



Original Research Article

From Prototypes to Living Labs: Advancing Sustainability Education in Rwanda and Côte d'Ivoire

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ABSTRACT

This paper evaluates the outcomes of two projects, "Industry-Integrated Dual Engineering Studies in a North-South Collaboration" in Côte d'Ivoire and "Growing Rwanda Energy Awareness Through Higher Education" in Rwanda. The first project has implemented a dual-study Master's program at the partner university in Côte d'Ivoire, integrating industry requirements into academic training. This curriculum incorporates a practice-oriented approach through the development of a prototype for a renewable energy and water treatment system, fostering sustainable solutions to local challenges. The second project in Rwanda focuses on implementing Living Labs, real-world environments that integrate renewable energy systems, community engagement, and educational innovation. Their integration into universities' study programs has enhanced hands-on learning and raised awareness about renewable energy solutions. Both projects establish Living Labs within the education system. The implemented systems include photovoltaic installations of up to 6.6 kWp and provide energy and water services to communities of up to 500 inhabitants while simultaneously supporting hands-on engineering education.

KEYWORDS

Living Labs, Practice-oriented learning, Sustainability education, Renewable energy, Sustainable Development Goals (SDGs), Dual-study programs, Academia-industry collaboration.

INTRODUCTION

The transition towards sustainable energy systems and climate-resilient societies requires not only technological innovation but also robust educational frameworks that equip future professionals with the knowledge and practical skills needed. In many regions of Sub-Saharan Africa, however, higher education institutions face challenges in providing practice-oriented training in fields such as renewable energy, sustainability, and energy efficiency. This paper examines how educational innovation and applied learning approaches can help address these challenges. After outlining the broader sustainability and educational context, the following sections present the specific challenges faced by higher education systems in Rwanda and Côte d'Ivoire, introduce the two case-study projects analysed in this paper, and discuss the theoretical foundations of Living Labs and experiential learning that underpin the implemented approaches.

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Renewable Energy Potential in Africa

Sustainability has become one of the most important principles in combating climate change and managing the transition to renewable energy. The African continent has by far the highest technical renewable energy potential for 2050, as shown in [Figure 1 \[1\]](#). With an estimated total technical potential for renewable energies worldwide of almost 12 EJ in 2050, Africa can cover 5.4 EJ. That means around 45% of and more than 50 times the worldwide primary energy demand in 2007 [\[1\]](#). Many African countries already have a relatively high share of renewable energy in the electricity sector, but still rely mainly on fossil fuels for cooking and transport [\[2\]](#). For example, Kenya had a 90% share of renewable energy in the electricity production in 2024, while the overall energy matrix still consisted of 80% fossil fuels [\[3\]](#). The challenges of climate change and sustainability goals make it crucial for African countries to increase their energy independence [\[4\]](#). This trend can be best achieved by exploiting their extremely high renewable energy potential [\[5\]](#). By generating their own energy, they can be more self-sufficient and less dependent on grids or energy imports. This autonomy can make them less vulnerable in times of crisis, for example, due to climate change [\[6\]](#).

