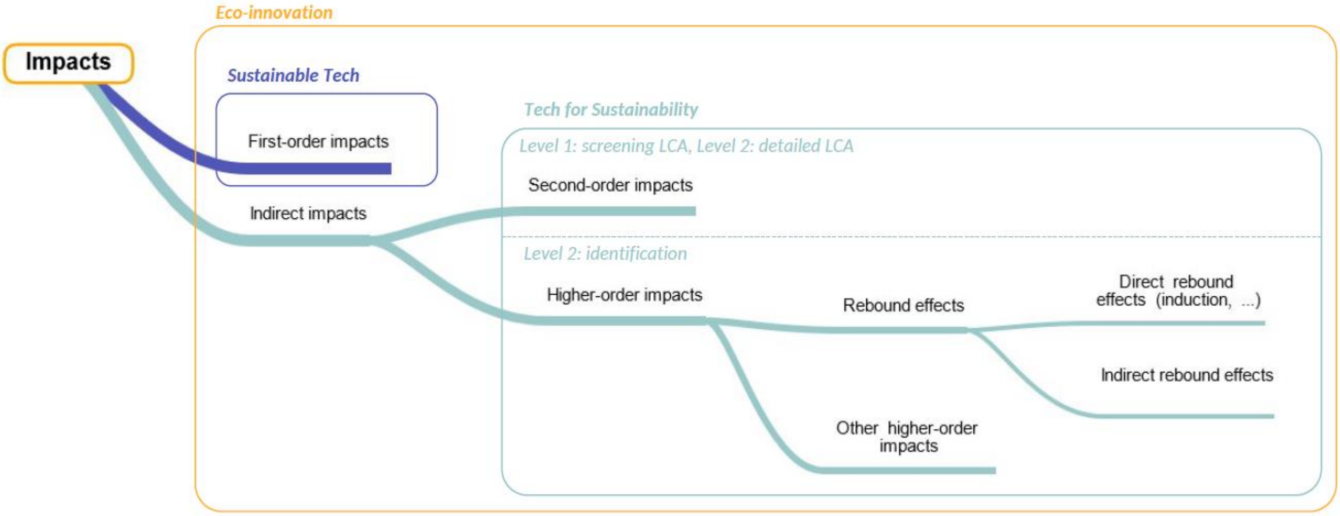

Figure 2: Impact types and mapping with maturity levels

The indirect impacts evaluation is supported by consequential LCA methodology that compares a solution enhanced by a technology with a reference scenario that would have occurred without the technology-enhanced solution deployment [13]. According to ITU-T L.1480 [14], the indirect impacts have two order levels: the *second* and the *higher orders*. The latter is also referred to as *third order* in some academic literature ([15] [16]).

The *second order* is the indirect impact created by the technology-enhanced solution, which may take effect through different impacting mechanisms such as substitution and optimization. Optimization intends to increase the efficiency of operations and processes, or intensify the use of assets and infrastructure. While the substitution mechanism aims for a positive impact by partially or completely replacing the reference scenario, the optimization mechanism can reduce its environmental impacts. Although the changes in the reference scenario differ between substitution and optimization, both mechanisms result in positive second order impact.

The *higher order* is the indirect impact triggered by changes in human behavioral patterns guided by users' lifestyles and value systems. Higher order impacts include *rebound effects*, which are twofold: *direct and indirect*. The *indirect rebound* occurs when the use of the technology-enhanced solution brings economic, time or space savings following increased efficiency gained through optimization strategies. The resources released by the indirect rebound could be reinvested to other activities that often decrease the positive impact of the technology-enhanced solution. The *direct rebound* is associated with the additional or increased usage of the technology-enhanced solution itself, due to its value proposition or advantage compared to the reference scenario. Such rebound usage is well known as *induction.* Note that ITU-T L.1480 considers the induction mechanism as part of the second order impact modeling and not higher order as presented here. This modeling decision demonstrates how the distinction between second order and higher order is not always obvious. The key would be to consider the intended effect of the technology-enhanced solution as second order while other effects not captured in the second order boundary could be interpreted as indirect rebound. Even though the induction mechanism could be categorized as an intended effect, this paper considers the induction as a rebound effect and thus includes the induction mechanism in higher order impact modeling.

By following the main guidelines of tier 3 of ITU-T L.1480, a Technology for sustainability in maturity level 1 shall consider second order impacts. In this maturity level, second order impacts are assessed by using screening LCA approach on the use phase only. Screening LCA is a first approximation and uses secondary data.

