



FLEX 4 FACT

Industrial flexibility platform
for sustainable factories

GUIDEBOOK ON FLEXIBILIZATION OF INDUSTRY

AND RELATED TRAINING MATERIALS

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
API	Application Programming Interface
BESS	Battery Energy Storage System
BTES	Borehole Thermal Energy Storage
CAPEX	Capital Expenditures
CPU	Central Processing Unit
CRM	Customer Relationship Management
DST	Decision Support Tool
EFPS	Energy Flex Production Scheduling Platform
ERP	Energy Resource Planning
ICFP	Industrial Cluster Flexibility Platform
MES	Manufacturing Execution System
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
OPC-UA	Open Platform Communications Unified Architecture
PPA	Power Purchase Agreement
PPS	Production Planning System
PV	Photo Voltaic
REST	Representational State Transfer
SCADA	Supervisory Control and Data Acquisition
SME	Small and Medium Enterprise
SQL	Structured Query Language
UI	User Interface

INTRODUCTION



This guidebook is designed to serve as a practical, evidence-based resource for manufacturing companies (including SMEs), grid operators, aggregators, DSOs/TSOs, and technology providers seeking to implement or scale up industrial flexibility. It brings together the key lessons, validated methodologies, and real-world results from the FLEX4FACT project, providing a clear pathway from initial assessment to full-scale operation.

1.1 HOW TO USE THIS GUIDEBOOK

To get the most out of this guide, start by reading the **Executive Summary** and **Reader Compass** to give you a clear orientation and highlight the key takeaways.

Next, dive into the **Implementation Roadmap**, which provides a step-by-step approach. As you progress, **benchmark your achievements** against real-world use case evidence.

Don't forget to **leverage the training materials** to upskill your team and secure a smooth, successful adoption. Finally, when planning for broader deployment or commercialisation, **consult the business model and scaling chapters** to guide your strategy and unlock future opportunities.

By following the structure and practical advice in this guidebook, you can accelerate your journey toward flexible, decarbonised, and digitally enabled manufacturing while delivering value for your organisation and contributing to Europe's energy transition.

After the How-To and the summary, we start with a **reader identification compass** helping you to quickly find the chapters most relevant to your company and role; whether you are a factory manager, energy manager, grid operator, or technology consultant.

To save valuable time, the document is structured to provide the **most actionable information up front**: typical implementation times, indicative costs, and validated benefits from the FLEX4FACT pilots. This enables you to estimate your own roadmap and business case before diving into technical details.

This is followed by the **technical description** from baseline assessment and digitalization, through digital twin deployment and flexibility scheduling, to aggregation, market participation, and continuous improvement. Each step is illustrated with practical tips and real-world timelines and costs.

- **Use Case Evidence:** Dedicated chapters present detailed case studies from the project's pilots, highlighting what worked, what didn't, and why. These sections provide concrete benchmarks and lessons learned to inform your own implementation.

- **For Grid and Market Actors:** Special chapters address the needs of grid operators, aggregators, and DSOs/TSOs, explaining how to access, verify, and activate industrial flexibility, and how to integrate it into grid operations and market mechanisms.
- **Tools and Training:** The annexes and dedicated sections provide checklists, and a modular training syllabus, supporting both initial deployment and ongoing upskilling.
- **Business Models and Scaling:** Guidance is provided on business model options, replication strategies, and scaling up from pilot to cluster, including cost/benefit analysis and funding opportunities.
- **References and Glossary:** The document concludes with a glossary and references for further reading, ensuring clarity and supporting deeper exploration.

1.2 READER IDENTIFICATION COMPASS

Use the map below to jump to the most relevant chapters for your role:

READER TYPE	GO TO CHAPTERS	KEY QUESTIONS ANSWERED
Manufacturing company / SME	4, 5, 7, 8	How do we implement flexibility? What are cost, time and returns?
Aggregator / Utility	4, 6, 7, 8	How do we source, verify and monetise flexibility?
DSO/TSO	6, 7, 8, 9	How to integrate industrial flexibility in grid system operations?
Technology provider / Consultant	4, 5, 6, 7, 8	How to support clients and scale solutions?

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1.3 WHAT EACH CHAPTER COVERS

2. **Executive Summary & Quick Start:** Key takeaways, implementation time, cost, and benefits.
3. **Reader Compass:** Navigation guide for different user types.
4. **Implementation Roadmap:** Step-by-step guidance from assessment to operation.
5. **Use Case Evidence:** Detailed results and lessons from five industrial pilots.
6. **Grid and Market Integration:** How to leverage flexibility for grid stability and market participation.
7. **Practical Tools and Training:** Templates, checklists, and training modules.
8. **Business Models and Scaling:** Options for commercialisation and replication.
9. **Concepts, Drivers, and Policy Context:** Why flexibility matters, and the policy/market landscape.

1.4 PROJECT GOALS

The main goal of the FLEX4FACT project was to enable flexible manufacturing in industry and create the conditions for the necessary energy transition in which all stakeholders could participate and benefit. Indeed, at least three key elements of the FLEX4FACT approach differed from previous offerings:

1. Enabling industrial flexibility through digital process twinning and machine learning techniques to address complex operational scenarios and exploit the full potential of the selected industrial cases;
2. The end-to-end approach of the FLEX4FACT platform, covering the entire technology stack required to achieve the results.
3. A modular and multi-level approach that leveraged flexible, hybrid architectures, open protocols, and standard interfaces to enable greater flexibility in the system itself and associated service offerings, remove barriers to entry for vendors in the value chain, and ensure data communication with existing IT legacy systems.

As a digital enabler for flexible energy consumption, the FLEX4FACT platform met the needs of companies of all sizes, including small and medium-sized enterprises (SMEs) that were affected by rising energy prices and had less "financial muscle" to deploy a combination of IT, manufacturing, and energy solutions.

The FLEX4FACT platform also reduced the digital divide between Northern and Southern Europe, another crucial aspect for European competitiveness: in fact, it was developed by a balanced European consortium in which critical technologies were developed and implemented by several partners in five industrial contexts, from North to South, all across Europe.

To meet the ambitions of FLEX4FACT, the project methodology was designed to pursue the following objectives:

Objective 1: Develop solutions to transform rigid production processes into flexible ones as a tool to achieve environmentally friendly production processes.

Objective 2: Create digital tools to enable flexibility and demand response in industrial processes.

Objective 3: Reuse excess energy of industrial processes.

Objective 4: Deliver a scalable and interoperable system architecture.

Objective 5: Demonstrate through 5 different pilots the benefits of the FLEX4FACT solution.

The Sustainable Development Goals (SDGs), also known as the Global Goals, were adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity. FLEX4FACT contributed to the SDGs in the following objectives:

Objective 7: Ensure access to affordable, reliable, sustainable, and modern energy for all.

Objective 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation; this was also related to CO₂ emissions per unit of value added.

1.5 USE CASES

In this section a description of the five industrial pilots of CELSA, Inaventa Solar, SEAC, SPS and Theben, is presented, together with the status at the start of the project for each industrial setting

(AS-IS). To map the manufacturing processes and constraints, the linked challenges, and objectives (quantified in KPIs), questionnaires have been sent to the industrial use cases. Second, field visits to physically map and understand the manufacturing process, IT infrastructure and other relevant control systems were carried out. Lastly, the AS-IS description has been reviewed and confirmed with the FLEX4FACT consortium.

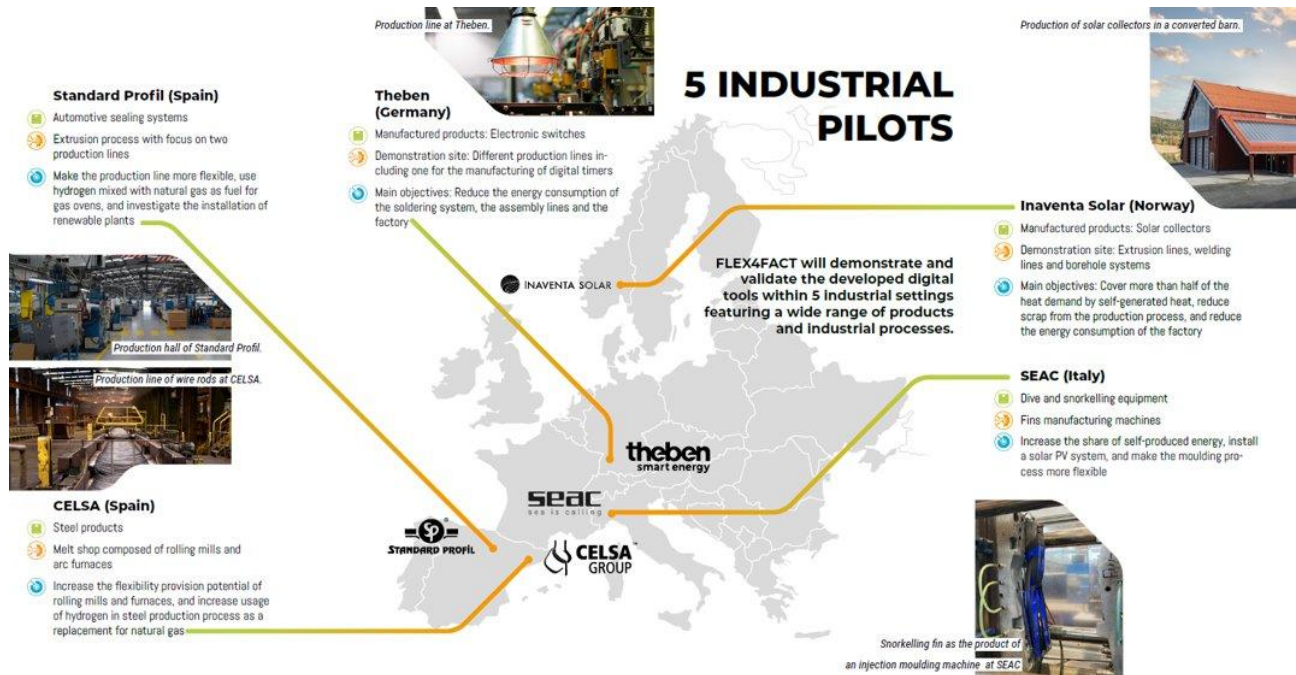


Figure 1. 5 Industrial plots

For each use case, the following model structure has been analysed and defined.

