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Validation of flexible demand models and strategies in smart grids for small and medium prosumers

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Abstract. Renewable energies have recently demonstrated their ability reducing the dependence on fossil fuels, contributing to the resilience of energy supply and playing an important role in reducing greenhouse gas emissions. This increasing use of renewable energy sources has led to the proliferation of prosumer microgrids, where users take on a dual role, both consumers of the self-generated electricity from renewables and producers of the system power. This distributed model of energy generation and consumption allows users not only to generate and consume electricity, but also to share it with others, encouraging greater participation in the energy system. However, the intermittent nature of renewable energies sources poses significant challenges to the stability and reliability of the electricity system. In this context, flexible demand has emerged as a key strategy to adapt energy consumption to the availability of generation. In this sense, prosumer microgrids represent an innovative approach to optimise energy, as flexible demands strategies can be applied by the same prosumer that control both generation and load. After an extensive flexible demand technologies and techniques analysis, the aim of this article is to propose a scalable system for flexible demand characterization, prosumer-oriented, based on a renewable microgrid and thermal tests.

Key words. Prosumer, microgrid, flexible demand, energy consumption management, distributed generation.

1. Introduction

Current climate emergency, mainly driven by greenhouse gas emissions (due to extensive use of fossil fuels), makes the integration of renewable energies into the energy system essential [1]. Additionally, according to European Commission [2], electricity consumption for stationary uses accounts for approximately 30-40% of total electricity consumption in society. In this sense, the increase in peak electricity consumption has aggravated the imbalance between electricity supply and demand in various sectors, which has generated serious issues in the regulation of electricity grid, affecting from domestic to industrial consumption [3].

In the shift toward a low-carbon economy, the rise of renewables has led to prosumer microgrids, where users become active participants through local generation, demand response, and efficiency measures [4]. However, the variability of sources like solar and wind challenges system stability, making flexible demand key to aligning consumption with generation.

Moreover, the growth of renewable Distributed Generation (DG) and emerging technologies challenges traditional grid control, now distributed across the network. Systems are being developed to manage DG, while new demand-side technologies increase variability and peaks, causing more disturbances [5]. As a result, smart grids and Demand Response (DR) programs are seen as essential to manage demand, reduce grid oversizing and costs, and enhance reliability. [6, 7, 8].

Regarding hydrogen technologies, it is worth highlighting their progressive application in more contexts, with greater implementation of small-scale PEM production technology for residential and commercial applications, and alkaline use in larger-scale industry. While safety is key, sufficient measures are currently being taken to ensure its integration, especially regarding its operation and detection. Although Spain does not yet have a hydrogen transportation network, many alternatives are being considered, ranging from vehicle transport to the use of current pipelines mixed with other gases [9].

This article firstly addresses the analysis of novel technological activities such as the evaluation of storage technologies and flexible demand as a tool for optimising the management of electricity grids. Based on this, and as the main aim of this work, it proposed a scalable system for flexible demand characterization, prosumer-oriented, based on a renewable microgrid and thermal tests. For this aim, an experimental microgrid, based on a DC bus is proposed. Its structure is based on photovoltaics source, electrochemical storages (mainly including batteries, supercapacitors and the use of hydrogen technology) and the possibility of flexible demand with load profiles and local grid connection.

2. Demand management in smart grid for prosumers

From the prosumer's perspective, demand flexibility is understood as the ability to reduce, increase or shift their energy demand by managing their consumption, generation or storage over a given period.
The prosumer figure presents advantages related to the decentralisation of production, as self-consumption and storage allow to manage the surplus of renewable energy for low production periods, stabilising supply and demand. Intermittency and variability also pose challenges in energy production (e.g. solar and wind), generating fluctuations. On the other hand, the bidirectionality of energy flow can generate stability and congestion problems in the grid.
This is why smart grids are needed to efficiently manage distributed production, with the digitalization and automation of the electricity grid being essential.
The smart grid concept (SG) for a small and medium-sized prosumer integrates generation, storage, and consumption technologies along management technologies, including IT and automation, and communication technologies to monitor, control, and maintain the electrical network, enabling the delivery of electricity with enhanced quality, sustainability, security, and reliability [10, 11, 12]. However, implementing this concept in a practical way requires adjustments to the existing network, such as installing sensors, real-time communication devices, and data processing centres, as well as modifying the energy commercialization process [13, 14, 15].

