



## D4.4. Innovative Business Models in Smart Buildings and Prosumer Communities

WP4 – End user of Energy and prosumers

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#### List of abbreviations

API	Application programming interface
BEN	Beneficiary
CCP	Cloud Computing Platform
COTS	commercial off-the-shelf
Dn	Deliverable (number)
DoA	Description of Action
DS	Doctoral School
ECP	Edge Computing Platform
EMS	Energy management system
ESR	Early Stage Researcher
ETN	European Training Network
GA	Grant Agreement
HIL	Hardware in the loop
IRP	Individual Research Project
ITN	Innovative Training Network
MSn	Milestone (number)
MSCA	Marie Skłodowska-Curie Actions
OSS	Open-source Software
PC	Project Coordinator
REC	Research Ethics Committee
RSC	Recruitment and Secondment Committee
ToU	Time of Use
TRL	Technology readiness level
WPn	Work Package (number)





## 1. Executive summary

The following text summarizes the core components and findings of the SMARTGYSUM Deliverable 4.4, which outlines business models for transitioning ESR's (Early Stage Researchers) work and research into commercially viable products.

The primary objective of this report is to present business strategies for three specific Individual Research Projects (IRPs) to ensure their profitability and market readiness. These projects address the broader goals of identifying new ways to manage electric energy, reducing consumption through smart technologies, and engaging customers in energy-related behavior changes. The work is driven by ESRs who have combined technical engineering with entrepreneurial training to bridge the gap between academic research and industry adoption.

The first model focuses on a two-level Energy Management System (EMS) architecture that utilizes an Edge Computing Platform (ECP) and a Cloud Computing Platform (CCP). This system uses a Raspberry Pi running Home Assistant to handle local, real-time decision-making and data acquisition, while a centralized cloud service performs heavy day-ahead optimizations. This "privacy-by-design" approach keeps sensitive household data local while providing users with optimized power references that can extend battery lifetimes beyond 13 years and reduce financial payback periods from 16 years down to approximately 7 years.

The second business model details an EMS designed specifically for DC-based residential microgrids. This software-driven product aims to maximize on-site energy self-consumption, which is a critical strategy in a market where selling surplus electricity back to the grid is becoming less profitable. By coordinating generation, storage, and loads, the system improves overall efficiency and reliability while maintaining a vendor-agnostic design that works with a wide range of standard commercial components.

The third model introduces the Integrated Real-Time Energy Intelligence (IREI) system, which provides diagnostic and optimization tools for smart buildings. It features non-intrusive load monitoring (NILM) to disaggregate energy usage into individual appliance data without requiring expensive per-appliance sensors. This system is designed for easy integration with home automation platforms like Home Assistant and offers a "freemium" revenue model, providing a basic manual tier for free while charging for advanced AI-driven diagnostics and photovoltaic performance analysis.

### 1.1. Objectives of the deliverable

The objectives of deliverable D4.4 are intrinsically linked to the broader goals of Work Package 4 (WP4), which focuses on "End user of Energy and prosumers". Specifically, this deliverable involves the contributions of researchers ESR9, ESR10, and ESR11, who focus on areas such as fault-tolerant embedded real-time systems, residential energy management systems with online identification of parameters, and the diagnosis and optimization of energy management in smart buildings. The primary objective of Deliverable 4.4 is to present the business model proposals developed by the Early Stage Researchers (ESRs) to ensure the commercial viability and profitability of their research within the framework of WP4. These models leverage the interdisciplinary competencies—ranging from green economy principles to entrepreneurial strategy—acquired by the ESRs through the specialized doctoral training modules provided by the SMARTGYsum project.

## 2. General information

### 2.1. WP4 Objectives and tasks

WP4 (End user of Energy and prosumers) objectives are:

- i. to identify and demonstrate new ways of using electric energy enabling ESS and consumption strategies using monitoring and exogenous information;
- ii. to reduce energy consumption by using emergent technology as smart meters
- iii. to analyse the benefits and possibilities of cooperation between power converters and ICT in Energy Management Systems;
- iv. to identify the main energy-related behaviour change requirements necessary to engage customers in energy applications.

WP4 (End user of Energy and prosumers) tasks are:

- Task 4.1: Development of embedded real-time system to enhance the tolerance and reliability of power electronics (UNL-USA-BRIG).





- Task 4.2: Design and in-loop Residential Energy Management Systems based on microgrid integrated Energy Storage Systems (UNL-KIT-OPAL).
- Task 4.3: On-line diagnosis and optimization of Energy Management Systems for Smart Buildings (UNL-USA).
- Task 4.4: Elaboration of partial and final scientific reports (UNL)

### 3. Deliverable description

#### 3.1. Preliminary information about deliverable

##### **IRP09 – Edge computing platform (ECP) for Fault Tolerant, High Reliable and Resilient Power Electronic in Prosumers Applications**

Residential prosumers with rooftop PV and Battery Energy Storage Systems (BESS) need smart Energy Management Systems (EMS) to reduce electricity bills, increase self-consumption, and monetize flexibility (e.g., export under feed-in / ToU rules). Many existing solutions either ignore battery degradation (causing unrealistic lifetime and cost estimates) or rely on continuous cloud control (raising privacy, latency, and reliability issues).