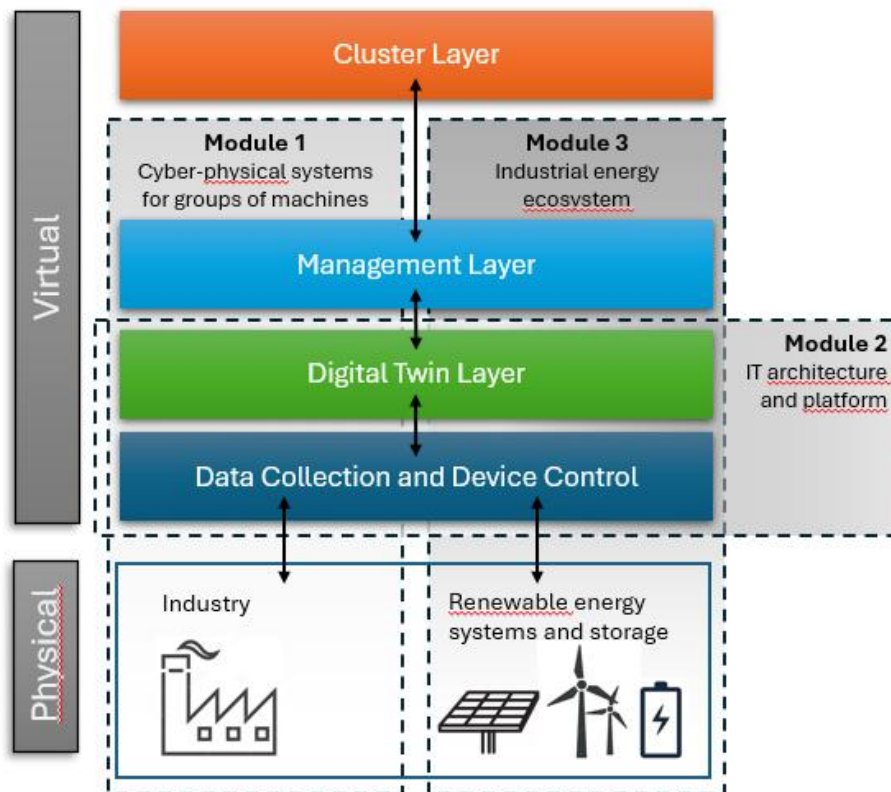


Figure 2. Model structure

1.5.1 CELSA

CELSA Group™ is one of the leading European multinationals in long steel products and has an industrial presence throughout Europe. They are one of the largest energy consumers in Spain, with an annual energy consumption of approximately 2,300 GWh. With the significant energy requirements for production, the Group has created its own platform, ALPA ENERGY, to procure energy directly from the electricity market for its own sites and later for third parties.

Locations

CELSA Group has six business units distributed all over Europe, with melt shops, rolling mills, final transformation plants, distribution companies, and scrap processors. CELSA has offices in Spain, France, Poland, the UK, Sweden, Denmark, Norway, and Finland. The headquarters is located in Castellbisbal. CELSA Group Spain has a total of 16 sites, integrating 3 melt shops with 4 electric arc furnaces (EAFs), 6 rolling mills, and 7 final transformation plants. The production layouts vary according to the machines and the product to be manufactured.

Markets and products:

The main target markets are the construction, automotive, energy, oil & gas, shipbuilding, and farming sectors. CELSA produces billets, forged products, steel aggregate, electro-welded mesh, structural profiles, basic armor, commercial bars, calibrated bars, corrugated steel, wire, wire rod, and enclosures tube.

Pilot description

The CELSA Group Melt Shop in Barcelona is one of the industrial demonstration sites of the FLEX4FACT project. It has two electric arc furnaces and three rolling mills used to produce steel. These industrial devices have great flexibility potential as they have significant power needs (40 MW each on average) and can react quickly to external requests.

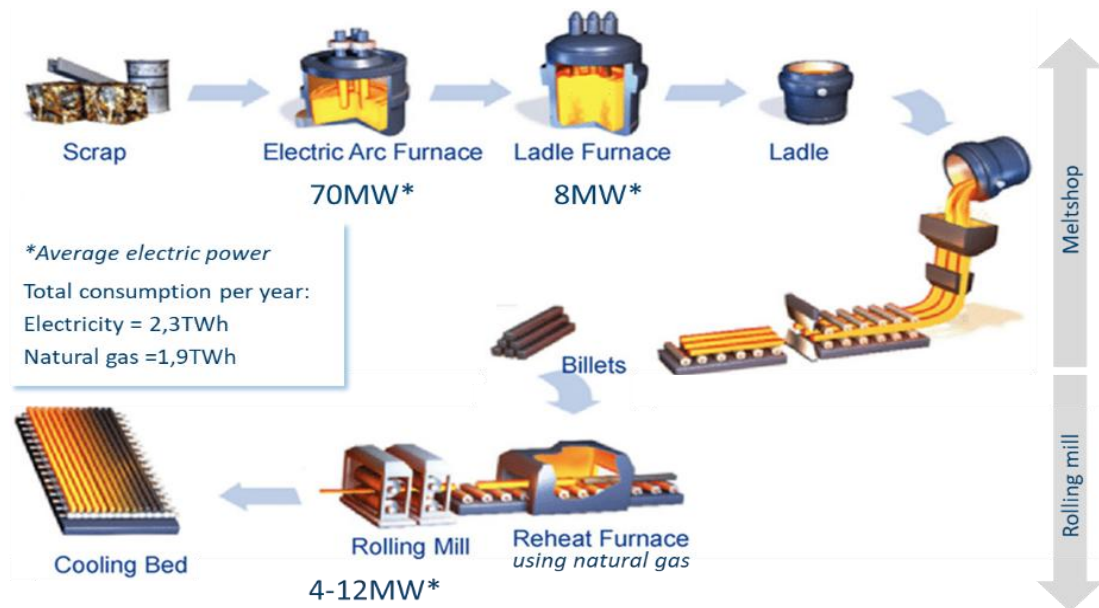


Figure 3. CELSA pilot

The objectives to be achieved under the FLEX4FACT project are:

1. to create an aggregator platform capable of forecasting electricity prices, thereby facilitating the adaption of production to optimal price scenarios;
2. to develop algorithms that enhance production flexibility, while accommodating specific operational constraints;
3. to continuously monitor the industry flexibility, achieved by predicting potential failures through the analysis of historical data from the meltshop.

Main manufacturing processes

There are four main manufacturing processes to transform the raw materials to products at CELSA:

1. **Scrap processing.** Scraps of different sizes and conditions pass through the processes of fragmentation, shearing, and torching to filter and prepare the material for the steel mill. The scrap is classified into different qualities and stored in the scrap yard in the corresponding pit according to their characteristics, separated from each other, for subsequent selective use to obtain the different types and grades of steel.

2. **Melting.** The raw material (mainly scrap) is melted to produce an intermediate product at the melt shop. The scrap gets melted in the electric arc furnace and the liquid steel is poured into the ladle furnace, where the final composition of the steel is determined, incorporating additives like ferroalloys. The charge mix recipe is determined for each type of steel by means of an optimization algorithm based on criteria of availability, quality, and cost. The liquid steel pours into the tundish and is distributed through moulds that will end up solidifying in billets or beam blanks.

3. **Lamination.** At the rolling mills, the intermediate product is laminated into long items and prepared before the final transformation. Most of CELSA's reheating furnaces are equipped with pressure and

oxygen control probes in the furnace atmosphere, combustion air oxygen enrichment systems, and flue gas heat recovery systems.

4. Final transformation. The semi-product is laminated and transformed to its final product such as rebar, rebar in coil, wire rod coil, smooth bar, bar in coil, small/medium or large structural sections.

Supply chain:

The raw material, mainly demolition waste and scrap, come to a large part of CELSA's scrap processing business units. CELSA follows the production strategy of make-to-stock (80%) and make-to-order (20%). The melting shops cast the billets and the rolling mills laminate the products based on demand and sales planning. The sales and operation planning forecasts demands, plans the production for the next weeks and months. Finally, the department allocates orders to melting shops and rolling mills and so aligns product demand with production output.

Challenges

The main challenge linked to these objectives is to increase flexibility potential through the flexible operation of the electrolyser and the associated hydrogen storage system. It will be essential to develop an interface between the aggregator and the Manufacture Executing System (MES) to best manage the steel production process and the provision of flexibility to the grid.

Another challenge will be the development of a digital twin of one of the rolling mills to get a better understanding of the mills' functioning and to know which factors impact most the process. This will contribute to improve the efficiency of the furnaces which is expected to lead to a reduction in CO2 emissions. Increasing amount of renewable power, either self-generated or purchased, will be required to run the electrolysers. CELSA plans to install solar PV systems on the roofs of its plant to produce renewable energy to power the electrolysers and produce green hydrogen.

1.5.2 INAVENTA SOLAR

Inaventa Solar is a Norwegian solar energy company that aims to industrialize and commercialize innovative solar collector technology based on high-temperature performance polymers. The company was established in 2019 as a subsidiary of the company "3 Norske", a group of several flagship Norwegian industrial enterprises. The annual production capacity of the company's extrusion line stands at 600 000 square meters of solar collector absorbers.