An important function of a SG is the Demand Side Management (DSM), which consists of controlling loads on the customer's side, aiming to operate the system with greater efficiency and sustainability [16]. Such management allows the use of different optimisation criteria related to the demand curve smoothing, increased use of renewable energies, reduced power transmission to the grid and improved economic benefits [16]. Demand regulation allows users to modify their consumption patterns, smoothing the load curve and reducing peaks. This active approach lowers operational costs and delays the need for new system investments. [17].
A primary objective of demand side management (DSM) is to reduce system peak demand, in order to minimize the need for additional investments in generation, transmission and distribution capacity [16]. These programs can apply direct or indirect load control. Indirect control uses tools like tariffs to influence demand without modifying it directly, requiring user interaction. In direct control, the distributor adjusts demand directly or via disconnection commands.
From the user's perspective, whether residential, commercial or industrial, the prosumer in a smart microgrid owns distributed generation and manages their demand. This gives them a central role in defining the microgrid's functions within economic, technical and social constraints. With high DG penetration, prosumers help optimize energy use by choosing whether to consume or sell their generation and adjusting their demand accordingly.
Figure 1 illustrates traditional demand-side management (DSM) strategies, showing their impact on the electrical load profile. These strategies can contribute to optimizing energy use, enhancing grid stability, and improving the integration of renewable energy sources. The red curve represents the original demand, while the blue curve depicts the adjusted demand after applying each strategy. The techniques include Peak shaving (reducing peak loads), Valley filling (increasing demand during low-consumption periods), Load shifting (redistributing demand to off-peak hours), Strategic growth (controlled demand increase), Strategic conservation (demand reduction), and Flexible load (adjustable consumption based on grid conditions).

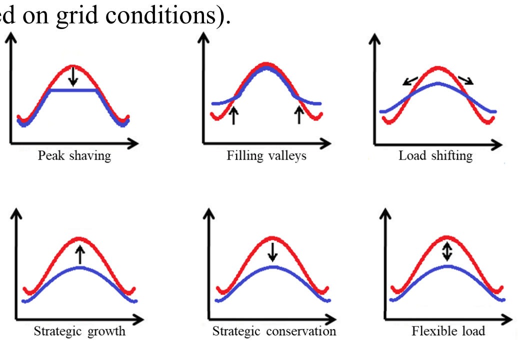

Fig. 1: Classical strategies used for the DSM [16].

This demand control enhances the reliability and responsiveness of the prosumer's grid in both normal conditions (such as demand and generation dispatch, voltage and frequency regulation) and during disturbances or demand peaks. Importantly, it must not affect user comfort. Control is applied at each prosumer level, enabling interaction with the grid and supporting a distributed control approach.

3. Technologies analysed for flexible demand regulation applied in prosumers systems

Flexible load techniques within the possible flexible demand strategies address a wide range of possible approaches. In this section, an in-depth analysis of these alternatives is carried out as a basis for the design of the flexible demand characterization system for prosumers. Below some of the main applicable strategies are described:
(a) Demand Response (DR). This strategy allows adjusting electricity consumption based on price signals or incentives. Two main approaches can be distinguished:
• Dynamic pricing-based: Consumption adjustment according to tariff variability (peak/off-peak).
• Incentive-based: Economic compensation for reducing demand during critical moments.
Therefore, prosumers consider the economic factor to adjust flexible demand.
(b) Intelligent Load Management. Through the use of IoT devices and energy management platforms, it is possible to schedule the operation of flexible loads, such as smart appliances and electric vehicles (V2G - Vehicle to Grid).