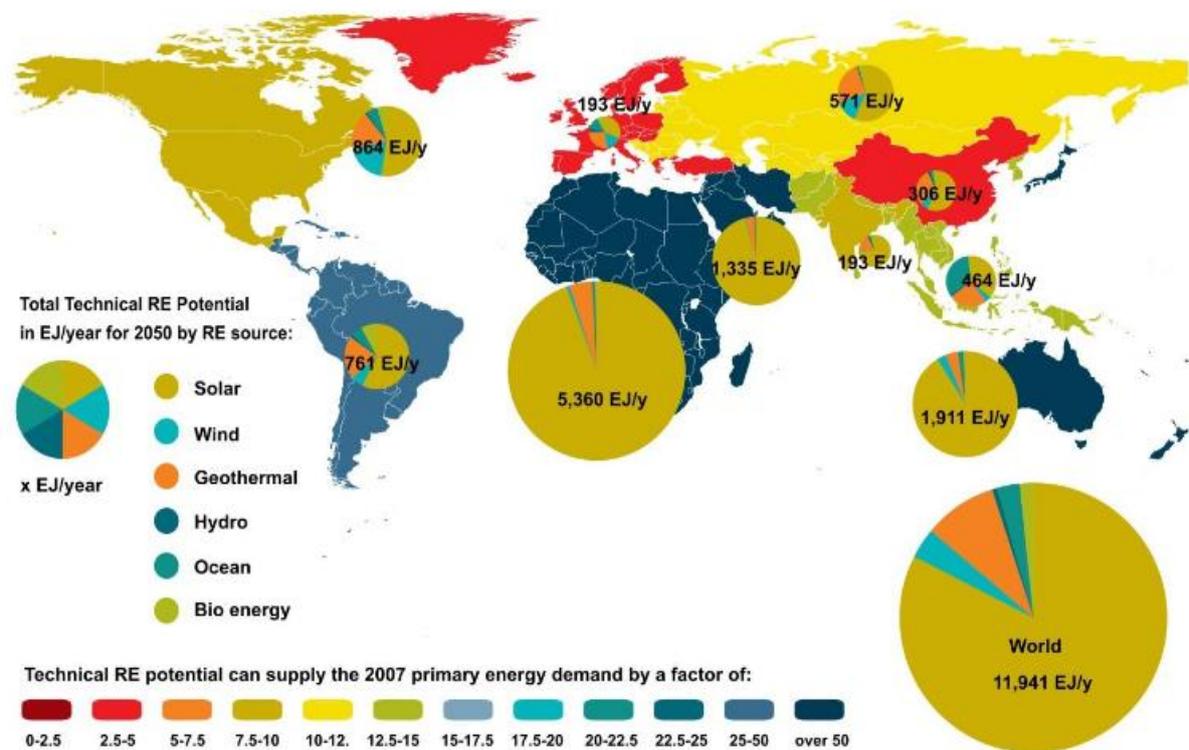


Figure 1. Technical renewable energy potential worldwide for 2050 [\[1\]](#)

Educational Challenges in Rwanda and Côte d'Ivoire

A key factor in increasing sustainability and, therefore, successfully tackling climate change in the long term is education [\[7\]](#). For this reason, the paper will focus on improving educational quality through practice-oriented approaches, which many education systems in African countries still lack [\[8\]](#). The main reasons for the lack of practical training in those countries' education systems include, among others, the shortage of teachers and professors with practical experience [\[9\]](#) and limited collaboration between academia and industry [\[8\]](#). The shortage of equipment at universities also plays an important role [\[10\]](#), as students must learn technology through hands-on experience. This practical experience is only possible with consumables [\[11\]](#), which students will wear out over time. In African countries, the procurement and replacement of those consumables are often too expensive, or the equipment

is unavailable altogether. This situation also causes a lack of practice-oriented learning in higher education [12].

Furthermore, topics such as sustainability and energy efficiency should be taught from a young age to reach more people and broaden the scope [13]. In this way, universities can teach their students more easily in those subjects by building on the existing knowledge base and eventually create skilled workers [14]. Since many countries in Africa still have high school dropout rates [15], raising awareness of sustainability, climate change, and renewable energy, and teaching people the basics of energy efficiency, often pose additional challenges [16]. With higher energy efficiency, the total energy demand of developing countries can be reduced, or their growth slowed, despite population growth and overall increasing energy consumption [17].

In the following, some characteristic figures for the education systems in Rwanda and Côte d'Ivoire will be presented, showing that each system comes with its own challenges. Despite improvements, educational quality in Rwanda remains a challenge, with children often failing to acquire practical skills or relevant knowledge from formal education, partly because effective learning years are fewer than the actual years spent in school [18]. Current data still indicate that a substantial number of school-age children and adolescents remain out of school in Rwanda due to poverty, early pregnancies, or low parental involvement [19]. The enrolment ratio for tertiary education, including universities in Rwanda, remains low, especially among women [20]. In Côte d'Ivoire, the primary school completion rate in 2022 was below 70 % [21]. Lower secondary completion rates were below 40 %, indicating a significant dropout rate between primary and lower secondary education [22]. In 2020, children in Côte d'Ivoire were expected to complete eight years of schooling by age 18 [23]. Gross enrolment in tertiary education was only around 11 % in total for both sexes in 2022 [24].