Locations:

Inaventa Solar's factory in Jevnaker is part of a larger complex focused on energy, environment, and sustainability. This includes the production of organic food and pilot testing of new heat/storage solutions as well as the production of renewable energy from solar collectors. Head office: Inaventa Solar AS, Pustutveien 18, 1396 Billingstad, Norway Production: Inaventa Solar AS, Glassverkvegen 91, 3520 Jevnaker, Norway

Markets and products:

Inaventa Solar's key product are solar collectors for building integration (BI), replacing conventional surface claddings and simultaneously producing thermal energy. As the solar collector parts are almost all extruded, any collector length between 2-6 m can be produced and fitted, as necessary for building envelop systems.

Target markets for Inaventa Solar's collectors are applications for domestic hot water (DHW) preparation and space heating of residential homes, larger-scale projects and commercial buildings. The Inaventa Solar BI technology preferably addresses "professional customers"; direct sales to

larger projects and through partners (e.g., type house companies, district heating companies, public owned properties, building and construction companies, application within agriculture).

Pilot description

The Norwegian Inaventa use case includes the production of polymer solar collectors with PPS sheet extrusion and infrared welding for jointing the absorber parts as core processes. Renewable heat will be produced by installed roof-integrated solar collectors for domestic hot water preparation and space heating of the factory building. Excess heat from the extrusion process and the solar collector system can be stored in a borehole thermal energy storage (BTES).

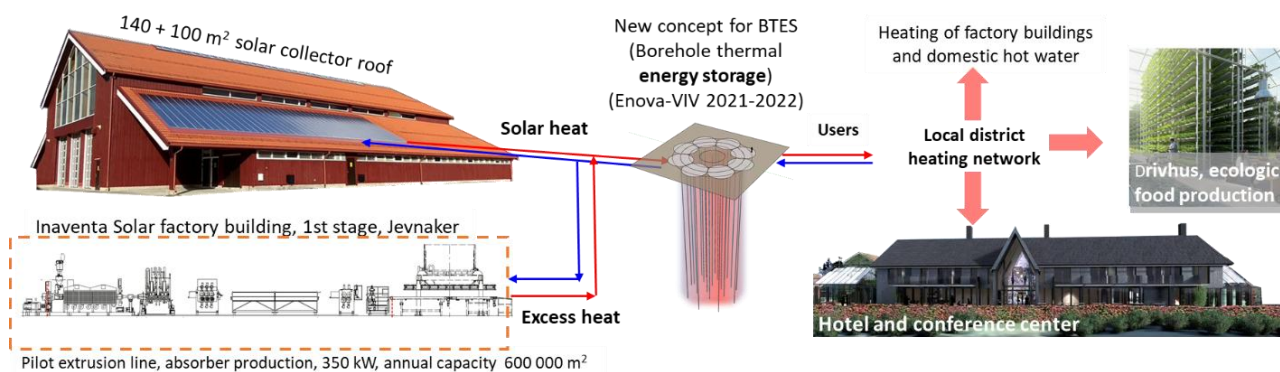


Figure 4. Inaventa Solar pilot

This use case aims to reduce scrap production in the extrusion of PPS to less than 5% resulting in less wasted energy. In addition, the heat demand of the factory building is to be covered by up to 60% by self-generated heat. Another goal is to recover 50% of the energy supplied to the BTES after reaching a steady state and to reduce the energy consumption of the factory by up to 20%.

Main manufacturing processes:

The main manufacturing processes performed in-house are extrusion, infrared welding, surface coating of the absorber, cutting of aluminium frames and solar collector cover sheets:

1. Extrusion of the high-temperature performance polymer PPS (polyphenylene sulphide) to sheets with intrinsic channels (twin-wall sheets), which is the so-called "absorber"
2. Infrared (IR)-welding of 2 injection-moulded endcaps at each side of the extruded absorber sheet
3. Surface coating of the absorber: Water-based paint coatings are applied in a spray coating line to enhance the solar absorptance (and reduce thermal emittance) of the absorber. The coating line includes a hot-air drying oven to reduce the drying time.
4. Cutting of aluminium collector frame profiles (circular saw).
5. Cutting of solar collector cover sheets ("blade").

Supply chain:

Inaventa Solar purchases several products from external suppliers. The injection moulder of solar collector endcaps, which are moulded of black glass-fibre reinforced PPS, is purchased from an injection moulder in Vestfold, Norway. Twin-wall sheets of polycarbonate, which are the transparent collector cover of Inaventa's Solar collector are purchased from the extrusion company in France. Solar collector frame profiles are purchased from aluminium extrusion company in Norway. And finally, a mineral wool supplier in Slovenia delivers high-temperature grade rock wool, which is used as the thermal insulation of Inaventa's Solar collectors.

Challenges

To minimize scrap production, energy and raw material consumption in the extrusion process, condition monitoring and predictive maintenance will be implemented. This will help avoid non-planned maintenance stops and optimize the scheduling of the process, resulting in fewer operations hours, energy, and material costs. The borehole thermal energy storage will allow the storage of excess heat from the extrusion process and the solar thermal system and allow flexible utilization at the plant site or surrounding buildings.

Other challenges connected to the objectives will be the development of a digital energy twin, to forecast the energy behaviour of the factory, including its surroundings. By using the flexibility options, energy costs can be reduced by 20%.

1.5.3 SEAC

SEACSUB is an Italian SME founded in 1971, a leader in the diving sector with a worldwide reputation, that can compete with big players on the international market thanks to their attention to quality and product sustainability. Over the past 3 years, SEAC started a process of re-nationalizing the production process, which was performed by international factories until then, while the assembly, quality control, and packaging was always carried out by SEAC's personnel.

Nine moulding machines were purchased to produce plastic components and products such as fins, masks, and thermoplastic components. This investment is extremely strategic as it allows SEAC to have a deeper control on products' customization and quality assurance processes but came with a substantial increase in the company's energy consumption which grew of over 200% since the first installation of moulding machines. The company is planning to install photovoltaic cells on the roof of their building in Italy. SEAC aims to utilize the generated energy through a local grid, but it will also investigate and evaluate the potential for sharing and monetizing the generated energy.

Locations:

The headquarters and main factory are located in San Colombano Certenoli, Italy. SEACSUB internationally operates and has a branch plant in Miami, US.

Markets and products:

SEACSUB produces scuba, freediving, snorkelling, spearfishing and swimming equipment. The company has a product portfolio of almost 4.000 products and 2.000 components and many different plastic raw materials. Plastic components and products are manufactured in moulding machines and are later used for the final product assembly: fins, masks, speargun components, mask components, fin components, regulator components, and components for buoyancy control devices.

Pilot description

The SEAC use case consists of the moulding process (10 moulding machines) as well as the energy management process. The goal is to fully redesign the production process to maximise the use of the energy flexibility offered by the process. The machines only consume electric power (over 65% of the company's consumption) and can be controlled remotely.



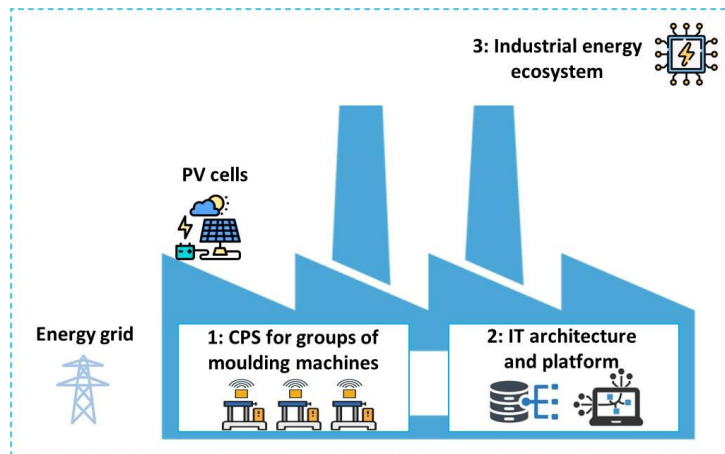


Figure 5. SEAC pilot

Main manufacturing processes:

SEACSUB performs moulding, assembly, quality control, and packaging in-house. Moulding is the main manufacturing activity. There are currently nine moulding machines producing plastic products such as fins, masks, and thermoplastic components. The machines perform discrete manufacturing moulding operations of plastic materials. The machines are powered solely by electric power and can be remotely controlled. Their consumption represents 65% of the company's total energy consumption. The rest of the consumption is given by loads not strictly related to production.

Supply chain:

Most of the product components are produced in-house, only a few parts are purchased, such as the glass for masks.

Challenges

The redesign of the production process to maximise the use of the energy flexibility involves the development of an energy digital twin of the SEAC moulding plant. This model, linked to the data acquisition system, will make it possible to know the energy behaviour of the plant in real time and estimate its energy consumption. Based on forecasts of energy prices and PV generation, the energy management of the entire plant will be optimised.

1.5.4 SPS

Standard Profil (SPS) is a Spanish company founded in 1969, specialised in the manufacturing of sealing systems for the automotive industry. With 1081 employees, the company generates a turnover of approximately €136 million per year. SPS is able to cover all phases from concept development to the manufacturing of complete sealing systems, including 3D design and prototyping, finite element structural analysis, computational fluid dynamics analysis, project management, tool design, and other disciplines related to product and process development.

Locations:

SPS has four production facilities in Spain. The Varea plant is the technology and mixing center. The Cantabria plant is specialized in EDPM & TEP extrusion. The Lipar and Mendavia plants focus on product finishing.

Markets and products:



SPS develops, manufactures, and supplies automotive sealing systems. The products manufactured by SPS are developed and designed according to customer (automotive OEMs) specifications and are made exclusively for each one of them. SPS delivers the produced parts to around 40 car assembly plants throughout Europe, and to almost all automotive manufacturers, from generalists to premium car manufacturers (Ford Motor, General Motors, Volkswagen, SEAT, Renault, Peugeot Citroën, Mercedes, Toyota, Nissan, Tesla, BMW, Mercedes Benz, Maserati, etc.).