This deliverable addresses the proposed two-level EMS architecture that splits responsibilities between:

- Edge Computing Platform (ECP): Raspberry Pi running Home Assistant. It provides a user-friendly interface, acquires measurements, predicts household consumption, and executes real-time decision making.
- Cloud Computing Platform (CCP): runs heavy day-ahead optimization and periodic multiparametric optimization that are sent back to the ECP.

The ECP uploads only what is strictly needed for optimization (e.g., aggregated forecasts such as day-ahead load profile), while sensitive/high-frequency information can remain local. The CCP returns a compact policy representation (critical regions) so the ECP can compute optimized real-time power references for the Energy Router (ER) without cloud latency.

Quantified technical economic details (from the degradation-aware PV-BESS optimization case study in Tallinn) conclude that optimized operation can extend battery lifetime beyond 13 years and reduce payback time from about 16 years (self-consumption only) to about 7 years (when export is allowed), while annual capacity fade is typically around 1.3–1.7% depending on season and conditions.

##### **IRP10 – Energy management systems for Residential micro-grids with integrated energy storage**

A comprehensive outline of the proposed business model for the Energy management system (EMS) designed for residential microgrids, developed within the framework of the IRP10 of WP4 of the project is presented. It presents the commercial potential, value proposition, and market opportunities of deploying an EMS designed specifically for DC residential microgrids.

The proposed EMS is conceived as a software-based product intended to support next-generation residential energy systems. Its primary function is to enable both local and global optimization of microgrid resources, including distributed energy generation, storage, and controllable loads. By intelligently coordinating these assets, the EMS seeks to enhance overall system efficiency, economic performance, and operational reliability.

Recent technological advances indicate that DC droop-controlled microgrids are transitioning from laboratory experimentation to pilot-scale deployment, demonstrating superior efficiency and lower conversion losses than conventional AC-based residential systems. As these systems mature, the need for advanced and adaptive energy management becomes increasingly critical. Efficient control and optimization of DC microgrids can deliver tangible benefits to homeowners, particularly those seeking to maximize returns on investment from residential renewable energy installations.

Within the European Union, the steady growth in residential renewable energy adoption, driven by decarbonization policies, rising energy costs, and increased consumer awareness, has reshaped traditional energy economics. Under current regulatory and market conditions, achieving financial break-even solely through the sale of surplus electricity to the grid is increasingly challenging. Consequently, maximizing on-site energy self-consumption has emerged as a key strategy for improving the profitability and sustainability of residential renewable systems. A well-designed, intelligently optimized EMS plays a vital role in enabling this transition by aligning energy generation, storage, and consumption in real time.

##### **IRP11 – On-line diagnosis and optimization of Energy Management Systems for Smart Buildings**





The business model designed for the Integrated Real-Time Energy Intelligence (IREI) system is presented. The model supports a hybrid edge–cloud architecture that enables privacy-preserving, real-time non-intrusive load monitoring (NILM), appliance modeling, load forecasting, and photovoltaic (PV) diagnostics.

Three journal articles form the core scientific background of the platform. The first, “Online real-time robust framework for non-intrusive load monitoring in constrained edge devices” [6], introduces the real-time NILM architecture that enables disaggregation directly on user-owned hardware. The second, “Self-adaptive single-diode model parameter identification under small mismatching conditions” [7], presents the PV modeling method used in the Pro tier for diagnostics and trend analysis. The third, “Transfer capabilities of Seq2Seq and Seq2Point CNN architectures in Non-intrusive Load Monitoring with unseen appliances” [8], supports the cloud-trained appliance embedding method by analyzing generalization strategies for appliance recognition using deep learning.

In addition to these journal articles, three conference papers contributed directly to the design of IREI’s PV diagnostic capabilities. The first, presented at the 2023 IEEE CPE-POWERENG, “Identification of static and dynamic parameters of PV models through multi-objective optimization” [9], helped establish the methodology for parameter identification under real-world conditions. The second, presented at the 2023 ICCEP, “Challenges in photovoltaic parameter identification under mismatching conditions” [10], highlighted the effects of real-time variability and informed the robustness requirements of the system. The third, presented at the 2025 ICCEP, “Detection of Series Resistance Degradation in PV Modules Using Measured Current-Voltage and Frequency-Domain Impedance” [11], provided direct input for implementing degradation detection in residential PV installations.

The IREI business model has been structured to translate these validated scientific methods into a commercial solution that meets market demands. By combining the technical innovations developed through these six publications with real-world constraints and user expectations, the model defines a path from academic research to product adoption. The collaboration between the University of Salerno and CY Cergy Paris Université ensured that the research was supported by interdisciplinary expertise and access to both laboratory and applied testing environments.

## 3.2. Business model presentation (IRP09 – Edge computing platform (ECP) for Fault Tolerant, High Reliable and Resilient Power Electronic in Prosumers Applications)

### 3.2.1. Introduction

This section presents the business model for the Edge Computing Platform and Cloud Computing Platform, to provide an effective consumer supervision to optimize energy production and enhance the physical and data safety, while reducing their cost and energy requirement and reducing consumer vulnerability and dependency on data connections

### 3.2.2. Value Proposition & Competitive Advantage

Customer value delivered (measurable outcomes):

- Lower electricity bill via optimal day-ahead scheduling under ToU tariffs and export rules (minimize import cost, maximize export revenue).
- Lower replacement cost and higher reliability by explicitly accounting for battery degradation (calendar + cyclic aging) within the optimization.
- Faster investment return: payback improvement demonstrated in the export-enabled scenario (e.g., ~16 → ~7 years).
- Real-time performance on low-cost hardware: critical regions enable fast ECP decisions without solving heavy optimization online.
- Privacy-by-design: critical household signals can remain on the ECP; cloud receives only aggregated forecasts or user-consented data.