Case Study Projects

To address the above-mentioned challenges and find possible solutions, two projects have been implemented. Both projects, "Industry-Integrated Dual Engineering Studies in a North-South Collaboration" (IIDES-NSC) in Côte d'Ivoire and "Growing Rwanda Energy Awareness Through highER Education" (GREATER) in Rwanda, serve as case studies for the analysis in this paper. It is important to note that IIDES-NSC has already been successfully implemented, while GREATER is still ongoing for another year. Both projects aim, among other things, to contribute to SDG 7, "Clean and affordable energy," and SDG 4, "Quality education" [25]. Since both countries, Côte d'Ivoire and Rwanda, have their own history, culture, political systems, geographical conditions, and education systems, this must be taken into account when transferring the projects' methods or results to other countries. As transferability is limited, only some aspects can be transferred, as explained in the results and conclusions sections of this paper.

Living Labs and Educational Theory

The implementation of Living Labs in this context is theoretically grounded in experiential learning theory and open innovation. By shifting from traditional classroom settings to real-world labs, the projects facilitate a "learning-by-doing" approach where students bridge the gap between abstract sustainability concepts and practical application. This trend aligns with innovation theory by positioning the university as an incubator that co-creates knowledge with local stakeholders, transforming academic research into community-driven technological solutions. According to Kolb's experiential learning theory, knowledge is created through the transformation of experience, combining concrete experience, reflective observation, abstract conceptualisation, and active experimentation [26]. Living Labs operationalise this pedagogical cycle by embedding students in real-world sustainability challenges where theory and application interact iteratively.

Furthermore, Living Labs can be understood within the framework of open innovation and quadruple helix models, which emphasise collaboration between academia, industry, government, and civil society. By integrating these actors into co-creation processes, Living Labs function as intermediary innovation spaces that foster socio-technical transitions toward sustainability. In sustainability education, such approaches align with transformative learning theory, which suggests that exposure to real-world complexity enables learners to reassess assumptions and develop systemic problem-solving competencies critically. Therefore, the projects presented in this study are not merely infrastructural interventions but pedagogical innovations embedded in sustainability transition theory.

Against this background, the following sections analyse how the presented projects address these challenges through practice-oriented sustainability education.

METHODS

The literature review in the introduction identifies the lack of energy infrastructure, practice-oriented learning, and sustainability education in African countries. It also analysed the connection between those topics and presented possible measures to solve the resulting challenges. This paper focuses on the measures implemented in the two projects, IIDES-NSC and GREATER, and examines their impacts by examining their interdisciplinary approaches and results. As shown in **Figure 2**, the evaluation is embedded in a circular process that compares the preceding research on the state-of-the-art [27] with both projects' results.

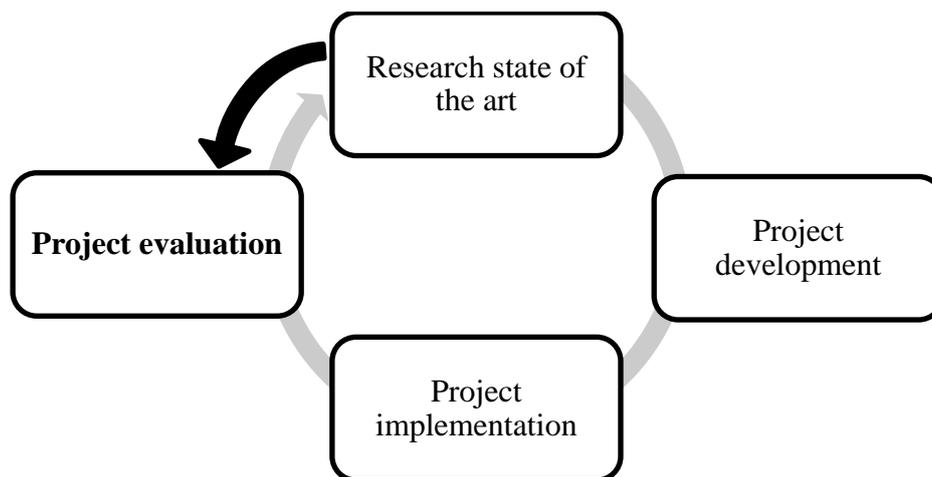


Figure 2. Four phases of a project cycle

This study evaluates both projects using a qualitative case study approach combined with stakeholder-based requirement analysis. In **Figure 2**, this is shown as the fourth phase of the project cycle. Based on the previous research conducted prior to the project idea development [28], this paper will analyse how the projects have been implemented and the results or impacts achieved so far. Each project will be evaluated separately in this paper. Before this evaluation, the methods used similarly in both projects will be explained in the following.