Pilot Description

As a core process of the SPS manufacturing system, the extrusion process will be SPS's pilot case within FLEX4FACT. It is a continuous process carried out along a line with successive sub-processes of about 120 m in length.

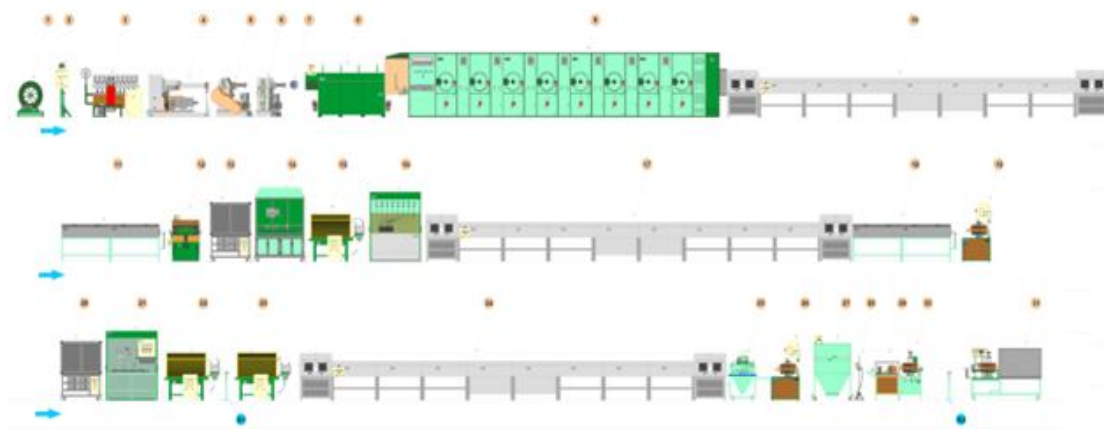


Figure 6. SPS pilot

SPS aims to make its extrusion lines more flexible by adjusting its production schedule and considering external factors as decision variables such as energy price and related CO₂ emissions as well as local availability of PV self-generation.

In addition, the feasibility of implementing an electrolyser and storage system to produce, store and use green hydrogen will be studied. Using hydrogen as fuel for gas ovens in a suitable mixture with natural gas will decrease the CO₂ emissions of the furnaces.

Main manufacturing processes

SPS manufactures sealing systems with different configurations of extruded profiles. Thereby, two overall manufacturing processes are applied:

- ✓ Manufacturing of rubber compounds
- ✓ Profile extrusion

SPS has a strong expertise in rubber compounds. The raw materials are mixed at the SPS plants to achieve high processing and usage performances. The extrusion process is an intermediate process in the SPS manufacturing flow. Different profiles are manufactured in extrusion process which are later used for the final assembly of the parts. These profiles are collected in bars or reels depending on the characteristics of the profile and the following finishing process.

Supply chain:

SPS has several raw materials suppliers. In general, none of the main manufacturing processes are subcontracted to suppliers. SPS produces the sealing systems and delivers the products to the car manufacturing plants with a Just-In-Time supply strategy.

Challenges

A challenge associated with these objectives will be the development of a digital twin of the extrusion process that model its behaviour, taking into account energy consumption and final product quality. In addition, a production planning system will be developed for the extrusion process, that could also be later used for other processes. The planning system will take the origin of the energy used and the associated emissions as an optimisation criterion.

Another challenge will be the development of a digital energy twin of the whole SPS extrusion plant in Cantabria, to gain knowledge on the real-time energy behaviour of the plant and be able to make energy consumption's forecast based on various plant management scenarios. An energy business model will be developed that includes the plant's energy flows and make a link to an external aggregation platform. It will be used as a decision support tool by the plant operator and plant energy manger to decide on the best energy management strategy.

1.5.5 THEBEN

Theben AG was founded in 1921 in Stuttgart. In the 1990s, Theben began developing European installation bus (EIB) technology with the first BUS- compatible time switches and twilight switches. Lately, Theben AG played a key role in the development of the EIB technology, the forerunner of the worldwide KNX standard for building system technology. The current developments of Theben AG concern smart energy innovations as well as smart metering systems with extended communication and visualization of data consumption. The CONEXA 3.0 Performance Smart Meter Gateway was approved by the Federal Office for Information Security for operation in the German power grid.

Locations:

Theben AG produces switches and electronic systems (e.g., smart home systems, dimmers, actuators) at its site in Haigerloch (Baden-Württemberg / Germany), with 13 subsidiaries and branches around the globe.

Markets and products:

The company is highly globally active and has an export rate of 64%. The product portfolio is divided into four segments of 1) controls & HVAC, 2) detection & lightening, 3) building automation, and 4) smart energy.

Pilot description

The Theben use case involves the production site of switches in Haigerloch. The production process consists of four soldering machines, a heat exchange, a photovoltaic system, various assembly lines.

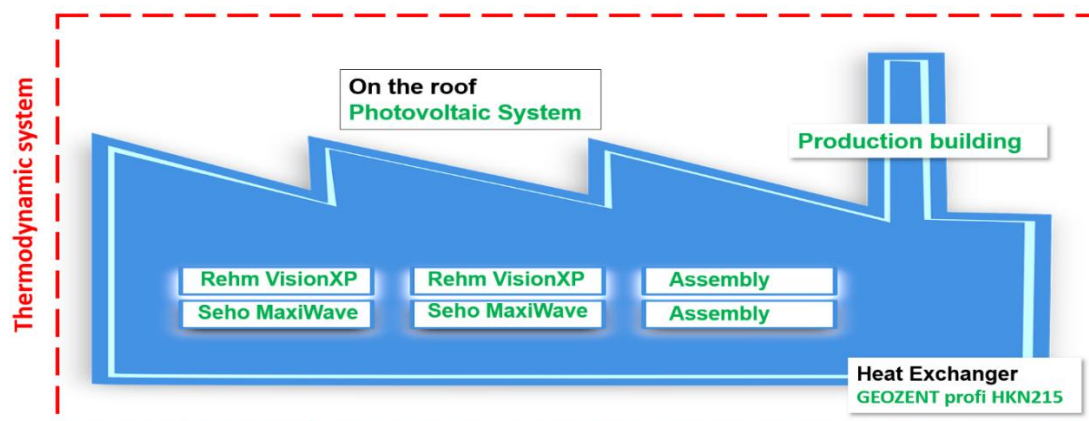


Figure 7. Theben pilot

The objectives of this use case will be to reduce the energy consumption of the soldering system, the assembly lines and the building by 5-10% by using smart sensors for data collection and using cyber-physical systems to optimize production. Furthermore, it is planned to increase the local energy generation of the photovoltaic system by 5-10%.

Main manufacturing processes:

Production is based on fully and partially automated processes. There are three main manufacturing processes:

- ✓ Soldering
- ✓ Assembling
 - 100% quality check in VDE-certificated laboratory with main equipment of 4x soldering lines, 1x heat exchanger, 1x photovoltaic system, several assembling lines.

Supply chain:

Theben has a large number of suppliers and there is not a significant main supplier. However, Theben is strongly impacted by the current supply chain disruption. The company has started to inventory crucial parts due to price fluctuations and availability. The availability of components significantly affects the daily operations and the production planning. Theben follows mainly a Make-To-Stock supply chain strategy.

Challenges

To reach these objectives, several challenges need to be addressed within this use case:

1. Coordination and interlinking of internal energy consumption with internal energy production;
2. Development of a digital twin of the process to map the energy flows;
3. Implementation of sensors to record energy consumption at the Haigerloch plant (e.g. smart meter gateway);
4. Introduction of a energy management system;
5. Reducing dependence on external energy suppliers by increasing on-site energy production through new solar PV capacity.

Please see Annex A and **D1.1** for further details.

1.6 CONCEPT AND ARCHITECTURE

FLEX4FACT builds on a **modular and multi-level architecture** that leverages the provision of flexibility from the industry through digital process twinning, machine learning techniques and novel algorithms supporting modern manufacturing planning and scheduling.

The FLEX4FACT concept consists of four layers:

- the **Factory Cyber-Physical** layer that links the digital tools and the physical processes of the industrial use cases,
- the **Factory Dynamic representation** layer which maps the energy needs and manufacturing constraints of the industrial processes,
- the **Factory Energy Flexibility** layer connecting the industrial clusters and sites to the energy markets and players,
- and the **Factory Renewable Integration** layer which helps to identify the potentials for renewable energy production, energy storage and valorisation of excess streams.