A Technology for sustainability in maturity level 2 follows the main guidelines of tier 2 of ITU-T L.1480 recommendation by assessing second order impacts using detailed LCA approach, and shall identify higher order impacts.

C. Eco-innovation

Achieving eco-innovation necessitates validating level 2 of both paths, and verifying that the sum of first order impacts, second order impacts, and higher order impacts are positive and therefore in favor of technology deployment.

IV. CASE STUDY: AI FOR HEAT PUMP

Artificial Intelligence for Heat Pump (AI4HP) is an on-going French-German ANR project consisting in using an innovative incremental Artificial Intelligence (AI) algorithm [17] [18] to be used in the command system of a Heat Pump (HP) in the perspective of better anticipating the needs in domestic hot water, and, therefore, saving energy by heating only the sufficient amount of water. This incremental AI algorithm can either be implemented in the cloud, or directly in the HP controller ('embedded computing'), either using a multipurpose Micro-Controller Unit (MCU) already present on the digital system, or by adding a dedicated AI accelerator.

This project has been chosen as a case study since it involves two reference units. The first reference unit is the AI algorithm, whose development follows the Sustainable technology path. The second focuses on the solution proposed to command the HP and belongs to the Technology for sustainability path. For both the reference units, the project currently fulfills the environmental requirements for the level 1 of the paths. The next two sections present the work done to fulfill environmental requirements for level 1, and what work needs to be done in order to comply with level 2 environmental requirements and, finally how to label this work as eco-innovation on the environmental aspect.

A. Technology for sustainability path

Maturity level 1 requires to clearly motivate the usage of the innovation to solve a sustainability problem, and to use secondary data to quantify expected positive impacts following technology deployment. For AI4HP project, a literature review has been made to outline how accurately controling an HP can lead to significant energy savings, and how much the proposed incremental AI algorithm could significantly enhance prediction accuracy compared to state of the art baselines.

One step towards level 2 has already been done as second order effects have been estimated. Indeed, laboratory tests, conducted by EDF R&D, quantified how much energy adopting AI-based control for HP could save in comparison with a baseline HP control solution, which gives second order impacts of the optimization mechanism. Those results could be transposed to estimate the second order impacts of substitution mechanism by comparing AI-based controlled HP with other domestic water heating systems. Remaining work to fulfill level 2 requirements is to identify higher order effects. In this extent, employing a consequential LCA could help to understand indirect rebound effects of deploying AI controlled HP, such as:

- How the money saved from energy reduction can be spent, and how this new spending could affect environmental and/or social impacts;
- How the perspective of saving money could increase the market share of HPs, thus potentially replacing more carbon intensive domestic water heating solutions, and how this substitution could help EU to fulfill its decarbonation strategy. This indirect rebound effect would be classified as 'economy-wide' by Horner *et al* taxonomy [16].

Maturity level 2 could be validated only if the results of such a consequential LCA is favorable to the technology's deployment.

B. Sustainable technology path

Level 1 involves using all the information available about the innovation and, if possible, its application, to take a snapshot of its sustainability impacts. A screening life cycle assessment has been carried out. As a great number of algorithm design and hardware implementation options remain open, this LCA is parametric in order to cover the different foreseen scenarios. One result of this LCA is the environmental impact of the AI algorithm function of the neural network size and computational complexity (measured in floating point operations (FLOPs) per inference), both for cloud computing with various cloud providers and virtual machine configurations, and embedded computing, with various digital system design assumptions.

In order to fulfill level 2 requirements, this parametric LCA should be used during further design cycles of the AI algorithm to minimize its environmental impacts while validating other KPIs, such as accuracy and performance. Several strategies such as pruning or quantization could be tested in order to study their consequences on all the KPIs, including environmental ones. It is important to note that various non-technological LCA parameters, such as average electrical mix of targeted consumers, or expected lifetime of the product have to be estimated to be able to conclude on the definitive algorithm and hardware design.

C. Eco-innovation

Providing that level 2 requirements of both paths have been validated, and that balance of environmental costs and benefits are in favor of technology's deployment, AI4HP work could be referred to as eco-innovation. Table 2 summarizes validated and missing requirements.