Additionally, the following strategies can be applied:
• Load shedding: Temporary disconnection of non-essential loads to balance demand.
• Time-based scheduling: Energy use during periods of lower cost or higher renewable generation.
In this way, although prosumers decide the preference and priority schedule of their consumption, it is an automated system, which may include predictive control, which facilitates the complex decision-making when regulating all consumption in a large prosumer network.
(c) Energy Storage. Battery storage or thermal storage allows managing renewable intermittency, promoting self-consumption, and improving system stability. The main applications include:
• Small and medium sized storage (electric energy): Batteries that store excess solar energy for nighttime use.
• Thermal storage: used in domestic and industrial applications, including water heaters, heat pumps, phase change and large-scale thermal energy storage installations.
• Electric vehicles (V2G): Energy transfer from vehicle batteries to the grid during high demand periods.
• Hydrogen storage: used in electrolyzers of different technologies, with varying response time characteristics and adaptability to the flexible demand regulation.
By using different storage alternatives, prosumers make their demand more flexible over different time ranges, giving their system greater resilience even for long periods.
(d) Self-Consumption Optimization and Energy Sharing Collective self-consumption and energy exchange among prosumers are facilitated through:
• Local energy communities: Networks of prosumers sharing locally generated electricity.
• Blockchain for energy transactions: Decentralized platforms enabling energy exchange without intermediaries.
This increases flexibility in demand and the overall energy balance of the facility through greater connectivity.
Taking into account these strategies, this section presents the technologies analyzed by the experimental system, which targets not only transport and distribution, but also behind-the-meter consumption. The system aims to validate flexibility strategies for small and medium prosumers by optimizing costs through the coordinated management of storage and flexible loads such as HVAC, battery and hydrogen storage, and EV charging. Among the demand regulation techniques considered are thermal energy conversion using water heaters, PCM systems, and heat pumps, which represent 20–40% of household electricity use [18, 19] and can act as virtual storage for demand response [20, 21]; hydrogen storage through electrolyzers with varied response times; and electrochemical storage, including stationary batteries and mobile systems like electric vehicles and hybrid supercapacitors.
For the effective implementation of these techniques, it is essential to identify, model and simulate the conditions under which they operate. For this reason, experimental systems are proposed in the following section that allow the validation of these flexible demand strategies applied to prosumers.

4. Results and Discussions

As part of the AGERAR PLUS project, and within the objectives of experimental validation flexible demand of this work, firstly, an experimental system is developed to perform thermal tests in the Energy Laboratory of the Instituto Tecnológico de Galicia (ITG) in Spain. The scope of these tests will be the evaluation of optimised demand response strategies for the charging of thermo-accumulators with electrical resistance, with a focus on savings and comfort. The following methodology will be applied:
- Development of numerical models of the storage water heaters,
- Selection of domestic hot water consumption profiles,
- Experimental validation to select a model sufficiently representative of real behaviour,
- Definition of cost and comfort indicators, and
- Evaluation of optimisation strategies based on cost and comfort indicators.

Likewise, the Laboratory of the National Institute of Aerospace Technology (INTA)'s Renewable Energy Area in El Arenosillo (Huelva, Spain) provides facilities based on a renewable microgrid to develop a flexible demand validation experimental system, aimed at prosumers, based on the use of different energy alternatives and control techniques. This includes different test benches for the evaluation and demonstration of electrochemical storage and power generation technologies (batteries, supercapacitors and fuel cells) at both cells and modules scale, for stationary and mobile applications. The experimental micro grid (Figure 2), where the most promising technologies are integrated and validated at pilot plant scale, complements these test facilities. The base objective of these testing facilities is to support demonstration and evaluation projects in this field, collaborating with companies and other R&D centres in the development and demonstration of their products and systems. The microgrid operation is based on a dc bus. While it isn't a common solution, this allows to safely integrates several electro-chemical devices that indeed operates on dc, and analyse their hybridization, with a more accuracy than a power-oriented focus when using an ac bus.
To demonstrate and validate the capability of prosumers in establishing a flexible demand, the renewable microgrid in the laboratory relies on the ability of its various components to manage their consumption and storage according to the available generation. A series of experimental tests are proposed to analyse how these consumptions can adapt to optimize the use of available renewable energy, minimizing the impact of generation fluctuations and allowing the system to operate in a stable and efficient manner while adequately regulating energy storage, according to previously analyzed techniques.

