The Role of Living Labs in Accelerating Smart and Energy-Efficient Solutions

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***Abstract* — The INNOFEIT Living Lab, hosted by the Center for Technology Transfer and Innovation at the Faculty of Electrical Engineering and Information Technologies in Skopje, represents a dynamic open innovation ecosystem focused on smart energy systems. Operating under the Quadruple Helix model, it facilitates co-creation among academia, industry, government, and citizens in a real-life environment. Equipped with advanced infrastructure—such as solar energy systems, battery storage, electric vehicle charging, IoT labs, and smart control systems—the lab directly supports the development and testing of sustainable technologies aligned with SDG 7 (affordable and clean energy) and SDG 12 (responsible consumption and production). This paper explores the structure, objectives, and innovation methodologies of the INNOFEIT Living Lab, positioning it as a scalable model for user-driven energy research and as a strategic instrument within the broader European energy transition framework.**

Keywords— Living Lab; Smart Energy Systems; Open Innovation; Sustainable Development Goals

I. INTRODUCTION

The global shift towards sustainable development and energy efficiency has intensified the need for innovation models that align technological advancements with real societal needs. In this context, Living Labs (LLs) have emerged as a promising frameworks for fostering user-driven, open innovation in real-life settings [1], [2]. By involving stakeholders from academia, industry, public institutions, and civil society, LLs enable the co-creation, experimentation, and validation of new energy solutions within actual environments—addressing limitations often present in traditional, isolated research settings [3].

In the domain of smart energy systems, Living Labs present notable advantages. They facilitate real-time data acquisition, iterative testing, and user feedback loops that are essential for deploying advanced energy technologies. For example, the ENERGISE project illustrated how subtle behavioral changes in household heating and laundry routines, introduced through a LL framework, contributed to measurable reductions in energy consumption and supported long-term habit shifts [4], [5]. University-based initiatives such as the University of British Columbia's Campus as a Living Lab further demonstrate the practical integration of renewable energy technologies into academic settings—enhancing education and reducing institutional carbon footprints [6].

However, despite their potential, LLs face significant implementation challenges. These include the absence of standardized conceptual and evaluation frameworks [7], governance complexities among heterogeneous stakeholders [8], and limitations in funding continuity and scalability [9]. This creates difficulties in cross-comparing LL outcomes and limits their broader applicability in energy transitions.

Yet, momentum continues to build. Research increasingly points to the importance of developing shared methodological standards [7], enhancing cross-sector integration, and embedding LLs within institutional and urban ecosystems [10] – [14]. These improvements are crucial for transitioning LLs from fragmented pilots into key instruments of energy policy and innovation [15].

Against this backdrop, the INNOFEIT Living Lab, launched by the Center for Technology Transfer and Innovation at the Faculty of Electrical Engineering and Information Technologies in Skopje, North Macedonia, offers a localized and strategic response. Focused on smart energy systems, it brings together academia, industry, and government actors to co-create and test advanced energy solutions. This paper explores Living Lab methodologies in the energy domain, discusses their benefits and limitations, and positions the INNOFEIT Living Lab within this evolving innovation landscape.

II. THE INNOFEIT LIVING LAB CONCEPT

The Center for Technology Transfer and Innovations, known as INNOFEIT (Fig.1), is an autonomous legal entity under the ownership of the Ss. Cyril and Methodius University in Skopje, operating within the Faculty of Electrical Engineering and Information Technologies. Since its inception in 2018, INNOFEIT has served as the central point for technology transfer and as a leading research and development hub within FEEIT. INNOFEIT aims to consolidate and streamline R&D for the industry under a single roof, thereby eliminating fragmentation and enhancing collaboration. This centralization is particularly significant given FEEIT's strong reputation in international research, which INNOFEIT continues to build upon. With a growing emphasis on innovation, INNOFEIT has become a crucial bridge between academic research and industrial applications.