Competitive advantages:

- Two-level architecture: CCP does heavy computation; ECP does real-time execution with guaranteed responsiveness.
- Multiparametric optimization deployment: reusable critical regions = real-time optimality without cloud latency.
- Degradation economics coupling: battery lifetime is dynamic and impacts replacement cost through annualized factors (CRF/SFF), avoiding oversizing.



### 3.2.3. Data Governance, Confidentiality & Security

Confidentiality principle: keep critical information at the edge by default.

- Default data locality: high-frequency measurements (per-5-min time series, appliance-level signals, occupancy cues) stored locally on the ECP.
- Cloud-minimalism: CCP receives only the aggregated day-ahead consumption forecast (as precise as desired by the user) and necessary tariff/forecast inputs.

### 3.2.4. Market & Customer Segments

Primary customer segments:

- Residential prosumers with PV planning to add storage.
- Residential prosumers with PV + BESS seeking higher savings and export revenue.
- Installers/integrators looking for a software layer to differentiate PV+BESS offerings.

Secondary/adjacent segments (medium-term):

- Energy communities / pilot microgrids requiring scalable coordination across homes.
- Aggregator / flexibility service providers.

### 3.2.5. Channels & Customer Relationships

Channels:

- Installer channel: package the EMS with PV+BESS installation or upgrade projects.
- OEM partnership: embed as an add-on module for Energy Router / hybrid inverter vendors.
- Direct-to-prosumer: Home Assistant community + online onboarding.

Customer relationships:

- Self-service onboarding via Home Assistant UI + guided setup.
- Subscription support: updates, tariff configuration, integration maintenance.
- Optional premium services: remote diagnostics and optimization tuning.

### 3.2.6. Revenue Model & Cost Structure

Revenue options:

- Subscription: day-ahead optimization + critical region updates + continuous improvements.
- Hardware bundle: preconfigured Raspberry Pi with EMS stack (ECP) and installer support.
- Tiered services: basic (self-consumption), advanced (export), premium (uncertainty-aware/robust).

Cost structure:

- Cloud compute for optimization and critical region generation.
- Cloud storage and secure delivery.
- Engineering & maintenance (integration, cybersecurity updates, model updates).
- Customer support and installer training.

### 3.2.7. Key Resources & Activities

Key resources:

- Optimization engine (day-ahead scheduling + multiparametric region generation).
- Battery lifetime/degradation model coupled to economics (CRF/SFF).
- Edge stack (Home Assistant integration, forecasting, real-time policy execution).
- Cloud stack (containerized solver services, authentication, monitoring).

Key activities:

- Operate the CCP optimization service (multi-tenant scheduling, monitoring, scaling).
- Generate and update critical regions (e.g., every 4 hours or event-driven).
- Improve forecasting models and validate across households/climates.
- Maintain integrations with Energy Router, meters, and tariffs.

### 3.2.8. Key Partnerships

Partnerships enabling delivery:

- ESR03 collaborator: operation of the CCP optimization service and compute infrastructure.
- ESR011 collaborator: for appliances monitoring and improving the consumption prediction based on NILM algorithms.



- Energy Router / inverter manufacturers: stable API for measurements and power references.
- Home Assistant ecosystem and smart-meter vendors.
- PV+BESS installers and maintenance providers.
- Cloud provider (AWS/Azure/GCP or EU-based).

### 3.2.9. Sustainability & Scalability

Sustainability:

- Higher PV self-consumption and reduced peak imports support renewable integration.
- Battery lifetime extension reduces material footprint and replacement waste.
- Flexible scheduling can reduce stress on distribution networks.

Scalability:

- CCP multi-tenant optimization: modernize processing reduces marginal cost per household.
- ECP real-time execution is lightweight: critical regions enable constant-time decisions.
- Configurable data retention: local-first storage; cloud storage is optional and minimized.

### 3.2.10. Financial Overview (Optional)

ECP/CCP Split of Responsibilities:

Edge Computing Platform (ECP): Raspberry Pi	Cloud Computing Platform (CCP): Cloud Service
<ul style="list-style-type: none"> <li>• Data acquisition (smart meter, PV, BESS, Energy Router)</li> <li>• Home Assistant UI (user-friendly)</li> <li>• Local consumption prediction</li> <li>• Real-time decision making (compute power references for ER)</li> <li>• Local storage (default)</li> </ul>	<ul style="list-style-type: none"> <li>• Day-ahead optimization (heavy compute)</li> <li>• Multiparametric optimization to compute critical regions</li> <li>• Tariff/forecast processing</li> <li>• Policy distribution + updates</li> <li>• Optional cloud storage (limited retention)</li> </ul>
Uploads: aggregated day-ahead forecast (and optional consented aggregates), not raw sensitive signals by default.	Returns: compact policy packages (critical regions) enabling fast real-time control on the ECP.
Operates in Real-time.	Runs on schedule (daily + every 4 hours).

#### Local Data Storage Estimate (5-minute sampling, 1 year)

Samples/year at 5-minute resolution:  $365 \times 24 \times 12 = 105,120$  samples.