Methodical Approach of the Projects

One goal of the projects is to integrate practice-oriented education into education systems. To achieve this, new study programs were implemented, or existing ones were revised at the partner universities, together with local stakeholders. By doing this, new and long-term collaborations with key stakeholders from industry, politics, and local communities can be established to identify gaps in the existing education system continuously. Those new or revised study programs focus on subjects such as energy efficiency, renewable energy and sustainability, thereby enhancing educational quality and raising standards. Another goal of the

projects is the design and implementation of so-called “Living Labs” by students and staff who are integrated into the education system through the new study programs.

Living Labs, in this case, are real-life locations, accessible to schools, universities, industry and local communities. They function as an education platform, from which all stakeholders can benefit. Living Labs allow students from schools and universities to experiment and learn in a realistic environment [29]. At the same time, they provide a strategic hub for community engagement, allowing local residents to get in touch and familiarise themselves with green technologies [30]. Additionally, the deployment and integration of Living Labs into education systems and communities can help raise awareness [31] of topics such as climate change, renewable energies and sustainability. Their overall goal is to serve as a multi-purpose facility that addresses the above-mentioned educational challenges on different levels.

User-Centred Design Approach

The so-called “user-centred design” (UCD) was used to identify and define the requirements of the Living Labs. UCD is a framework of processes that gives extensive attention to the usability goals, user characteristics, environment, tasks, and workflows of a product, service, or brand at each stage of the design process [32]. It is based on understanding a user’s demands, priorities, and experiences, and can lead to increased usability [32]. UCD differs from other product design philosophies, as it aims to optimise the product based on how users engage with it [33]. The goal is that users are not forced to change their behaviour and expectations to accommodate the product [31]. With this approach, different stakeholder groups, including universities (lecturers, staff, students), local industry (companies, energy providers), political institutions (government and ministries), and local communities, were involved throughout the design and implementation of the Living Labs.

By conducting surveys, interviews and workshops, the partner universities gained insights into their needs and expectations. First, the project partners conducted on-site surveys and interviews to collect data, which were then added to the project’s data collection platform. Specific online questionnaires were jointly designed by the partner universities and distributed to the different stakeholders. It was mandatory to reach a minimum of 10 participants from each stakeholder group mentioned above, resulting in approximately 50 participants per cycle. Stakeholders getting tired of being interviewed was avoided by reducing the number of questions in each cycle and providing advance notice of the planned number of questionnaires. The results of the first questionnaires were analysed with open-source software and evaluated in a workshop together with the project partners. The evaluation results were then used to develop new questions, eliminate questions or alter them based on the previous answers. Based on that, a new questionnaire was developed, distributed to the same stakeholder group within one month and evaluated afterwards. This iterative process was repeated three times until the results were detailed enough to continue with the design phase.

RESULTS AND DISCUSSION

This section of the paper presents and discusses the results of both projects. The project IIDES-NSC included a students’ pilot project to design a prototype at the partner university Université Nangui Abrogoua (UNA) in Côte d’Ivoire, as a basis for the first Living Lab. The design and implementation processes were carried out by a group of 10 students, who were the first cohort of the newly implemented dual-study Master’s program at UNA. It was supervised jointly by the German and the Ivorian project partner universities and supported by local industry and non-governmental organisations (NGOs). After testing the prototype at UNA, the students’ design was adapted to the requirements of rural areas and the Living Lab was put into operation at the village of Legroskro in Western Côte d’Ivoire. Based on the experiences from the project IIDES-NSC, the design for the Living Labs was improved and further developed in the project GREATER. With four Rwandan partner universities participating in this project,

the aim is to implement four Living Labs with the same basic structure, showing different use cases. All of them are connected to each other through a central data cloud and monitoring system.