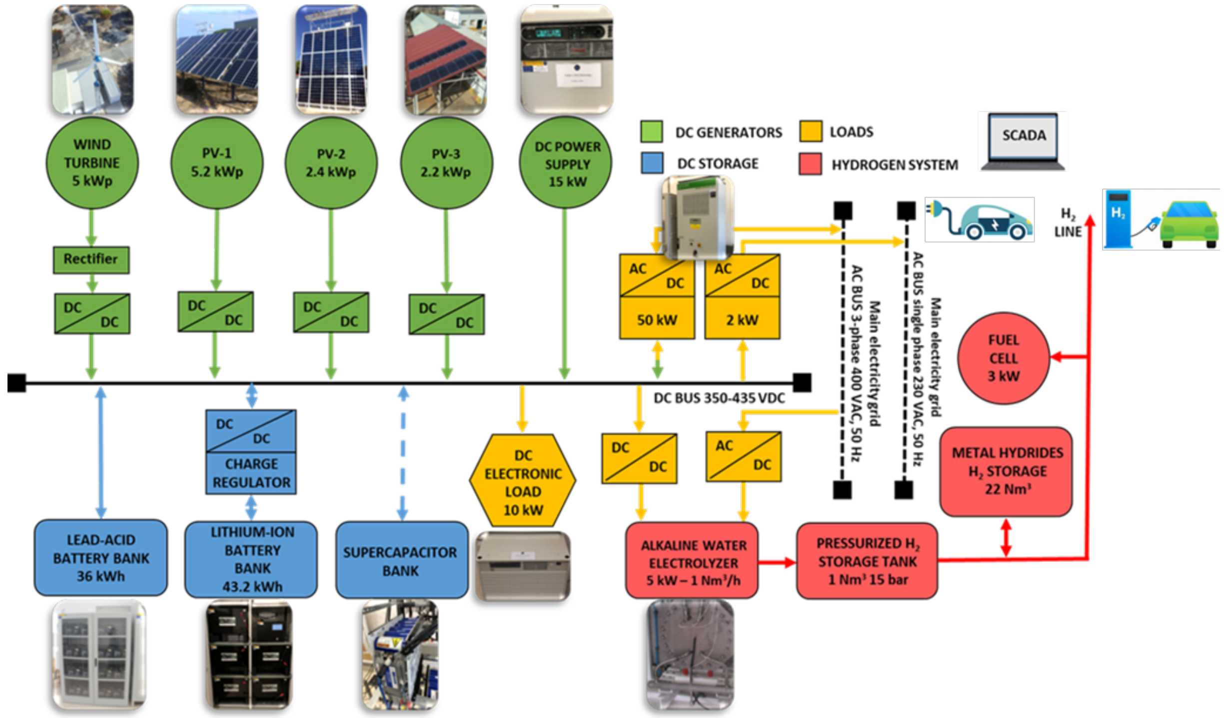

Fig. 2. Diagram block INTA Microgrid.

In the experimental system, the most relevant consumptions for validating flexible demand include the bidirectional converter with a connection to the local grid, which allows for typical consumption scenarios ranging from domestic to industrial levels, the alkaline electrolyzer as an alternative to electrochemical energy storage within the microgrid, the charging of lithium-ion batteries, which serve as the primary regulatory storage, several loads as electric vehicles or electrolyzers and the electronic load, which enables a more precise characterization of various consumption profiles. Each of these elements presents different degrees of flexibility that can be leveraged to adapt demand based on the status of energy storage and available generation. The bidirectional converter facilitates interaction between the DC bus of the microgrid, its storage and generation systems, and the connection to the local grid with high power levels, enabling the regulation of large-scale energy flows in a realistic scenario where the system's adaptation to demand changes can be analyzed. The electrolyzer, by converting excess energy into hydrogen, represents an adjustable load designed to operate during periods when renewable generation significantly exceeds consumption. Due to the slow startup inertia of this type of equipment, the electrolyzer also constitutes a demand that must be managed with an effective activation strategy to avoid causing critical supply shortages for higher-priority loads. Lithium-ion batteries, in addition to acting as the primary energy storage for the microgrid, can also be managed as a load that activates when there is excess generation and disconnects when it is necessary to reduce demand. This corresponds to a more continuous form of flexible demand over long periods, aligning well with the intermittent availability of renewable sources. The electronic load, on the other hand, allows the simulation of different consumption profiles, which is useful for evaluating the microgrid's response capability to variations in energy availability with greater precision, albeit at a smaller scale compared to other components.

The proposed tests focus on different operational scenarios in which consumptions dynamically adjust and are controlled through established strategies based on renewable generation and available storage capacity. For individualized demand flexibility tests aimed at accessible analysis, several alternatives are proposed.