If each sample stores ~13 fields (timestamp + 12 numeric variables):

- Binary (floats):  $105,120 \times 13 \times 8 \text{ bytes} \approx 10.9 \text{ MB/year}$ .
- CSV/text (typical):  $\approx 30\text{--}150 \text{ MB/year}$  depending on precision and number of columns.

Edge storage requirements are modest. A typical microSD/SSD can store multi-year histories for a single household.

#### Edge Hardware Cost (indicative)

A realistic planning range for a complete ECP (Raspberry Pi + power supply + storage) is typically in the order of €80–€150, depending on model and retailer availability.

#### Cloud Compute Cost Estimate (per household, dedicated worst-case)

Measured runtimes on a local laptop (Intel Core i7 12th Gen, 32 GB RAM):

- Day-ahead optimization: 408–1350 s per run
- Critical-region computation: ~2.04 min per run, every 4 hours ( $\approx 6$  runs/day)

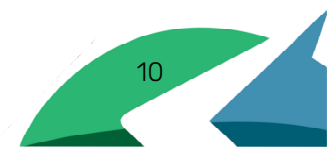
Approximate dedicated monthly compute time (worst-case):

- Day-ahead:  $\sim 15 \text{ min/day} \times 30 \approx 7.5 \text{ h/month}$
- Regions:  $2.04 \text{ min/run} \times 6/\text{day} \times 30 \approx 6.1 \text{ h/month}$

Total  $\approx 13.6 \text{ h/month}$ .

Reference price for compute (Europe/Paris region): c7i-flex.4xlarge on-demand is reported at 1.283€/hour [5].

Dedicated worst-case compute cost:  $13.6 \text{ h/month} \times 1.283\text{€/h} \approx 17.45 \text{ €/month}$  per household. With multi-tenant batching, the marginal cost per household is expected to be significantly lower.





### Subscription pricing and provider benefits

A simple pricing structure can combine a one-time deployment fee (hardware + installation) and a monthly subscription for cloud optimization, updates, and support.

Tier	What the customer gets	Indicative price	Notes
Basic (Edge-only)	Local monitoring + prediction (no cloud optimization).	0-4 €/month	Suitable when customers want privacy-first.
Premium (Cloud-Edge + Insights)	Standard + longer data retention (opt-in) + advanced reports (payback, degradation, CO <sub>2</sub> ) + priority support + bill saving cost+ Demand Side Management (DSM).	20-25 €/month	Targets prosumers with PV+BESS and high tariffs/FIT.

The end user bears the one-time installation cost, which is included in the PV+BESS and Energy Router (ER) installation/retrofit package delivered by certified partner installers. Our company supplies the Edge Computing Platform (ECP) and onboarding support, while partners invoice installation as part of their standard project scope.

#### 3.2.11. Remarks

This work positions a cloud/edge EMS architecture as a practical pathway from research-grade optimization to deployable residential energy management. A key outcome is the availability of an open-access, generic residential load-profile predictor, already implemented on a Raspberry Pi 4 and integrated within a user-friendly interface (Home Assistant). This edge-level capability enables continuous data acquisition and short-term consumption prediction while preserving user confidentiality by keeping high-resolution household data locally when required.

Building on this foundation, the ongoing work focuses on completing (i) day-ahead optimization in the cloud, where heavy computation is executed to generate multiparametric solutions (critical regions), and (ii) the real-time decision-making layer on the ECP, which uses the received critical regions to compute optimized power references for the energy router with minimal computational burden. The final objective is a fully operational real-case study combining day-ahead scheduling and real-time control on a residential prosumer setup.

Finally, a preliminary cost estimation is provided as a first step toward industrialization, covering edge hardware requirements (Raspberry Pi 4), local data storage needs, and indicative cloud compute costs for periodic optimization runs. This assessment supports early feasibility analysis before full customization and experimental validation on the prototyped ER.

## 3.3. Business model presentation (IRP10 – Energy management systems for Residential micro-grids with integrated energy storage)

### 3.3.1. Introduction

This section presents a comprehensive outline of the proposed business model for the Energy management system designed for residential microgrids. It presents the commercial potential, value proposition, and market opportunities of deploying an EMS designed specifically for DC residential microgrids.

### 3.3.2. Value Proposition & Competitive Advantage

Current residential renewable energy installations face several structural and operational limitations, including multiple power-conversion stages, synchronization requirements across converters, increased material use, and limited operational flexibility. These inefficiencies become more pronounced with high renewable penetration, where residential prosumers are often unable to fully capitalize on the economic potential of their systems. As a result, overall system performance is reduced, and the payback period for capital investments gets extended.





The proposed EMS for DC residential microgrids directly addresses these challenges by enabling a more streamlined, efficient, and flexible energy architecture. By leveraging the inherent advantages of DC systems and advanced control strategies, the EMS enhances both technical performance and economic returns for residential users.

The core value propositions of the EMS include:

- Enhanced Energy Efficiency through the reduction of unnecessary power conversion stages, the use of high-efficiency interface converters, and intelligent optimization of residential energy flows across generation, storage, and loads.
- Improved Energy Flexibility enabled by droop control and real-time, online manipulation of droop characteristics. This allows the system to dynamically respond to varying operational scenarios, such as changing weather conditions, energy market signals, or emergency operating modes.
- Scalable and Multi-Level Integration of Renewable Resources, whereby the EMS can be deployed not only at the individual household level, but also extended to community, district, or aggregated microgrid configurations, supporting coordinated energy management across multiple scales.
- Reduced Environmental Impact achieved through the use of higher switching frequencies in interface converters, which lowers material requirements, reduces system bulk, and contributes to more sustainable hardware designs.
- Simplified electrical infrastructure and appliance Integration through the implementation of droop control at the appliance level, enabling smart, plug-and-play connectivity of distributed assets and reducing installation complexity.