	Tech for sustainability	Sustainable tech
Level 1	**Done** Literature review to quantify how much energy a HP controlled using incremental AI algorithm could save compared to state of the art solutions.	**Done** Parametric LCA to compute environmental impacts of the technology, covering all foreseen design solutions and implementation scenarios.
Level 2	**Done** Laboratory tests to measure the energy gain of HP when using the technology compared to baseline solution. **To do** Consequential LCA to identify high order effects of the deployment of an AI controlled HP. Level 2 would be achieved only if conclusions are in favor of technology's deployment.	**To do** Use parametric LCA developed in level 1 to compare various designs and implementation solutions and choose the optimal one.
Eco-innovation	**To do** Using results of both path's level 2, demonstrate that environmental benefits of eco-designed technology's deployment exceed its costs.	

Table 2: Application of the eco-innovation framework to the case study AI4HP

V. CONCLUSIONS AND PERSPECTIVES

Nowadays, in a context of growing concerns about sustainability, there is also increasing confusion about different terminology and notions related to sustainable development of technology and eco-innovation. This paper aims to contribute to a clarification of the concepts and proposes a solution to structure the possible approaches linking technology and sustainability towards eco-innovation.

An open point of the framework, that can be discussed in future works, concerns the classification of sustainability for the applications of technology. In other terms, guidelines or criteria are required to establish which applications can be considered sustainable. Another perspective of this work concerns the assessment of social impacts for the evaluation of the maturity levels taking into account the social pillar. Regarding the assessment of higher order impacts, the current paper proposes to identify the rebound effects of a technology-enhanced solution. This qualitative approach is a first step towards a more detailed quantification that should be addressed in future works, where methodologies for assessing economic and social rebound effects could also be considered.

ACKNOWLEDGMENT

This work was partially supported by the EECONE project, that received funding from the Chips Joint Undertaking under grant agreement 101112065.

The authors would like to thank Marina Reyboz and Hugues Bosche, who work on the AI4HP project, for the information provided and their help.

REFERENCES

[1] World Commission on Environment and Development, «Our common future,» 1987.

[2] J. Elkington, «Accounting for the Triple Bottom Line,» Measuring Business Excellence, 1998.

[3] R. Goodland, Encyclopedia of global environmental change, Wiley & Sons, 2002.

[4] B. Penzenstadler et H. Femmer, «A generic model for sustainability with process- and product-specific instances,» GIBSE, 2013.

[5] B. Giddings, B. Hopwood et G. O'Brien, «Environment, economy and society: Fitting them together into sustainable development,» Sustainable development, 2002.

[6] C. Diaz-Garcia, A. Gonzalez-Moreno et F. Saez-Martinez, «Eco-innovation: insights from a literature review,» Innovation: Management, Policy & Practice, 2015.

[7] T. Schiederig, F. Tietze et C. Herstatt, «Green innovation in technology and innovation management - an exploratory literature review,» R&D management , 2012.

[8] L. Colombo, M. Pansera et R. Owen, «The discourse of eco-innovation in the European Union: An analysis

of the Eco-innovation Action Plan and Horizon 2020,» Journal of Cleaner Production, 2019.

[9] European Commission, «Decision No 1639/2006/EC of the European Parliament and of the Council of 24 October 2006 establishing a Competitiveness and Innovation Framework Programme (2007 to 2013),» Official Journal of the European Union, 2006.

[10] European Commission, « Innovation for a sustainable future — the eco-innovation action plan (Eco-AP),» Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, 2011.

[11] European Commission, «Eco-innovation: the key to Europe's future competitiveness,» Publications Office, 2012.

[12] European Commission, «Green Business,» [En ligne]. Available: https://green-business.ec.europa.eu.

[13] World Business Council for Sustainable Development, «Guidance on Avoided Emissions,» 2023.

[14] International Telecommunication Union, «Recommendation ITU-T L.1480,» ITUPublications, 2022.

[15] A. Ligozat, J. Lefevre, A. Bugeau et J. Combaz, «Unraveling the hidden environmental impacts of AI solutions for Environment Life Cycle Assessment of AI solutions,» Sustainability, 2022.

[16] N. Horner, A. Shehabi et I. Azevedo, «Known unknowns: indirect energy effects of information and communication technology,» Environmental Research Letters, vol. 11, 2016.

[17] P. Compagnon, A. Lomet, M. Reyboz et M. Mermillod, «Domestic hot water forecasting for individual housing with deep learning,» Joint European Conference on Machine Learning and Knowledge Discovery in Databases, pp. 223-235, 2022.

[18] M. Mainsant, M. Mermillod, C. Godin et M. Reyboz, «A study of the Dream Net model robustness across continual learning scenarios,» IEEE International Conference on Data Mining Workshops (ICDMW), pp. 824-833, 2022.