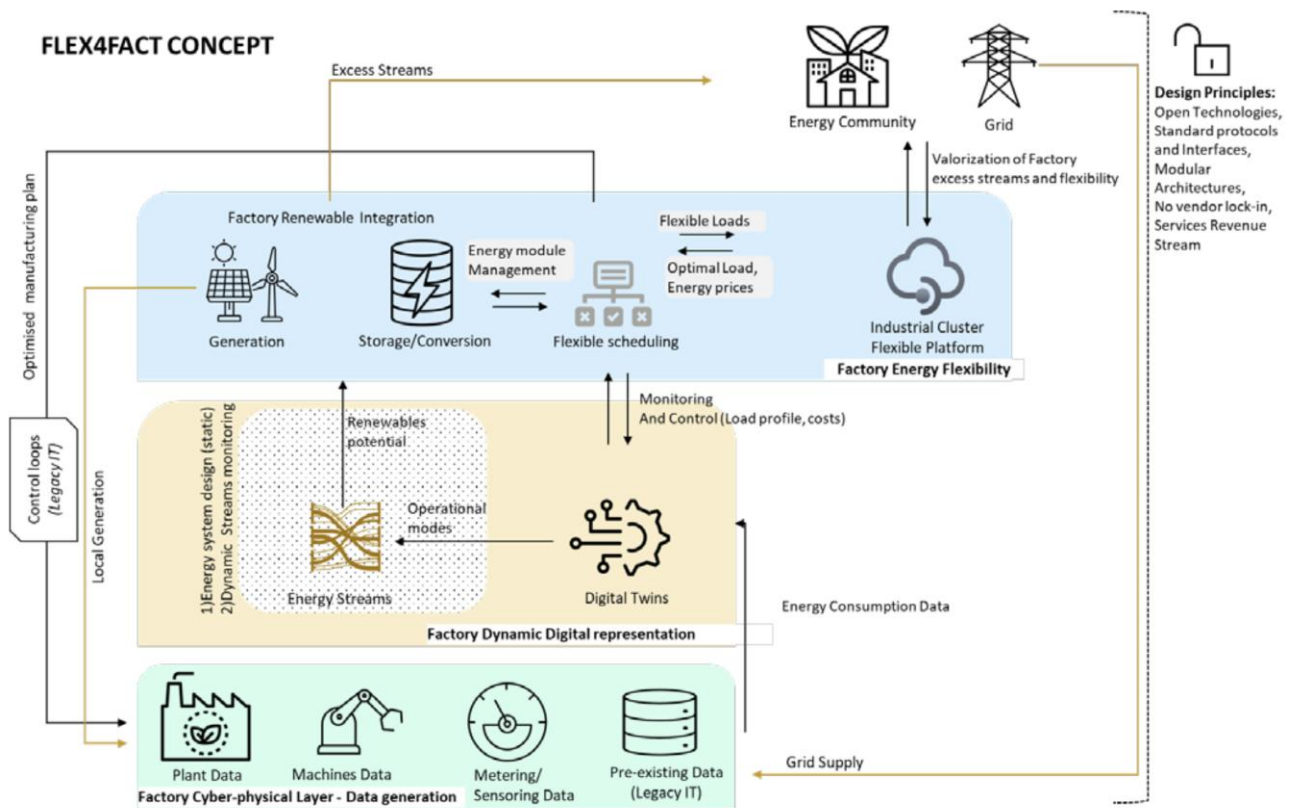


Figure 8. FLEX4FACT concept

To define and develop the reference architecture and design principles at the FLEX4FACT system level, a **Three-step approach** has been implemented. This approach involved conducting a systematic literature review, a digital survey and a series of digital workshops.

1.7 REFERENCE ARCHITECTURE

The published frameworks identified in the literature review mainly focus on the interaction between the smart grid and aggregator layers or have a strong energy demand management focus in industrial cases. Throughout the workshops with experts from the aggregator, energy, digitalization, and manufacturing sites, all agreed that the current frameworks in literature lack a **comprehensive framework** that allows for the implementation in industrial companies and for layers to be connected and communicated **from the physical to the aggregator layer**. The literature review results emphasize the importance of smart grid systems in enabling industrial demand response, which can help create a stable, efficient, scalable, and cleaner electrical energy system. As a result, the developed framework focuses specifically on the key activities relevant to aggregators and industrial manufacturing companies. Both the literature and the expert group have recognized the general DT framework as suitable for representing the entire communication line with critical activities for industrial demand response services.

Manufacturing companies can find interruptions or significant reductions in production difficult to manage. To provide demand response capabilities that are attractive, it is advantageous to have

local renewable energy and storage systems. These systems can be highly effective in allowing production to continue while simultaneously providing demand services to reduce energy peaks in the grid. However, these systems must be properly managed to interact with production and the aggregator at the right time. Therefore, it is essential to establish an end-to-end data infrastructure. Data plays a critical role in identifying high-energy consumers in production and understanding energy reduction capabilities. Appropriate sensors and meters need to be selected and applied to identify high-energy consumers in manufacturing, and machine data needs to be extracted. In the digital layer, which includes the data infrastructure layer, it is important to define data collection, interfaces, data structure, and data storage to ensure consistency, interoperability, and system robustness. The data must be processed (e.g., data cleaning, fusion, etc.) to enable data-driven simulation and optimizations. In the DT layer, various DTs need to be established and interact to reflect both manufacturing and energy flow processes. Their detailed representation allows for the simulation and optimization of complex manufacturing processes, with a focus on energy factors, to provide a baseline and different scenarios for energy consumption profiles. The results of simulation and optimization must be presented and visualized for decision-making, which occurs in the management layer.

The management layer focuses on establishing a manufacturing and energy system for flexible and adaptive consumption profiles. Decision-making in this layer ranges from strategic to operational levels. Production needs to identify its manufacturing flexibility in times of production scheduling, while energy needs to integrate renewable energy and storage systems and drive effective demand-side management. The aggregator agent that provides demand response services connects many different manufacturing companies and performs forecasting of energy demands and supplies to identify potential energy gaps, providing flexibility to the grid. By communicating with manufacturing companies and exchanging possible consumption profiles, the aggregator can optimize the cluster and provide incentives back to the manufacturing companies to encourage them to provide energy flexibility to the grid.



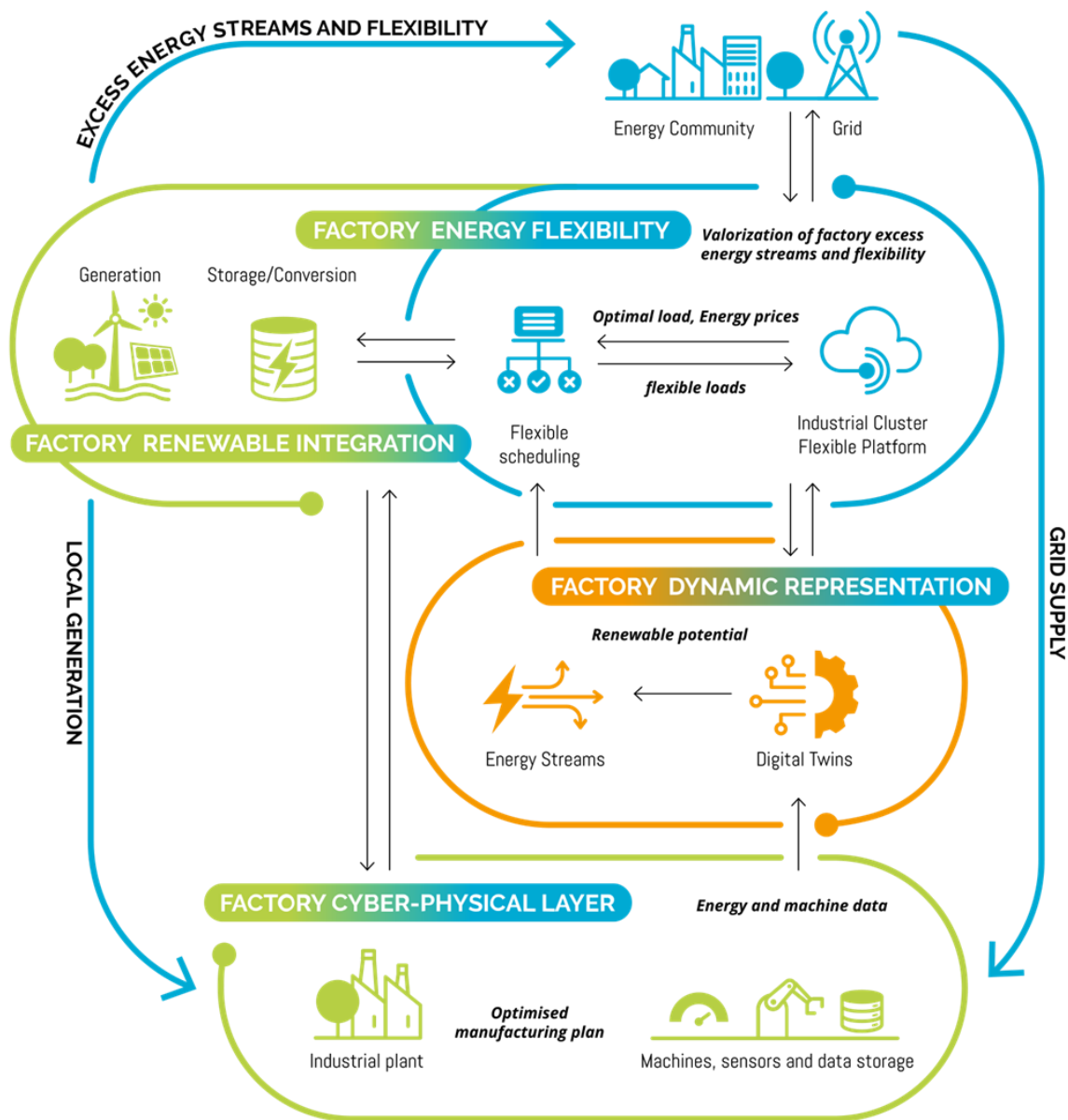


Figure 9: Reference architecture

To enable demand response services, consistent and seamless interaction between the physical, data infrastructure, DT, management, and aggregator layers is essential. Through the use of an SLR and workshops with experts, the crucial activities and communication structure required for industrial demand response services have been identified and integrated into a framework.

This framework is visualized in Figure 9 above.

2 QUICK START

Implementing flexibility solutions requires careful planning—not only in terms of technical steps but also in understanding the resources involved. The Time and Cost Assessment table provides a clear overview of the estimated effort and investment for each stage of the roadmap. It helps you anticipate project timelines, allocate budgets effectively, and identify phases that may require additional support. By using this table as a reference, you can set realistic expectations, prioritise actions, and ensure that your flexibility strategy delivers maximum impact within your operational and financial constraints.