A key competitive advantage of the EMS lies in its vendor-agnostic architecture. The system is designed to support the integration of a wide range of commercial off-the-shelf (COTS) interface converters, appliances, and protection devices, minimizing vendor lock-in and lowering adoption barriers. In contrast to most existing EMS solutions, which are primarily tailored to AC-based renewable systems, the proposed solution is specifically designed for DC microgrids. It aligns with the technological trajectory of future residential energy networks.

By entering a largely untapped market segment with an innovative, software-driven EMS tailored to DC residential microgrids, the solution benefits from a first-mover advantage, minimal direct competition, and increasing market relevance driven by the growing adoption of residential renewable energy systems and prosumer-oriented energy models.

### 3.3.3. Market & Customer Segments

The EMS addresses a diverse and growing market driven by decentralization, sustainability goals, and regulatory pressures. The primary target customer segments include:

- Energy communities and collective self-consumption groups, seeking efficient, scalable, and easily deployable energy management solutions to optimize shared renewable generation, storage, and consumption while minimizing system complexity.
- Owners and operators of eco-conscious apartment buildings and residential complexes, aiming to reduce energy costs, improve sustainability performance, and enhance energy autonomy through advanced, low-loss DC-based energy infrastructures.
- New homeowners and property developers are required to comply with increasingly stringent renewable energy and energy efficiency regulations, who seek future-proof solutions that simplify compliance while maximizing on-site renewable utilization.
- Residents in remote, islanded, or grid-constrained locations where weak or unreliable grid infrastructure necessitates resilient, locally optimized energy systems capable of maintaining stability and continuity of supply.

### 3.3.4. Channels & Customer Relationships

The proposed EMS will be delivered to customers through a combination of physical and digital distribution channels, ensuring broad accessibility while leveraging existing partner networks.

The solution will be made available through partners' physical retail outlets, enabling direct engagement with customers who prefer in-person consultation, particularly during the planning or installation phase of residential energy systems. In parallel, the EMS will be offered via a dedicated online sales platform, enabling customers to access product information, configuration options, and purchasing services in a streamlined, scalable manner.

Customer relationships will primarily be structured around a self-service model, supported by comprehensive online resources, including documentation, tutorials, and configuration tools, hosted on the project website. This approach minimizes operational overhead while empowering users to manage and optimize their energy systems independently.



To complement the self-service model, technical support and operational assistance will be provided through collaboration with distribution system operators (DSOs) and energy aggregators. These stakeholders will play a key role in system integration, ongoing optimization, and participation in advanced services such as flexibility markets or demand response programs, ensuring reliable long-term customer engagement and system performance.

### 3.3.5. Revenue Model & Cost Structure

The proposed EMS is supported by a diversified revenue model that combines one-time product sales with recurring service-based income, ensuring both short-term revenue generation and long-term financial sustainability. Revenue Streams include:

- Sales of Hardware Solutions, comprising the EMS platform and its associated ecosystem of compatible components. This includes self-developed interface converters, power nodes, protection devices, and DC-compatible appliances designed to operate seamlessly within the microgrid, creating additional value through system-level integration.
- Subscription-Based Services, offering advanced functionality beyond the core EMS features. These services may include cloud-based monitoring, artificial intelligence-driven optimization, and enhanced analytics, enabling customers to have continuous performance improvements and generate recurring revenue.
- Revenue and profit-sharing mechanisms with DSOs, particularly in cases where the EMS enables grid-support services such as flexibility provision, congestion management, or participation in local energy markets. This model aligns incentives across stakeholders while unlocking additional income streams.

The cost structure reflects the technology-driven and innovation-focused nature of the solution and includes:

- System design and development costs, which are primarily variable and linked to the ongoing development, customization, and scaling of the EMS software and associated hardware components.
- Marketing, publicity, and dissemination costs, covering customer acquisition, partner engagement, demonstration activities, and communication efforts required to support market entry and adoption.
- Continuous research and development costs, ensuring ongoing innovation, system upgrades, cybersecurity enhancements, and compliance with evolving regulatory and technical standards.

### 3.3.6. Key Resources & Activities

The successful development, deployment, and commercialization of the EMS relies on a set of core activities supported by strategically important technical and organizational resources. Key Activities include:

- Design and development of EMS hardware and software, including control algorithms, optimization logic, communication interfaces, and embedded functionality for reliable operation in DC residential microgrids.
- System integration and validation up to technology readiness level (TRL) 6, including comprehensive testing procedures such as burn-in testing, Hardware-in-the-loop (HIL) validation, and performance verification under realistic operational scenarios to ensure robustness, safety, and scalability.
- Dissemination and outreach activities, aimed at increasing public and stakeholder awareness through seminars, workshops, technical demonstrations, and project showcases. These activities support market uptake, knowledge transfer, and engagement with industry, policymakers, and end users.