Project in Côte d'Ivoire

The prototype design for the Living Lab at UNA was carried out by students during the Master's study program in a practice or project phase. An overview of the system as it is implemented on campus is shown in **Figure 3**. The prototype consists of two main parts: a photovoltaic system for electricity generation, and a borehole with a water pump and reservoir for water distribution. The electrical installations are inside an overseas container, including a battery, an alternating current/direct current (AC/DC) converter, an inverter and wiring. The photovoltaic (PV) panels are mounted on the container roof with two panel strings connected in parallel. Next to the container is the borehole with a solar-powered water pump, and a scaffolding with the water reservoir on top. The water distribution system consists of a water faucet directly connected to the reservoir for domestic water. Another water faucet is connected to an ultraviolet (UV) filter system for water treatment, allowing the water to be used for drinking.

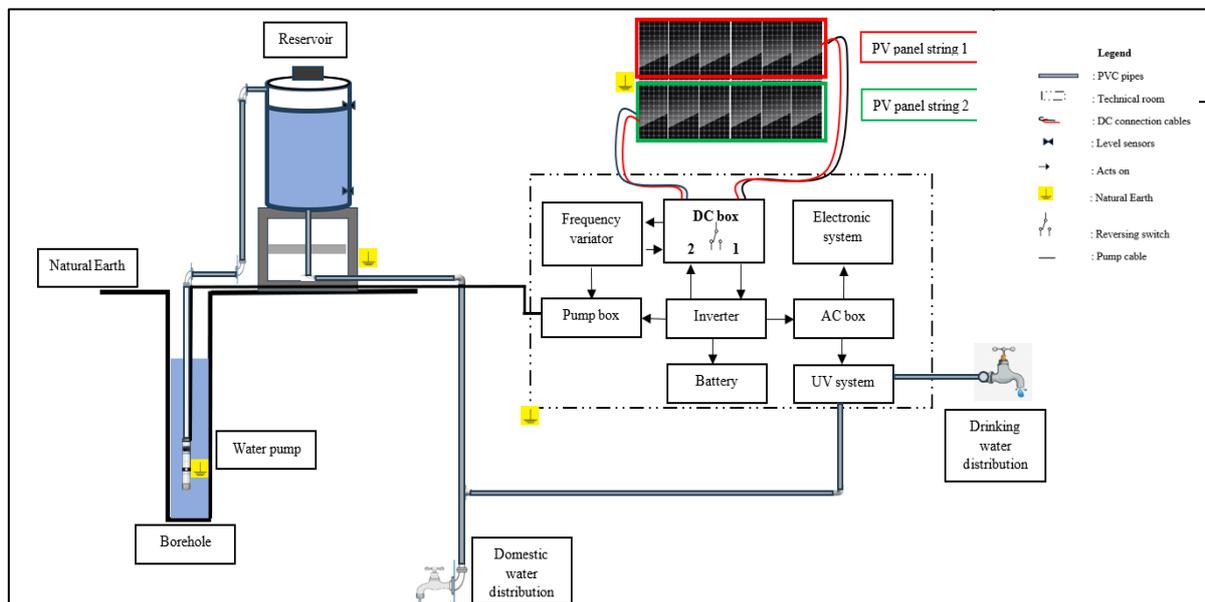


Figure 3. General system overview of the prototype at UNA

After successfully installing the prototype at UNA, the student group further developed and adapted its design to the needs of the rural area around the village of Legroskro. An adjustment was to use a flexible building structure instead of a heavy, expensive container, so the construction can be easily extended in the future. Regarding domestic water distribution, several water faucets were installed so that people in the village can use them simultaneously and avoid queues, since Legroskro has around 500 inhabitants. Furthermore, another water outlet was added at an approximate height of 2 metres above ground level. This requirement resulted from the UCD and enables local people to fill buckets placed on their heads while standing, preventing them from lifting heavy objects or spilling water while doing so. With the adaptations mentioned above, the Living Lab was implemented according to the model shown in **Figure 4**. The system consists of 12 solar panels, connected in two parallel strings of 6 panels each. With a panel power of 550 W, the PV system has a total power of 6.6 kWp, and the lead-acid battery has a capacity of 10 kWh.