ITEM	TYPICAL IMPLEMENTATION TIME	INDICATIVE COST RANGE	VALIDATED BENEFIT (EXAMPLES)
ICFP usage replication (cluster platform)	1–3 weeks	Up to ~€130k for new cluster; lower within same corporate group	External market: ~€500/day for ~0.305 MWh/day positive flexibility; battery rightsizing insight avoided oversizing
EFSP scheduling rollout	Weeks (pilot dependent)	Case-specific (connectors, cloud)	Energy cost reduction and higher RES share (e.g. +64% RES at a pilot; energy –17%)
Digital Twins (site level)	1–10 days for similar sites (typical)	One person-week to five-digit investment depending on scope	Real-time KPIs, quality/energy optimisation, flexibility identification
BESS investments (site level)	2–6 months (specification→ commissioning)	Battery: ~€400/kWh; inverter: ~€60/kW (+EPC)	Self-consumption increase, bill savings; payback feasible for smaller sizes in some pilots
Hydrogen blending (industry-specific)	6–18 months (feasibility→ pilot)	PEM electrolyser: ~€750/kW; storage (30 bar): ~€654/kg (+balance of plant)	CO ₂ reduction proportional to NG substitution; economics depend on electricity price vs gas

Table 1: Metrics from FLEX4FACT pilots



3 IMPLEMENTATION ROADMAP: FROM ASSESSMENT TO OPERATION

The Implementation Roadmap is your practical guide to transforming flexibility concepts into operational reality. It provides a structured, 6-step approach that helps you move from initial assessment to full-scale deployment with confidence. By following this roadmap, you will learn how to map your energy and process flows, integrate digital tools, and leverage advanced optimisation techniques. Each stage is designed to build on the previous one, ensuring a smooth transition from planning to execution while maximising efficiency, sustainability, and business value. Whether your goal is cost reduction, CO₂ savings, or market participation, this roadmap equips you with the tools, templates, and best practices to succeed.

3.1 STEP 1 — BASELINE ASSESSMENT

Begin by mapping your energy flows and core processes to understand where flexibility can be introduced. Conduct a flexibility screening to identify assets that can shift or modulate demand without compromising production. At the same time, perform a digital maturity check to assess your readiness for integration and automation. This will guide the level of investment and technology adoption needed.

3.2 STEP 2 — DATA & INTEGRATION

Prioritise existing data signals from your current infrastructure and plan connectors for systems such as SCADA, ERP, MES, and IoT devices. Ensure interoperability and scalability from the start. Apply a security-by-design approach to protect sensitive operational and market data, embedding cybersecurity measures into every integration step.

3.3 STEP 3 — DIGITAL TWINS

Start small by creating a digital twin for one production line or critical asset. Validate its accuracy using real operational data and calibrate the models to reflect actual performance. Define clear KPIs, such as energy efficiency, flexibility potential, and cost impact to measure success and inform future scaling.

3.4 STEP 4 — SCHEDULING & OPTIMISATION

Deploy the Energy Flexibility Planning and Scheduling Platform (EFPSP) to optimise operations. Configure price and CO₂ forecasts to enable cost-effective and sustainable scheduling. Test internal flexibility markets using APPs to simulate trading scenarios and identify the most profitable and environmentally friendly strategies.

3.5 STEP 5 — AGGREGATION & MARKETS

Onboard your site to the Industrial Flexibility Platform (ICFP) and run internal markets that account



for both cost and CO₂ impact. Once internal optimisation is proven, test external market participation through day-ahead and ancillary service offers.

3.6 STEP 6 — ENERGY STRATEGY IDENTIFICATION

Identify additional levers to maximise flexibility and sustainability beyond scheduling. Evaluate the feasibility and impact of integrating technologies such as Battery Energy Storage Systems (BESS), photovoltaic (PV) generation, and hydrogen blending. Use scenario modelling to compare cost savings, CO₂ reduction potential, and payback periods. Prioritise options that align with your operational profile and market conditions, ensuring scalability and compliance with safety standards.

3.7 STEP 7 — ACCEPTANCE, TRAINING AND CHANGE MANAGEMENT

Ensure successful adoption by engaging operators and planners early in the process. Conduct user acceptance tests on digital twin interfaces and EFPSP dashboards to validate usability and functionality. Provide training sessions focused on interpreting KPIs, generating flexibility offers, and managing exceptions. Establish clear SOPs and a RACI matrix to define roles and responsibilities. Continuous feedback loops and incremental improvements will secure long-term integration and cultural acceptance of flexibility practices.

3.8 M&V AND CONTINUOUS IMPROVEMENT

Implement dashboards for real-time monitoring and conduct regular audits to verify performance. Adjust storage sizing and operational strategies based on measured results. Continuously iterate your business case to reflect updated market conditions, technology improvements, and sustainability targets, ensuring long-term competitiveness.

3.9 TIME AND COST

Understanding the time and cost implications of each implementation step is essential for effective planning and resource allocation. This table provides a clear overview of the estimated effort and investment required for each phase of the roadmap, helping you prioritise actions and align them with your budget and timeline. By reviewing these figures upfront, you can set realistic expectations, identify potential bottlenecks, and ensure that your flexibility strategy delivers maximum value with optimal efficiency.

WORKSTREAM	TYPICAL TIME	INDICATIVE COST NOTE
Digital twin (similar site)	1–10 days (configuration)	One person-week to several k€ depending on complexity

EFPSP onboarding	Weeks (data connectors, pilots)	Depends on IT integration and training
ICFP replication	1–3 weeks	Up to ~€130k for new cluster; lower for roll-outs in same group
BESS sizing & procurement	2–6 months	Battery ~€400/kWh; inverter ~€60/kW (+EPC/O&M)
Hydrogen pilot (blending)	6–18 months	PEM ~€750/kW; storage ~€654/kg (+BOP)

Table 2: Indicative timelines and costs (context-dependent; see Use Cases)

4 USE CASE EVIDENCE: PILOTS, RESULTS AND TECHNICAL IMPLEMENTATION

If you decide to invest in the digitalisation of your factory to achieve energy flexibility, it’s essential to understand the practical steps and success factors for implementation. Drawing on the five use cases from Flex4Fact, this guide outlines the key activities, technologies, and organisational requirements that enabled measurable reductions in energy costs and emissions. By following these evidence-based steps covering data preparation, digital twin deployment, production scheduling optimisation, cluster participation, and energy strategy pilots, you can replicate proven results and maximise the return on your digitalisation investment.

4.1 STANDARD PROFIL (SPS)

Standard Profil (SPS) implemented a digital twin for its extrusion lines, enabling real-time monitoring and optimisation of energy consumption and process parameters. This allowed SPS to improve extrusion efficiency and increase line speed by over 25% on the pilot line, while maintaining product quality.

The EFPSP was integrated across six production lines. EFPSP algorithms generated optimised production schedules in under five minutes, achieving an average daily energy flexibility of 942.8 kWh (target: >700 kWh), an average daily energy cost reduction of 7.6% (target: >5%), and an average CO₂ emissions reduction of 8.6% (target: >5%).

Flex4Fact’s cluster concept, via the Industrial Cluster Flexibility Platform (ICFP), enabled SPS to offer flexibility to the local energy market, supporting both internal and external optimisation. This provided additional economic benefit and supported decarbonisation at the cluster level.

Battery Energy Storage System (BESS) scenarios were modelled to further increase flexibility, enabling load shifting and peak shaving for additional cost savings. Hydrogen blending scenarios, based on comparable plants, showed the potential for annual CO₂ reductions of up to 163,000

tonnes when substituting 30% of natural gas with green hydrogen. For SPS, CO₂ reduction is proportional to the hydrogen share and gas usage.

Flex4Fact's digital twin, EFPSP, and cluster tools delivered measurable economic and environmental benefits for SPS: reduced energy costs, increased operational flexibility, and lower emissions, with further gains possible through BESS and hydrogen blending.

- The **DT** gave SPS a validated energy vs. speed model to adjust operations without sacrificing quality.
- The **EFPSP** translated that into **<5minute** optimised plans, **~943 kWh/day** flexibility, **7.6%** energy cost cuts, and **8.6%** CO₂ reduction on average.
- Via **ICFP**, this flexibility becomes **tradable**, creating monetisation paths and cluster-level impact.

4.1.1 SITE PREPARATION & DATA FOUNDATION

OBJECTIVE

Make production and energy data available, reliable, and secure for modelling and scheduling.

Inputs

- Existing PLC/SCADA for six co-extrusion lines (extruders, IR/MW/gas convection ovens).
- Energy meters (electricity) and gas consumption data.
- Production plan (jobs, profiles, line speeds, set-ups, labour constraints).

Activities

- Map the **tag list** and signals per line (temperatures, set-points, speeds, power).
- Establish data export from OT layer (e.g., OPC-UA/SCADA historian) to the modelling stack.
- Clean historical datasets (typical weeks and peak/low periods) for baseline calibration.

Deliverables

- A **data inventory** (signals, sampling rates, units).
- **Historical datasets** aligned to shifts for baseline and KPI calculations (for details see D6.9).

Roles

- SPS maintenance/automation lead (signals), Flex4Fact DT & scheduling engineers (data model).

Effort drivers

- Heterogeneity of lines/profiles; availability of historical gas/electricity time series matched to orders.



4.1.2 DIGITAL TWIN (DT) DEVELOPMENT & VALIDATION OF THE EXTRUSION PROCESS

Objective

- Build a hybrid physics-based/data-driven DT to predict **energy use vs. line velocity** while preserving **quality constraints** (vulcanisation/foaming/geometry).