Key resources supporting these activities include:

- Novel DC-DC and AC-DC Converter Architectures with Integrated IoT Connectivity, enabling efficient power conversion, real-time monitoring, and seamless communication with the EMS for advanced control and optimization.
- A Dedicated DC test laboratory, consisting of different power electronic equipment that emulates a DC residential household. This infrastructure enables controlled testing, system validation, and demonstration of the EMS under representative operating conditions.
- Third-party system integrations, including access to existing open-source software (OSS) frameworks, as well as application programming interfaces (APIs) provided by DSOs. These integrations support interoperability, grid interaction, and participation in advanced energy services.

Together, these key activities and resources form the technological and operational foundation required to advance the EMS from development to pilot-scale deployment, while ensuring readiness for future commercialization and large-scale adoption.

### 3.3.7. Key Partnerships

The successful development and deployment of the EMS relies on strategic collaborations with key stakeholders across the energy value chain. DSOs play a central role in enabling grid integration, validating grid-support services, and aligning with regulatory and operational requirements. Component and device manufacturers are essential



partners for ensuring compatibility, reliability, and scalability of converters, protection devices, and DC-compatible appliances within the EMS ecosystem. In addition, collaboration with DC grid guideline and standards organizations supports compliance with emerging standards, contributes to interoperability, and helps position the solution in line with future DC grid regulations and best practices.

### 3.3.8. Sustainability & Scalability

The EMS offers an environmentally sustainable solution for future residential energy systems by significantly improving energy efficiency and maximizing on-site renewable energy self-consumption. By enhancing the economic performance of residential renewable installations and enabling participation in grid-support and flexibility services, the EMS supports long-term financial sustainability for prosumers and system operators alike. Its modular, vendor-agnostic architecture ensures seamless integration with commercially available components while remaining adaptable to evolving technologies and standards. Furthermore, the software-centric design allows the EMS to scale from individual households to community and district-level applications, positioning it as a future-proof enabler of decentralized, low-carbon energy systems.

## 3.4. Business model presentation (IRP11 – On-line diagnosis and optimization of Energy Management Systems for Smart Buildings)

### 3.4.1. Introduction

This section introduces the business model designed for the Integrated Real-Time Energy Intelligence (IREI) system. The model supports a hybrid edge-cloud architecture that enables privacy-preserving, real-time non-intrusive load monitoring (NILM), appliance modelling, load forecasting, and photovoltaic (PV) diagnostics.

### 3.4.2. Value Proposition & Competitive Advantage

IREI addresses the problem of inaccessible or costly appliance-level energy monitoring. While many homes are equipped with smart meters, their data remains underutilized due to low temporal resolution, privacy concerns, or lack of compatible solutions. Existing NILM platforms are either cloud-dependent, requiring continuous data upload, or hardware-based, which increases installation complexity and costs.

IREI offers a unique solution by processing energy data locally using user-owned computing platforms such as single-board computers. The free tier enables users to manually define appliance models, while the Pro tier adds AI-trained appliance embeddings, load forecasting, PV diagnostics, and energy efficiency insights. All features operate with compact data models that preserve privacy and minimize bandwidth usage.

Customers will choose IREI because it offers a flexible, low-cost entry point with the ability to scale through modular enhancements. The system's architecture supports both manual and AI-driven modeling, and its integration with home automation platforms ensures seamless operation. Its competitive edge lies in combining accuracy, privacy, and interoperability without the need for costly per-appliance sensors.

As shown in Figure 1, IREI integrates into the Home Assistant interface to provide real-time appliance-level monitoring. This visualization demonstrates the system's ability to disaggregate loads and present individual appliance data such as power use from the fridge, microwave, or dishwasher; all updated in real time.



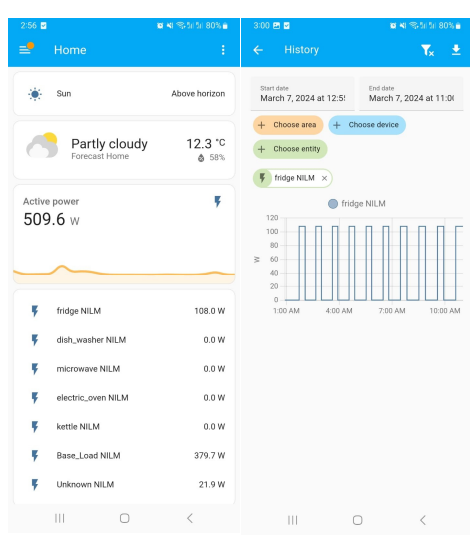


Figure 1. Real-time appliance-level energy disaggregation in Home Assistant using IREI.

### 3.4.3. Market & Customer Segments

IREI targets three main customer segments. The first is composed of home automation users who rely on platforms such as Home Assistant to control and monitor their devices. As shown in Figure 2, the number of Home Assistant installations has grown significantly between 2021 and 2025, indicating a rapidly expanding user base interested in energy data and automation. These users often seek deeper energy insight and system automation capabilities. A large portion of this community already employs compatible smart meters such as the Shelly EM. Figure 3 illustrates that Shelly devices account for a notable share of the energy metering hardware in Home Assistant environments. This reinforces that a significant number of users are already monitoring their consumption and are likely to be receptive to paying for advanced analytics, including load disaggregation, forecasting, and diagnostics. The second customer segment includes PV system owners who need diagnostic tools to monitor panel performance and ensure long-term reliability. The third group consists of energy service providers, including installers and consultants, who seek scalable and cost-effective solutions for residential energy monitoring.