First, **Test 1** is designed to analyze the charging of lithium-ion batteries, managed according to the availability of renewable generation and overall demand. During periods of high generation, battery charging is prioritized to maximize the use of renewable energy, while in low-generation periods, charging is interrupted to reduce demand on the system. This approach allows for analyzing the batteries' ability to flexibly absorb excess energy without compromising the stability of the bus while assessing the impact of this strategy on the microgrid's autonomy. Following this, **Test 2** examines the interaction of the microgrid with the local grid demand under different renewable generation scenarios. The flexibility of this demand is analyzed by studying critical cases and establishing supply criteria based on the state of storage and priority consumption levels. In this way, the bidirectional converter will facilitate demand flexibility in tests by simultaneously controlling renewable generation and the potential supply from lithium batteries, which, in turn, will also flexibly adjust their demand by changing their operational state or even just their demand setpoint. This experimental scenario also enables an evaluation of the microgrid's autonomy in supplying energy to the local grid adaptively. The system configuration for this scenario is depicted in the Figure 3.

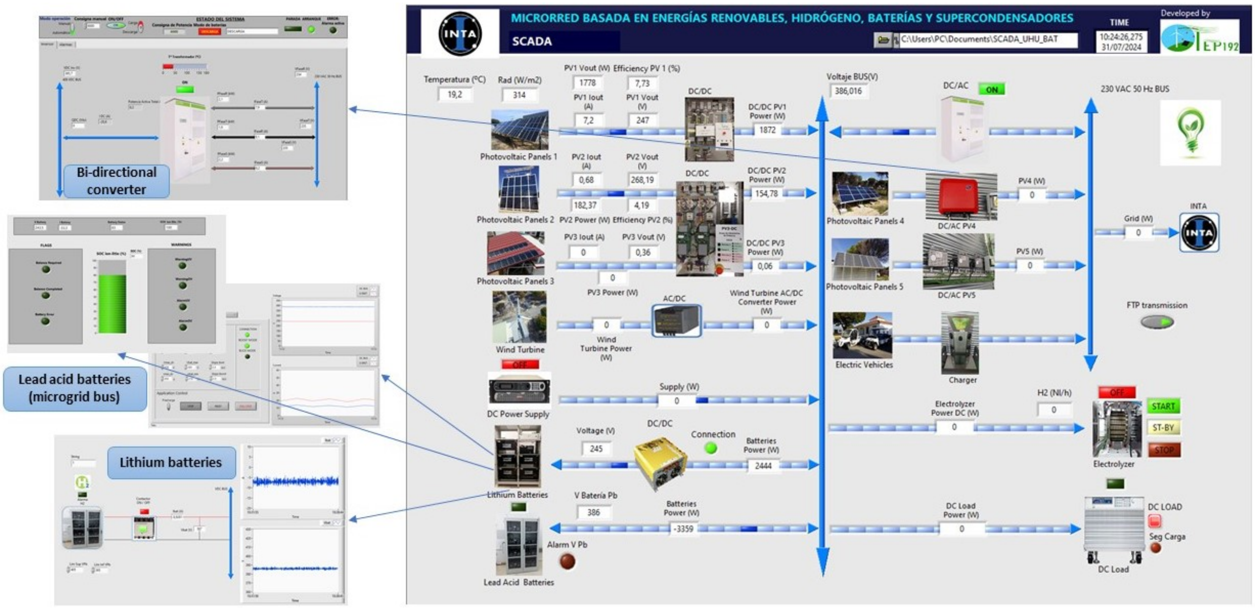

Fig. 3. Control system SCADA INTA.