Activities

- Develop a **manufacturing line DT** that couples:
 - **CFD** of co-extrusion head (reduced to a ROM for speed).
 - **FEM** of curing/foaming in IR, MW, and gas convection ovens.
- Build a **gas convection oven DT** (CFD) to study loss mechanisms and redesign options (e.g., lid insulation, rockwool quality, window inflow).
 - Construct a **plant-level DT** for the 6 lines using line-3 physics extrapolated to others for real-time plant energy estimation.
 - **Validate** against shop-floor measurements at several velocities ($\pm 20\%$) and with oven outlet temperatures.

Measured results

- **DT accuracy:** 96.7% (per-oven accuracies: IR 94.8%, MW 95.9%, GC1 97.4%, GC2 98.9%).
- **Energy-efficiency redesign** (via oven DoE): up to **12–13%** oven energy savings with improved insulation and reduced inflow; some measures implemented at SPS with **reported gas reduction**.

Deliverables

- Executable DT models + configuration for each line.
- Validation report (test points, deviations, confidence intervals).
- Operator-facing **web UI** for parameter exploration and what-ifs.

Roles

- DT model developers (CFD/FEM), SPS process engineers (tests & measurements), OT/IT for data access.

Effort drivers

- Access to line trials at multiple speeds; temperature and gas flow measurements; ROM calibration time.

4.1.3 EFPSP (ENERGY-FLEX PRODUCTION SCHEDULING PLATFORM) INTEGRATION

Objective

- Generate **cost optimal**, constraint-feasible schedules and **flexibility offers** across six lines; run fast enough for day-ahead use.

Activities

- Formalise production constraints: shared labour, setups, job deadlines.
 - Parameterise **energy demand per profile** using DT outputs at relevant speeds; include gas and electricity costs.
 - Implement three optimisation layers:
 - **Baseline** (weekly horizon): minimise total energy cost (elec + gas) while meeting orders.
 - **Internal optimisation**: create **APPs** (Alternative Production Plans) for day-ahead flexibility.
 - **External optimisation**: hourly flexibility offers for external markets (when applicable).
 - Deploy EFPSP on-prem and connect to SPS data feeds and price/CO₂ factors.

Measured results

- **Run-time**: < 5 minutes per plan (production environment).
- **Flexibility**: **942.8 kWh/day** average (target >700 kWh; range 244–1592).
- **Energy cost reduction**: **7.6%** average (target >5%; range 0.3–27%).
- **CO₂ reduction**: **8.6%** average (target >5%; range 0.2–24%).

Deliverables

- EFPSP instance configured for SPS (6 lines, profiles, shift calendars).
- APP generation workflow; report templates for KPIs.

Roles

- Scheduling/OR engineer, SPS planner, IT admin (hosting, backups), EFPSP product owner.

Effort drivers

- Quality of master data (BOM/recipes), accuracy of energy coefficients, need for user training on APPs.

4.1.4 CLUSTER PARTICIPATION VIA ICFP (INDUSTRIAL CLUSTER FLEXIBILITY PLATFORM)

Objective

- Offer SPS flexibility to the **cluster** and (via aggregator) to **external markets**; ensure traceable, secure transactions.

Activities

- Connect EFPSP outputs (APPs/FOs) to **ICFP**.
- Use ICFP to **aggregate** offers, select cluster-optimal plan, and **record** energy/economic transactions (prototype blockchain writer as per D6.9).
- Align with cluster's operational window (day-ahead, hourly).

Measured results

- SPS flexibility (avg. **942.8 kWh/day**) becomes **tradable**; CO₂ and cost benefits achieved at **factory** and **cluster** levels.

- Economic transactions can be **written to blockchain** for auditability (pilot mode).

Deliverables

- ICFP connection/config, offer formats, operator SOPs.
- (Optional) On-meter device (F4F-OM) deployment template for verified metering.

Roles

- Aggregator ops, SPS energy manager, ICFP admin.

Effort drivers

- Market product definition, cluster processes, and governance (who triggers which plan, when).

4.1.5 ENERGY STRATEGY PILOTS: BESS & HYDROGEN BLENDING (SCENARIO SUPPORT)

Objective

- Provide levers to further reduce cost/CO₂ beyond scheduling.

BESS

- Use EFPSP scenarios to simulate BESS-assisted shifting/peak shaving.
- (From D6.9 multi-pilot insights) BESS raises **offered flexibility**; cost outcomes depend on tariff spread and PV availability. Add **CO₂-aware charging** to avoid emissions backfire.

Hydrogen blending

- Use DT + EFPSP cost/CO₂ stack to evaluate **partial substitution** of natural gas in ovens.
- Comparable Spanish steel-plant modelling shows **~163,115 tCO₂/yr** reduction at **30%** blending; for SPS, reductions scale **proportionally** with gas use and blend ratio.

Deliverables

- Scenario playbooks (cost/CO₂), sensitivity to prices, blend % and duty cycles.

Roles

- Energy manager, process engineer, finance controller.

Effort drivers

- Local gas pricing, H₂ availability, safety & burner compatibility assessments (outside EFPSP scope).

4.1.6 ACCEPTANCE, TRAINING, AND CHANGE MANAGEMENT

Objective

- Ensure the tools are **used daily** and results are sustained.

Activities

- User acceptance tests (planners/operators) on DT UI and EFPSP screens.

- KPI dashboards for **daily** tracking (1.3.1, 5.2, 5.5.1 + plant-specific metrics).
- SOPs for **day-ahead APP** generation and **exception handling**.

Measured outcomes

- High user acceptance scores (most questions 9/10); requests (e.g., parameter persistence across tabs) implemented.

4.1.7 TYPICAL TIMELINE & REPLICATION CHECKLIST TIMELINE

Actual times depend on data readiness and line diversity; below reflects SPS experience scale.

- **Weeks 0–4:** Data mapping, historian access, baseline dataset preparation.
- **Weeks 5–10:** DT build (ROMs), first validation runs at nominal speed; plant-DT aggregation.
- **Weeks 11–14:** EFPSP configuration (constraints, costs), first baseline schedule; APP workflow.
- **Weeks 15–18:** ICFP connection, pilot cluster runs, transaction logging.
- **Weeks 19–22:** BESS/H₂ scenario runs, CO₂-aware logic refinements; training & SOPs.

Replication checklist

- Tag list + historian access (electricity & gas), aligned to shifts/orders.
- Profiles catalogue with energy coefficients at relevant speeds (from DT).
- Constraint set (labour, mould/tassello change, maintenance windows).
- EFPSP instance (baseline + internal/external optimisation) with KPI templates.
- ICFP connectivity and offer formats; aggregator contact & processes.
- Optional: BESS and hydrogen scenario templates; CO₂-aware charging rule.
- UAT plan; roles & RACI for planners, process & energy managers.

What most influences replication effort?

1. **Data quality & access** (biggest accelerator/slow-down).
2. **Line diversity** (number of profiles/speeds that need DT calibration).
3. **Changeover complexity** (set-up logic in EFPSP).
4. **Cluster readiness** (ICFP onboarding & governance).
5. **Energy strategy levers** (BESS/H₂—technical feasibility, procurement, safety).

4.2 CELSA (STEEL, SPAIN)

CELSA implemented a digital twin for its melting shop, modelling the energy consumption of electric arc furnaces (EAFs). These furnaces operate in two modes, each with different power levels, which can be adjusted to provide flexibility depending on casting and plant scheduling. The operation modes have nominal power ratings of 70/90 MW (B/A), respectively, although the actual power consumption fluctuates within a certain range during casting. The digital twin is based on semi-analytical models that combine data with numerical approximations.



The algorithm takes as inputs the EAF operating mode and the steel grade to be produced. As outputs, it provides the power consumption profile throughout the casting process and statistics on the average power consumption.

It achieved a predictive accuracy of 98.98%, supporting reliable optimisation of energy use.

The EFPSP was integrated to optimise production planning and energy flexibility. EFPSP algorithms generated cost-optimal schedules and flexibility offers, enabling CELSA to respond to market signals and energy price fluctuations. Key results included an average daily energy flexibility offered of 318 MWh exceeding the target of >50 MWh, an average daily energy cost reduction of 18.8% and an average CO₂ emissions reduction of 8.2%.

Hydrogen blending scenarios were modelled for reheating furnaces, showing that substituting 30% of natural gas with green hydrogen could reduce annual CO₂ emissions by 163,115 tonnes at a comparable Spanish steel plant. For CELSA, reductions are proportional to the hydrogen share and gas usage.

Electrolyser and storage sizing were evaluated to support market-linked operation. By integrating on-site hydrogen production and storage, CELSA can optimise hydrogen use based on energy market prices, further reducing emissions and improving economic performance.

The cluster concept, enabled by the Industrial Cluster Flexibility Platform (ICFP), allowed CELSA to aggregate flexibility offers with other factories and participate in local energy markets. Through ICFP, CELSA's flexibility (318 MWh/day) was traded at the cluster level, maximising economic and environmental benefits. The ICFP facilitated secure, transparent transactions and enabled CELSA to interact with external energy markets via the aggregator, without direct market exposure.

The Flex4Fact's digital twin, EFPSP, and cluster tools delivered measurable economic and environmental benefits for CELSA: reduced energy costs, increased operational flexibility, and lower emissions, with further gains possible through hydrogen blending and market-linked electrolyser operation.

The DT gave CELSA a validated energy model for melting shop operations.

The EFPSP translated that into <15-minute optimised plans, 318 MWh/day flexibility, 18.8% energy-cost cuts, and 8.2% CO₂ reduction on average.

Via ICFP, this flexibility becomes tradable, creating monetisation paths and cluster-level impact.

4.2.1 SITE PREPARATION & DATA FOUNDATION

Objective

Make production and energy data available, reliable, and secure for modelling and scheduling.

Inputs

- Existing PLC/SCADA for melting shop (electric arc furnaces) and rolling mill (reheating furnaces).
- Energy meters (electricity) and gas consumption data.
- Production plan (castings, steel grades, furnace schedules, labour constraints).