Customer needs include accurate real-time monitoring, data privacy, ease of integration with existing systems, and actionable energy insights. Pain points addressed by IREI include the high cost of smart plugs or hardware sensors, privacy risks associated with cloud-based NILM, and the lack of real-time capabilities in existing solutions. The residential energy market is evolving toward digitalization, decentralization, and user empowerment. The rise of smart homes and self-generation systems has created demand for solutions like IREI that maximize existing infrastructure. IREI is positioned to compete with both traditional monitoring hardware and cloud-based energy analytics platforms by offering a leaner, privacy-focused alternative.

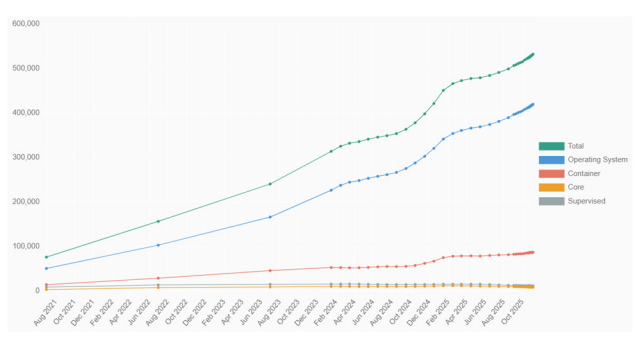
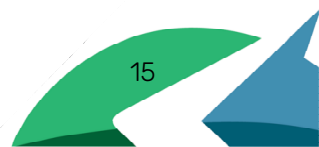


Figure 2. Growth of Home Assistant installations from 2021 to 2025.

20	Internet Printing Protocol (IPP)	124,873 (28.4%)
21	DLNA Digital Media Renderer	124,214 (28.2%)
22	Zigbee Home Automation	113,171 (25.7%)
23	ESPHome	111,899 (25.4%)
24	Shelly	100,122 (22.8%)
25	DLNA Digital Media Server	93,470 (21.3%)
26	Input number	90,330 (20.5%)

Figure 3. Adoption rate of Shelly devices in Home Assistant installations.



### 3.4.4. Channels & Customer Relationships

IREI is distributed through digital channels including GitHub, the Home Assistant add-on ecosystem, and energy-focused online communities. Marketing and outreach efforts target forums, conferences, and open-source platforms that cater to home automation and energy efficiency users. Strategic partnerships with hardware vendors and PV installers help reach non-technical audiences through bundled solutions.

Customer relationships vary depending on the product tier. The free tier operates on a self-service basis with community-driven support, while the Pro tier includes access to structured documentation, updates, and optional technical assistance. Communication is primarily digital, ensuring scalability while keeping support costs manageable. Retention strategies focus on demonstrating the value of appliance-level data through virtual sensors and automation. By offering visible performance improvements and convenience in the free tier, the system naturally encourages users to upgrade to paid features. The modular structure allows incremental investment, reducing barriers to long-term engagement.

### 3.4.5. Revenue Model & Cost Structure

The IREI business model includes multiple revenue streams. The free tier serves as a user acquisition tool, offering appliance modeling through finite state machines at no cost. Revenue is generated from the Pro features via two models: a one-time fee per appliance embedding (3–5 euros) and a monthly subscription (5–7 euros) that includes up to ten embeddings per year along with forecasting, diagnostics, and AI-based insights. Pricing is designed to be accessible while delivering high perceived value. The per-appliance model allows for gradual user engagement, while the subscription model offers bundled services with ongoing updates.

Major cost drivers include R&D for algorithm development, cloud infrastructure to support Pro features, software maintenance, and user support. Cost optimization is achieved through reliance on user-owned hardware, lightweight data processing, and open-source distribution channels that reduce overhead and marketing expenses.

### 3.4.6. Key Resources & Activities

Core resources include the local NILM engine, cloud-based analytical services, appliance modeling infrastructure, and integration interfaces for home automation systems. Intellectual assets consist of the algorithms, training pipelines, and software components that enable local processing and secure cloud interaction.

As shown in Figure 4, installation of IREI relies on integrating devices such as the Shelly EM, which requires minimal hardware effort while delivering full compatibility with the IREI platform. This supports rapid deployment in both self-install and professional scenarios.

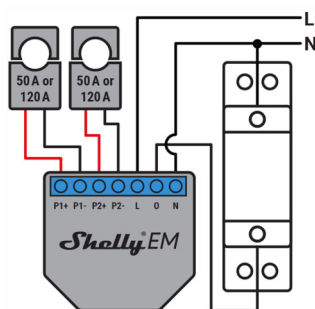


Figure 4. Installation diagram of the Shelly EM meter for IREI deployment.

A large share of Home Assistant users rely on low-cost, single-board computers and embedded platforms that are compatible with local energy analytics, such as the IREI model. These include Raspberry Pi variants, ODROID boards, and pre-configured appliances like Home Assistant Yellow. Figure 5 illustrates the distribution of hardware platforms among Home Assistant users. The prevalence of Raspberry Pi 4 and 5, together with other embedded systems, confirms the feasibility of deploying the local NILM engine without the need for high-end devices.