Figure 4. Living Lab model for project IIDES-NSC

The Living Lab has been operating for almost one year and has already shown improvements in the area. Before, there was neither a grid electricity supply nor any off-grid electricity systems. The PV system on the roof of the Living Lab has provided a continuous electricity supply for a refrigerator, enabling local people to store and preserve food, and for the mobile charging station. It also generates enough electricity during the day to charge the battery. With this battery, four LED floodlights can be supplied during nighttime, two in the vicinity of the Living Lab and one at each end of the village. Additionally, the PV system powers the water pump to keep the water tank filled and maintain drinking water treatment. The pictures in [Figure 5](#) show the operating Living Lab in the village of Legroskro after the inauguration in 2024. The picture on the left side shows the PV system and the water tank; the picture on the right side shows the water distribution system.

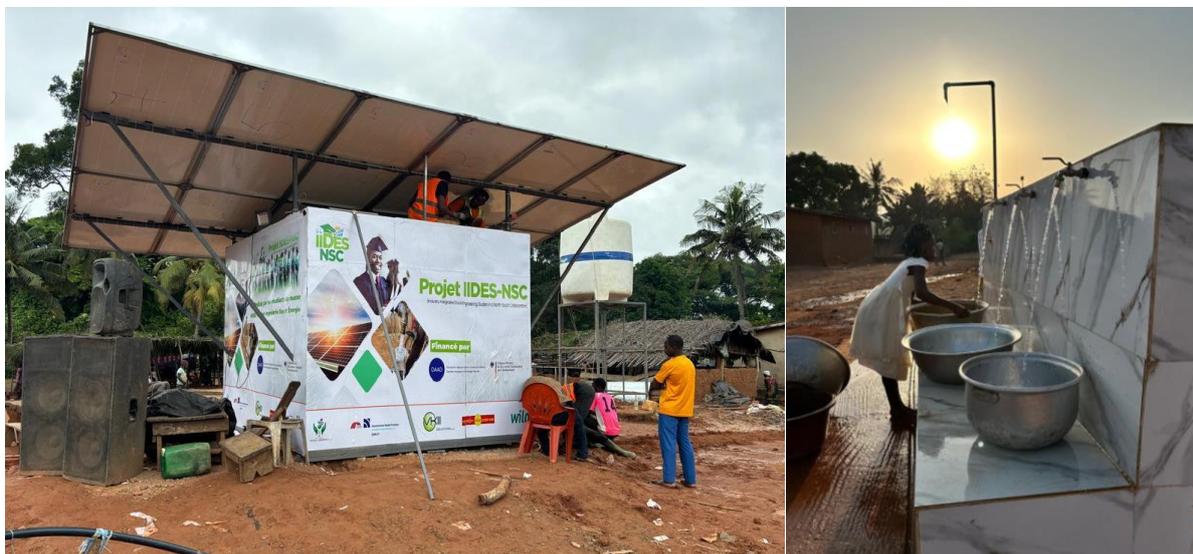


Figure 5. Operating Living Lab in Legroskro, Côte d'Ivoire; source: Derval Toukam

The prototype at UNA is currently serving students in different engineering study programs in their educational path. They can learn from the prototype through practical exercises and data analysis. The study programs also include projects in which student groups must improve the architecture of the Living Lab, assist communities in maintaining it, and implement further similar Living Labs in other rural areas of Côte d'Ivoire. Furthermore, a research group at UNA is currently investigating the new water source of the prototype on campus for possible usage in

the agricultural sector. This research project strengthens cooperation between different faculties and benefits both the engineering and the agricultural departments.

Project in Rwanda

For the GREATER project in Rwanda, the same process was used to design and implement the Living Labs. The UCD approach, with several rounds of questionnaires and feedback loops, led to an overall catalogue of general requirements for a Living Lab. Although the specific designs and use cases are individual and very different from each other, this catalogue can be used as a basic design. The basic design of a Living Lab consists of a building or container with an off-grid, stand-alone energy system powered by renewable energies. All Living Labs are to be equipped with PV systems as they are the most affordable and flexible renewable energy technology available in Rwanda. The necessary electrical installations, as well as basic consumer devices such as lights, internet access devices, electrical sockets, measuring devices, a monitoring system with remote access and some experimental stations or showcases are installed inside the Living Lab. Additionally, it includes a real-life use case, which does not necessarily have to be located inside the building. This use case is supplied with electricity generated by the renewable energy system.

Through the UCD approach, each of the four partner universities decided on a use case they want to analyse with their Living Lab:

1. Water pump and smart-irrigation system for agriculture;
2. Off-grid electricity supply for a village;
3. Laboratories and classrooms for a secondary school;
4. Community centre with solar cooking and a tailoring workshop.