Fig. 1. Center for Technology Transfer and Innovations - INNOFEIT

An important recent milestone in the development of INNOFEIT is the Living Lab Project, funded by the Ministry of Economy. This project runs in 2025 (a period of 9 months), and represents a forward-looking initiative to further develop open innovation environments grounded in real-life applications.

The INNOFEIT Living Lab is a real-life, open innovation ecosystem designed to integrate research and innovation through a systematic user co-creation approach. This model facilitates the development and testing of smart energy systems in environments that simulate real-world conditions. Unlike traditional labs, Living Labs emphasize continuous engagement with end-users and stakeholders, promoting a feedback-rich environment that enhances the applicability and impact of innovations.

The Living Lab operates on the principles of the Quadruple Helix Model, which brings together the four main societal actors:

- Citizens – as users and contributors to the co-creation process,
- Government – as policy makers and enablers,
- Industry – as developers and implementers of innovation,
- Academia – as sources of research and development expertise.

By uniting these actors in a collaborative setting, INNOFEIT Living Lab facilitates rapid prototyping, validation, and scaling of smart energy solutions. It is both a testbed and a meeting ground where ideas evolve into tangible innovations aligned with societal and environmental goals.

A. *Objectives and Strategic Alignment*

The INNOFEIT Living Lab is designed with a specific set of objectives that align with broader institutional and European strategic goals, particularly the United Nations Sustainable Development Goals (SDGs). Out of the ten SDGs commonly associated with Living Labs (SDG2, SDG3, SDG6, SDG7, SDG11, SDG12, SDG13, SDG14, SDG15, and SDG17), the INNOFEIT Living Lab specifically contributes to:

- SDG 7 – Ensure access to affordable, reliable, sustainable, and modern energy for all.
- SDG 12 – Ensure sustainable consumption and production patterns.

These alignments underline the lab's focus on sustainable energy systems and responsible innovation practices.

Key objectives of the INNOFEIT Living Lab include:

- Integration of all available infrastructure under the Center for Technology Transfer and Innovation to ensure streamlined and efficient use of resources.
- Provision of an open innovation ecosystem for external stakeholders to engage in co-creation and experimentation activities.
- Support for experimental and R&D activities by stakeholders and members of the Smart Energy Systems Group (SEGS) within the INITIATE Project. The INITIATE Project, funded by the European Union (Grant No. 101136775), aims to conduct institutional reforms at pilot sites, with replication potential at other institutions across the EU.

B. *Infrastructure and Technological Capacity*

The infrastructure supporting the INNOFEIT Living Lab spans approximately 500 m² over two floors given in Fig.2. This physical space includes: 3 dedicated offices for industry and university research staff, a fully equipped Internet of Things (IoT) laboratory (Fig. 3), multifunctional meeting room, events hall to host workshops, and demonstrations.

In terms of technological infrastructure, the Living Lab includes:

1) *Energy Infrastructure:*

- Solar Power Plant (Fig. 4) – Total capacity of 30 kW, divided into three segments of 10 kW each.
- Battery Storage System (Fig. 5) – Capacity of 100 kWh to support partial energy autonomy and system reliability.
- Electric Vehicle Charger (Fig. 6) – Two charging plugs with 12 kW capacity each.

2) *Heating and Cooling*

- SPRSUN Heat Pump – Rated for 9.5 kW of maximum heating and 8.5 kW of cooling, with an operating temperature range of -20 °C to 45 °C.
- Thermal Buffers – Two thermal buffer tanks, each with a capacity of 500 liters, ensuring energy efficiency in heat distribution.
- Central Water Heating System – Providing experimental needs combined with the heat pump.