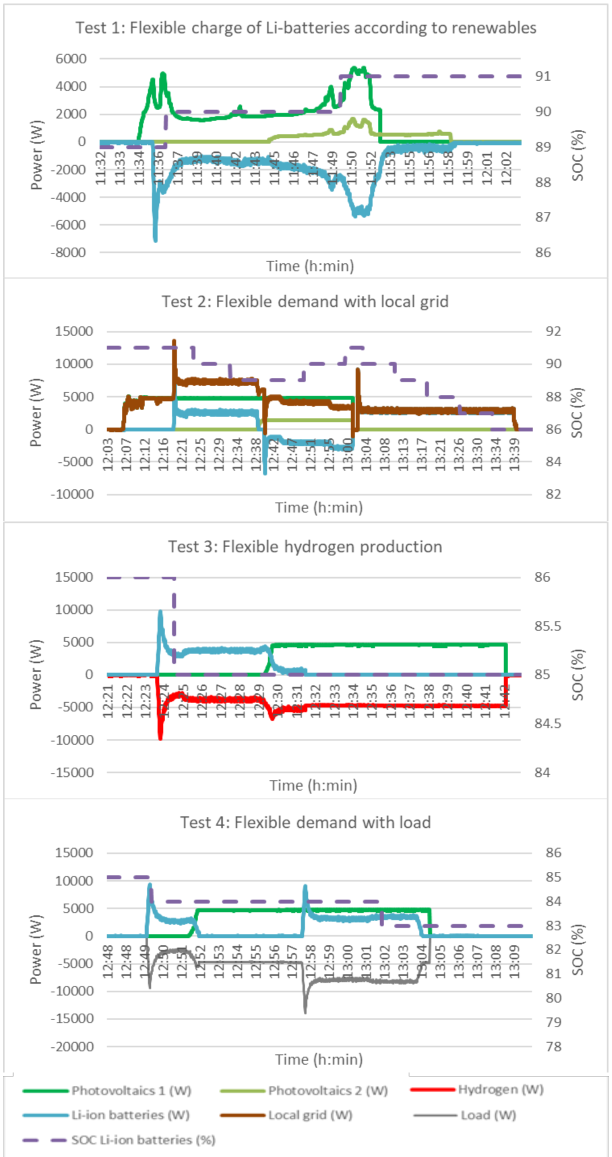

Fig. 4. Experimental results for flexible demand.

Test 3 focuses on regulating the electrolyzer's consumption based on the charge status of lithium-ion batteries and renewable generation. The aim is to determine the charge threshold of the batteries at which it becomes effective to supply energy to meet the electrolyzer's demand without compromising system stability while evaluating how overall efficiency varies when hydrogen is used as an energy storage medium. Finally, the ability of the electronic load to compensate for fluctuations in renewable generation is analyzed in **Test 4**, adjusting its consumption to maintain the stability of the DC bus. In this case, the focus is primarily on precise demand flexibility without fluctuations or ripple effects associated with other components.

The results of these tests, Figure 4, allow for the identification of the most effective strategies for managing flexible demand within the microgrid, determining which elements offer the greatest adaptability and how their management can optimize the use of renewable energy. The system's stability, energy balance, and overall efficiency of the implemented strategies are analyzed. These findings provide scalable results for developing efficient management systems that can be integrated into sustainable flexible demand frameworks.

Based on the results, the technical and economic performance of hybrid generation, storage, and management solutions are able to be evaluated by reproducing real profiles and analyzing how different storage combinations and variable loads align supply with demand flexibility. This also enables the validation of experimental models.

5. Conclusions

The analysis of flexible energy demand for prosumers demonstrates the potential of active energy consumption management to optimize the use of resources and improve the efficiency of the electricity system. Throughout the study, it has been shown that the implementation of flexible demand strategies, such as demand response and the use of energy storage, can significantly reduce costs, lower dependence on non-renewable energy sources and encourage greater integration of clean energy. It has been observed that prosumers, with distributed generation and storage technologies, can actively participate in demand management, adjusting their consumption according to market conditions and the availability of renewable energy. This not only allows them to reduce their electricity bills, but also contributes to the stability and resilience of the electricity system. Therefore, flexible demand represents a key enabler towards a more sustainable and decentralized energy system. The active participation of prosumers, combined with advances in digitalization and automation, will enable greater efficiency and equity in energy access, promoting a faster and more effective energy transition.

The AGERAR PLUS project analyses different energy storage technologies applicable to small and medium prosumers, and will support important challenges posed by the transformation of the energy sector (with serious problems in the distribution of electricity), and technological innovations will contribute to system flexibility and the massive deployment of renewable energies and will enable the entry of new market participants such as prosumers and aggregators. Continuing this research, this work proposes specific experimental systems for the validation of flexible demand energy systems, oriented to prosumers, where different previously analysed strategies can be applied.

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