One upgrade from the Living Lab in the project IIDES-NSC is the interconnection of the different Living Labs in the project GREATER. This means each Living Lab will be equipped with a locally installed monitoring and control system inside the building. This system collects data from the electricity generation and on-site measurement systems. The collected data will be sent from each Living Lab to a central cloud that is managed by the universities. Thus, each university will have remote access to the Living Labs and will be able to monitor, analyse and evaluate the data. The general architecture of this ecosystem is shown in **Figure 6**.

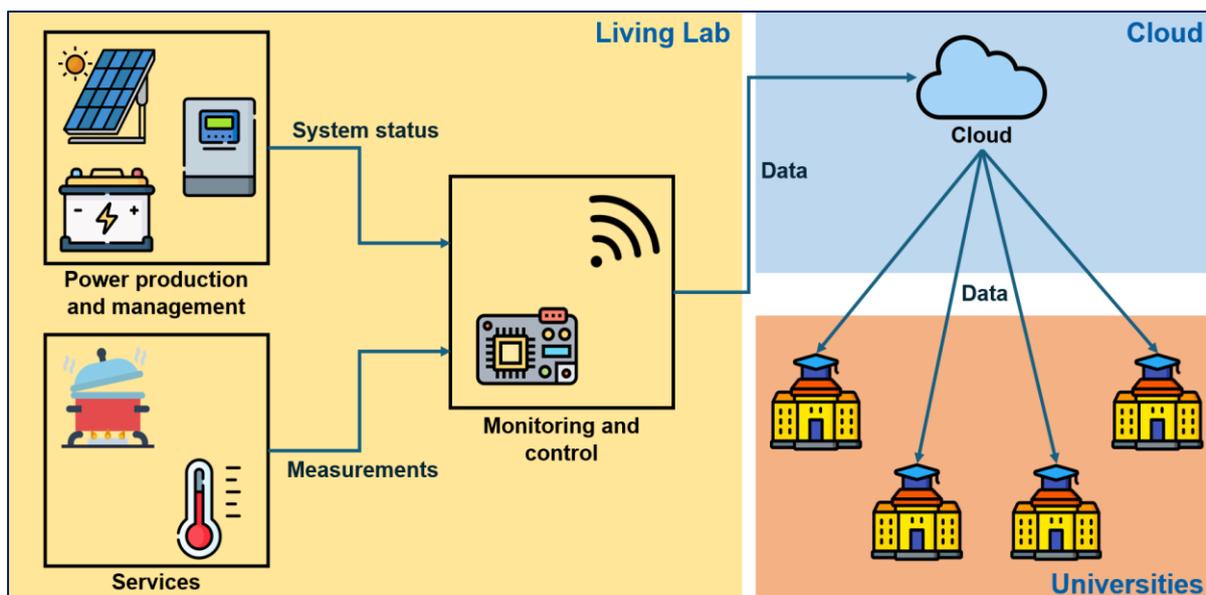


Figure 6. Architecture of the Living Lab ecosystem in Rwanda [34]

By installing a standardised monitoring and control system in every Living Lab, it will be easier to connect them all to one central cloud service that all universities can use. With this

approach, the universities can still access all Living Labs individually, without issues related to software or interface compatibility. As a result, students from different study programs at all partner universities will be able to do on-site experiments and learn, for example, how to monitor, analyse and evaluate data. Lecturers can integrate interdisciplinary projects into their study programs, in which student groups will maintain existing Living Labs, improve the architecture and even identify additional use cases to be investigated for new Living Labs. In addition, universities and schools will host local events around the Living Labs to raise public awareness of topics such as climate change, renewable energy, and sustainability. In this way, they will serve as a community centre with strong public relations and, at the same time, as an education platform not only for students but also for younger people, such as schoolchildren.

Performance Indicators and Comparative Evaluation

To facilitate a deeper comparative analysis between the two projects, several key performance indicators (KPIs) were defined, as shown in [Table 1](#).