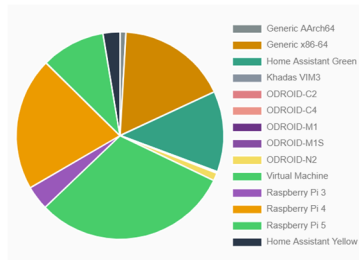


Figure 4. Distribution of Home Assistant hardware platforms among users.

The main business activities are research and development of NILM and PV diagnostics, appliance modeling, software updates, user support, and strategic partnership management. Continuous improvement of model accuracy and compatibility is central to maintaining a competitive edge. Community engagement and documentation are also vital for user onboarding and retention.

### 3.4.7. Key Partnerships

IREI benefits from partnerships with smart home communities, hardware manufacturers, and energy service providers. Collaborations with inverter manufacturers ensure compatibility with PV diagnostics features. Partnerships with Home Assistant developers and GitHub contributors help maintain platform integration and visibility. Alliances with PV installers and smart energy consultants enable field testing, direct deployment, and expansion into service-based markets. These relationships reduce market entry barriers and accelerate adoption, especially among users who prefer plug-and-play solutions over manual configuration.

### 3.4.8. Sustainability & Scalability

IREI is designed to scale horizontally through software distribution and vertically through Pro feature adoption. Its modular structure allows the addition of new cloud-based services without altering the core local engine. The system's reliance on user-owned hardware ensures that scaling does not require significant capital investment in infrastructure.

From a sustainability perspective, IREI contributes by reducing the need for dedicated sensors and hardware, which lowers material waste. Its ability to optimize household energy use and detect PV performance issues supports long-term environmental benefits. The business model is inherently adaptable. As the number of supported appliances and analytical modules grows, the system can address new market segments, including small commercial buildings and community energy monitoring setups.

### 3.4.9. Financial Overview

Initial revenue projections are based on conservative conversion rates within the Home Assistant user base. With over one million active users, a 5 percent conversion to paid appliance embeddings could generate significant one-time income. A smaller percentage subscribing to the Pro tier could establish a stable monthly revenue stream.

Key expenses include R&D, cloud services, and community management. The open-source model reduces support costs and allows the project to grow with minimal financial overhead. Future funding could support service expansion, including AI model refinement, broader appliance coverage, and partnerships with energy providers.

## 4. General Conclusions

The three Individual Research Projects within Work Package 4 showcase an interesting suite of end use of energy and prosumers solutions covering the entire value chain from hardware to software, aligned with Work Package 4 objectives.

### IRP09 – Edge computing platform (ECP) for Fault Tolerant, High Reliable and Resilient Power Electronic in Prosumers Applications

This work positions a cloud/edge EMS architecture as a practical pathway from research-grade optimization to deployable residential energy management. A key outcome is the availability of an open-access, generic residential load-profile predictor, already implemented on a Raspberry Pi 4 and integrated within a user-friendly interface (Home Assistant). This edge-level capability enables continuous data acquisition and short-term consumption prediction while preserving user confidentiality by keeping high-resolution household data locally when required.





Building on this foundation, the ongoing work focuses on completing (i) day-ahead optimization in the cloud, where heavy computation is executed to generate multiparametric solutions (critical regions), and (ii) the real-time decision-making layer on the ECP, which uses the received critical regions to compute optimized power references for the energy router with minimal computational burden. The final objective is a fully operational real-case study combining day-ahead scheduling and real-time control on a residential prosumer setup.

Finally, a preliminary cost estimation is provided as a first step toward industrialization, covering edge hardware requirements (Raspberry Pi 4), local data storage needs, and indicative cloud compute costs for periodic optimization runs. This assessment supports early feasibility analysis before full customization and experimental validation on the prototyped ER.

#### **IRP10 – Energy management systems for Residential micro-grids with integrated energy storage**

This deliverable presents a comprehensive business and technical perspective on an energy management system (EMS) for DC residential microgrids, highlighting its value proposition, market relevance, and competitive advantages. The proposed solution addresses key inefficiencies of conventional residential energy systems by enabling higher efficiency, flexibility, and renewable self-consumption through advanced DC-based architectures. A diversified revenue model, a lean operational structure, and a strong partner ecosystem strengthen the EMS's commercial viability and long-term sustainability. Its modular, vendor-agnostic, and standards-aligned design ensures scalability across households, energy communities, and district-level applications. Overall, the EMS represents a future-proof, impactful solution that supports the transition toward decentralized, efficient, and low-carbon residential energy systems.

#### **IRP11 – On-line diagnosis and optimization of Energy Management Systems for Smart Buildings**

The Integrated Real-Time Energy Intelligence (IREI) system is a hybrid edge-cloud platform designed to deliver real-time, privacy-respecting, appliance-level energy disaggregation and analytics. It leverages existing user-owned smart meters and local computing infrastructure to provide accurate monitoring without requiring additional hardware. The business idea focuses on enabling homeowners, solar system users, and energy service providers to access advanced energy intelligence at a fraction of the cost of conventional systems.

The mission of IREI is to democratize access to smart energy monitoring by making it affordable, accurate, and respectful of user privacy. Its vision is to become a reference solution in residential energy intelligence by transforming underused smart meter data into actionable insights. Key goals include widespread adoption among home automation users, strategic integration with solar energy ecosystems, and continued development of modular analytical services.

Success will be measured through free-to-paid conversion rates, Pro subscription retention, disaggregation accuracy benchmarks, and the volume of cloud-trained appliance embeddings delivered. Strategic priorities include strengthening platform integration,



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