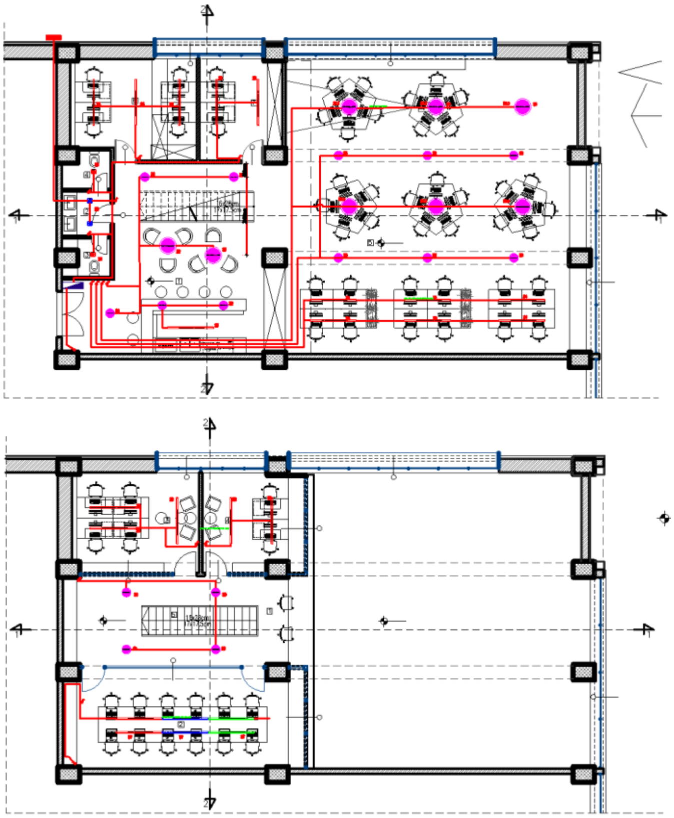

Fig. 2. Ground and first floor of INNOFEIT Living Lab

Fig. 3. INNOFEIT Living Lab Internet-of-Things laboratory

3) Monitoring and Control Systems

- Programmable Logic Controllers (PLCs) – For automation and control of all systems.
- Ambient Monitoring Sensors – Track temperature, humidity, air quality, and occupancy.
- Lighting Control and Presence Detection – Enhance energy efficiency and adaptivity of indoor spaces.
- Weather Station – Collects real-time data on solar radiation, wind speed and direction, and rainfall, feeding into predictive models and control algorithms.
- Dedicated Server for Digital Twin (DT) Integration – Central to data management and simulation activities supporting the lab's smart systems.

The Digital Twin capabilities play a crucial role in the INNOFEIT Living Lab and are co-alligned with the GOTOTWIN project, an INTERREG IPA ADRION initiative coordinated by FEEIT, which aims to advance the deployment of DT technologies to renewable energy sources infrastructure and services across the Adriatic-Ionian region. By integrating these capabilities into the INNOFEIT Living Lab, the project gains access to a fully operational, real-life testing environment that enables the validation of advanced DT methodologies, the assessment of interoperability across diverse technological domains, and the development of replicable use-cases in smart energy management.

More significantly, this collaboration contributes directly to enhancing energy resilience in the Adriatic-Ionian region. By enabling real-time simulation, predictive analysis, and remote experimentation, the Digital Twin infrastructure strengthens the ability of energy systems to anticipate, absorb, and adapt to external disruptions, including climate variability, grid instability, and fluctuating renewable energy supply. These capabilities are essential for building robust and adaptive energy infrastructures across regional public institutions and urban environments.

Additionally, the INNOFEIT Living Lab supports the GOTOTWIN project in promoting energy efficiency of renewable energy sources. Through precise modeling and optimization of solar generation, battery storage, and load management, the Living Lab provides actionable insights into how renewable systems can be operated with maximum efficiency and minimal waste. The data-driven approach enhances control strategies and decision-making processes, leading to smarter, more sustainable energy use.

The synergy between GOTOTWIN and the INNOFEIT Living Lab thus reinforces digital transformation while actively contributing to regional energy goals. It supports policy harmonization, fosters institutional innovation, and demonstrates how Digital Twins can be leveraged to accelerate the twin transition—digital and green—across the Adriatic-Ionian area.