Table 1. Educational, technical and community KPIs for both projects

KPI	Category	IIDES-NSC	GREATER
Students directly involved	Education	10	80
New or revised study modules	Education	21	94
Interdisciplinary projects	Education	1	2
Community members accessing services	Community	500	350
Public outreach events conducted	Community	6	9
Installed PV capacity	Technical	6.6 kWp	24 kWp
Number of end-users supplied	Technical	500	120

Compared to the IIDES-NSC project, the GREATER project demonstrates higher systemic integration through digital interconnection and cross-university collaboration. However, the project in Côte d'Ivoire has a deeper local infrastructural impact due to the direct provision of water and electricity to an off-grid village. While IIDES-NSC emphasises prototype-to-implementation transfer, GREATER prioritises networked Living Lab ecosystems and data-driven educational integration.

CONCLUSION

The projects discussed in this paper, IIDES-NSC in Côte d'Ivoire and GREATER in Rwanda, highlight the transformative potential of integrating industry-driven education models into sustainability-focused higher education. These programs exemplify how universities can serve as incubators for innovation and skill development in renewable energy and sustainability by effectively bridging the gap between academic training and practical industry needs. The findings confirm that Living Labs can operationalise experiential learning approaches by integrating theoretical knowledge with real-world experimentation in sustainability education.

The goal of IIDES-NSC is to show that dual-study programs integrating theoretical education with hands-on industry experience enhance students' employability and directly contribute to the renewable energy sector. Through collaboration with UNA and local industry partners, a dynamic learning environment can be fostered using the prototype and the Living Lab, equipping graduates with both technical expertise and real-world problem-solving capabilities. Meanwhile, GREATER aims to reinforce the role of Living Labs in facilitating

experiential learning, allowing students to engage in applied research and directly contribute to Rwanda's energy transition goals.

Limitations and Transferability

Despite the promising results presented in this study, several limitations should be acknowledged. First, stakeholder participation in the UCD process was limited in number and may therefore not fully represent the diversity of perspectives within the respective national contexts. Although multiple stakeholder groups were involved, like universities, industry representatives, political institutions, and local communities, the sample size remained relatively small due to logistical and project-related constraints.

Second, the UCD process itself was limited to three iterative cycles within the available project timeframe. While this iterative approach allowed for continuous refinement of the Living Lab concepts and ensured stakeholder involvement in the design process, additional iterations could potentially have generated more detailed requirements and stronger validation of the design choices. Furthermore, the survey instruments used in the questionnaires were developed collaboratively within the project consortium but were not externally validated with independent stakeholder groups. While this approach ensured contextual relevance and stakeholder ownership, it may limit the statistical robustness and generalisability of the results.

Another limitation concerns the evaluation timeframe. Long-term technical and socio-economic performance data are currently not available, particularly for the Living Labs implemented within the GREATER project, which are still under development. As a result, the present study focuses on early implementation outcomes and educational impacts rather than long-term operational performance or sustainability of the infrastructure.

Contextual factors also play an important role in the success of such initiatives. Institutional commitment, funding availability, technical capacity, and local governance structures differ significantly between countries and regions. These factors influence the feasibility and effectiveness of implementing Living Labs and industry-integrated educational models.

Therefore, direct transferability of the specific project implementations to other regions in Sub-Saharan Africa is limited. However, the methodological framework developed in this study, combining stakeholder co-creation through UCD, integration of Living Labs into academic curricula, and collaboration between universities, industry, and communities, represents a transferable approach that can be adapted to different local contexts. Future research should prioritise longitudinal studies to evaluate the long-term educational, technical, and socio-economic impacts of Living Labs and to assess their sustainability beyond the duration of externally funded projects.

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This research was conducted within the framework of two collaborative projects that have greatly contributed to the development and implementation of the ideas presented in this paper.

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The success of this research would not have been possible without the collaboration, trust, and shared commitment of all these institutions and individuals. We are sincerely grateful for their support.

NOMENCLATURE

Abbreviations

AC	Alternating Current
DC	Direct Current
GmbH	Gesellschaft mit beschränkter Haftung
GREATER	Growing Rwanda Energy Awareness Through highER education
IIDES-NSC	Industry-Integrated Dual Engineering Studies in a North-South Collaboration
kWh	Kilowatt hour
kWp	Kilowatt peak
LED	Light-Emitting Diode
PV	Photovoltaic
SDGs	Sustainable Development Goals
SE	Societas Europaea
UCD	User-Centred Design
UNA	Université NANGUI Abrogoua

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