Fig. 4. INNOFEIT Living Lab 30 kW solar power plant

Fig. 5. INNOFEIT Living Lab inverter and battery storadge

Fig. 6. INNOFEIT Living Lab 24 kW electrical vehicle charger

Collectively, this infrastructure provides a robust foundation for experimentation, co-creation, and innovation in the realm of smart energy systems, enabling the INNOFEIT Living Lab to serve as a model for institutional reform and cross-sectoral collaboration.

III. Experimental possibilities and scenarios for energy efficiency at the INNOFEIT Living Lab

The INNOFEIT Living Lab provides a comprehensive, real-world environment ideally suited for experimentation in energy efficiency by merging physical infrastructure with advanced digital technologies in both local and international contexts. At its core, the Living Lab is designed to function as a dynamic, user-centric experimentation ground where smart energy technologies can be rapidly prototyped and refined. The integration of renewable energy systems, energy storage, intelligent control mechanisms, and real-time monitoring facilitates a wide array of experimental scenarios—ranging from demand-side management and thermal comfort optimization to smart grid simulation and renewable integration strategies.

A defining feature of the INNOFEIT Living Lab is its Digital Twin infrastructure, supported by a dedicated server system that enables virtual modeling, simulation, and predictive control of the lab's energy systems. This capability significantly enhances the lab's potential as a testbed, allowing for remote access, continuous performance evaluation, and scenario-based experimentation in a risk-free virtual environment that mirrors real operational conditions. Crucially, this infrastructure supports international remote experimentation, enabling stakeholders and research institutions beyond national borders to engage with the Living Lab. This model opens up new possibilities for collaborative research, student training, and EU-wide pilot projects, positioning the INNOFEIT Living Lab as a cross-border innovation enabler.

The DT-enabled remote experimentation framework is directly aligned with the objectives of the GOTOTWIN projectfor the co-development and testing of scalable DT methodologies, enhancing digital transformation in energy management and supporting policy harmonization and replication at regional levels.

Scenarios for energy efficiency experimentation at INNOFEIT Living Lab for the scientific community include:

- Smart building automation: Testing adaptive lighting, heating, and cooling strategies using ambient and occupancy sensors.
- Renewable energy integration: Simulating solar energy availability and optimizing battery storage cycles for different load profiles.
- Electric mobility: Evaluating load impacts and charging patterns from electric vehicle infrastructure.
- User behavior modeling: Incorporating end-user interaction data into feedback loops for energy-saving behavioral interventions.

IV. CONCLUSIONS

The INNOFEIT Living Lab represents a strategic and forward-looking response to the evolving demands of energy transition and sustainable development. Positioned within the broader European and global innovation ecosystems, it leverages the Quadruple Helix model to co-create smart energy solutions in a real-life setting that bridges academia, industry, government, and civil society.

By integrating renewable energy infrastructure, advanced digital monitoring, and a robust Digital Twin environment, the INNOFEIT Living Lab transcends the traditional boundaries of academic research. It provides a replicable, scalable, and user-centric platform for energy efficiency experimentation, remote collaboration, and cross-border innovation. These capabilities are particularly enhanced through its alignment with strategic initiatives such as the EU-funded INITIATE and GOTOTWIN projects, allowing it to function as both a national testbed and a regional enabler of digital transformation.

Moreover, the Living Lab's targeted contribution to SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production) underlines its relevance to contemporary policy goals. Its infrastructure, governance model, and methodological framework collectively demonstrate how institutional reform, interdisciplinary collaboration, and digital technologies can converge to accelerate sustainable innovation.

It can be noted that the INNOFEIT Living Lab not only serves as a practical experimentation hub for smart energy systems but also stands as a model for embedding Living Lab methodologies into higher education and public infrastructure. Future work will focus on expanding international engagement, deepening integration with policy frameworks, and continuously refining the lab's digital capabilities to support the next generation of energy and climate solutions.

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