Activities

- Map the tag list and signals per furnace (power, temperature, steel grade, casting time).



- Establish data export from OT layer (e.g., MES, historian) to the modelling stack.
- Clean historical datasets (typical weeks and peak/low periods) for baseline calibration.

Deliverables

- Data inventory (signals, sampling rates, units).
- Historical datasets aligned to shifts for baseline and KPI calculations.

Roles

- CELSA automation/maintenance lead (signals), Flex4Fact DT & scheduling engineers (data model).

Effort drivers

- Diversity of steel grades/casting schedules; availability of historical electricity/gas time series matched to production orders.

4.2.2 DIGITAL TWIN DEVELOPMENT & VALIDATION OF THE MELTING SHOP

Objective

Build a hybrid physics-based/data-driven DT to predict energy use vs. operational mode while preserving quality constraints (steel grade, casting time).

Activities

- Develop a melting shop DT that couples:
 - Semi-analytical models for EAF power consumption (based on MES and metering data).
 - Scenario analysis for reheat furnace operation and hydrogen blending.
- Validate DT against shop-floor measurements (power, temperature, casting time).

Measured results

- DT accuracy: 98.98% (MAPE).
- User acceptance: high scores for usability and decision support.

Deliverables

- Executable DT models + configuration for each furnace.
- Validation report (test points, deviations, confidence intervals).
- Operator-facing web UI for scenario exploration.

Roles

- DT model developers, CELSA process engineers (tests & measurements), OT/IT for data access.

Effort drivers

- Access to casting trials; power and temperature measurements; model calibration time.



4.2.3 EFPSP INTEGRATION

Objective

Generate cost-optimal, constraint-feasible schedules and flexibility offers across melting shop and rolling mill; run fast enough for day-ahead use.

Activities

- Formalise production constraints: casting schedules, steel grades, labour, maintenance.
- Parameterise energy demand per casting using DT outputs; include electricity and gas costs.
- Implement three optimisation layers:
 - Baseline (15-day horizon): minimise total energy cost while meeting production targets.
 - Internal optimisation: create APPs (Alternative Production Plans) for day-ahead flexibility.
 - External optimisation: hourly flexibility offers for external markets.
- Deploy EFPSP on-prem and connect to CELSA data feeds and price/CO₂ factors.

Measured results

- Run-time: < 15 minutes per plan.
- Flexibility: 318 MWh/day average (target >50 MWh; range 45–450).
- Energy cost reduction: 18.8% average (target >10%; range 4–33%).
- CO₂ reduction: 8.2% average (target >5%; range 3–14%).

Deliverables

- EFPSP instance configured for CELSA (melting shop, rolling mill, shift calendars).
- APP generation workflow; report templates for KPIs.

Roles

- Scheduling/OR engineer, CELSA manager, IT admin (hosting, backups), EFPSP product owner.

Effort drivers

- Quality of master data (steel grades, casting plans), accuracy of energy coefficients, need for user training on APPs.

4.2.4 CLUSTER PARTICIPATION VIA ICFP

Objective

Offer CELSA flexibility to the cluster and (via aggregator) to external markets; ensure traceable, secure transactions.

Activities

- Connect EFPSP outputs (APPs/FOs) to ICFP.
- Use ICFP to aggregate offers, select cluster-optimal plan, and record energy/economic ~~transactions~~ transactions.
- Align with cluster's operational window (day-ahead, hourly).

Measured results

- CELSA flexibility (avg. 318 MWh/day) becomes tradable; CO₂ and cost benefits achieved at factory and cluster levels.
- Economic transactions can be written to blockchain for auditability (pilot mode).

Deliverables

- ICFP connection/config, offer formats, operator SOPs.
- (Optional) On-meter device (F4F-OM) deployment template for verified metering.

Roles

- Aggregator ops, CELSA energy manager, ICFP admin.

Effort drivers

- Market product definition, cluster processes, and governance (who triggers which plan, when).

4.2.5 ENERGY STRATEGY PILOTS: ELECTROLYSER + STORAGE & HYDROGEN BLENDING (SCENARIO SUPPORT)

Objective

Provide levers to further reduce cost/CO₂ beyond scheduling.

Electrolyser + Storage

- Use DT + EFPSP scenarios to size electrolyser and storage for market-linked hydrogen production.
- Optimise hydrogen use based on energy market prices and storage levels.

Hydrogen blending

- Use DT + EFPSP cost/CO₂ stack to evaluate partial substitution of natural gas in reheat furnaces.
- Modelling shows up to 163,115 tCO₂/yr reduction at 30% blending (comparable plant); for CELSA, reductions scale proportionally with gas use and blend ratio.

Deliverables

- Scenario playbooks (cost/CO₂), sensitivity to prices, blend % and duty cycles.

Roles

- Energy manager, process engineer, finance controller.

Effort drivers

- Local gas pricing, H₂ availability, electrolyser sizing, safety & burner compatibility assessments.

4.2.6 ACCEPTANCE, TRAINING, AND CHANGE MANAGEMENT

Objective

Ensure the tools are used daily and results are sustained.

Activities

- User acceptance tests (planners/operators) on DT UI and EFPSP screens.
- KPI dashboards for daily tracking plant-specific metrics).
- SOPs for day-ahead APP generation and exception handling.

Measured outcomes

- High user acceptance scores; requests for usability improvements implemented.

- **7) Typical timeline & replication checklist (indicative)**

Weeks 0–4: Data mapping, historian access, baseline dataset preparation.

Weeks 5–10: DT build, first validation runs; plant-DT aggregation.

Weeks 11–14: EFPSP configuration, first baseline schedule; APP workflow.

Weeks 15–18: ICFP connection, pilot cluster runs, transaction logging.

Weeks 19–22: Electrolyser/hydrogen scenario runs, logic refinements; training & SOPs.

Replication checklist

- Tag list + historian access (elec & gas), aligned to shifts/orders.
- Steel grades catalogue with energy coefficients (from DT).
- Constraint set (labour, casting schedules, maintenance windows).
- EFPSP instance (baseline + internal/external optimisation) with KPI templates.
- ICFP connectivity and offer formats; aggregator contact & processes.
- Optional: Electrolyser and hydrogen scenario templates.
- UAT plan; roles & RACI for planners, process & energy managers.

What most influences replication effort?

- Data quality & access (biggest accelerator/slow-down).
- Diversity of steel grades/casting schedules (DT calibration).
- Changeover complexity (set-up logic in EFPSP).
- Cluster readiness (ICFP onboarding & governance).
- Energy strategy levers (electrolyser/hydrogen—technical feasibility, procurement, safety).

4.3 SEAC (INJECTION MOULDING, ITALY)

SEAC implemented a digital twin for its extrusion process, enabling real-time monitoring and predictive modelling of energy consumption and production efficiency. This digital twin, fed by near real-time data from an edge device (F4F-OM), allowed SEAC to track energy use, identify inefficiencies, and optimise production schedules. The digital twin achieved high predictive accuracy of over 90%, supporting reliable energy management and process improvement.

The EFPSP was integrated to optimise job sequencing and energy use across extrusion lines. EFPSP algorithms generated cost-optimal production plans and flexibility offers, allowing SEAC to

shift production to periods of lower energy prices and higher renewable availability. Key results included an average daily energy flexibility offered of 99.7 kWh, an average daily energy cost reduction of 7.4%, and an average CO₂ emissions reduction above 5%.

A major focus was on maximising self-consumption of on-site PV generation using a Battery Energy Storage System (BESS). Simulations showed that even relatively small BESS capacities enabled significant increases in PV self-consumption and flexibility, with the most cost-effective gains achieved at modest battery sizes. The edge device provided near real-time data for both PV generation and consumption, enabling precise control and optimisation of battery charging and discharging. This approach reduced grid imports during peak price periods and maximised the use of renewable energy, directly lowering both costs and emissions.

The cluster concept, enabled by the Industrial ICFP, allowed SEAC to aggregate its flexibility offers with those of other factories and participate in local energy markets. Through ICFP, SEAC's flexibility was traded at the cluster level, maximising economic and environmental benefits. The ICFP facilitated secure, transparent transactions and enabled SEAC to interact with external energy markets via the aggregator, without direct market exposure. This approach provided additional revenue streams and supported cluster-wide decarbonisation.

- The DT gave SEAC a validated energy model for extrusion operations.
- The EFPSP translated that into <5-minute optimised plans, ~100 kWh/day flexibility, 7.4% energy-cost cuts, and 5% CO₂ reduction on average.
- Via ICFP, this flexibility becomes tradable, creating monetisation paths and cluster-level impact.

4.3.1 SITE PREPARATION & DATA FOUNDATION

Objective

Make production and energy data available, reliable, and secure for modelling and scheduling.

Inputs

- Existing PLC/SCADA for extrusion lines (aluminium melting, extrusion presses, ovens).
- Energy meters (electricity) and gas consumption data.
- Production plan (jobs, profiles, line speeds, set-ups, labour constraints).

Activities

- Map the tag list and signals per line (temperatures, set-points, speeds, power, oven states).
- Establish data export from OT layer (e.g., SCADA historian) to the modelling stack.
- Clean historical datasets (typical weeks and peak/low periods) for baseline calibration.

Deliverables

- Data inventory (signals, sampling rates, units).
- Historical datasets aligned to shifts for baseline and KPI calculations.

Roles



- SEAC maintenance/automation lead (signals), Flex4Fact DT & scheduling engineers (data model).

Effort drivers

- Heterogeneity of extrusion lines/profiles; availability of historical gas/elec time series matched to orders.

4.3.2 DIGITAL TWIN (DT) DEVELOPMENT & VALIDATION OF THE EXTRUSION PROCESS

Objective

Build a hybrid physics-based/data-driven DT to predict energy use vs. production schedule while preserving quality constraints (profile geometry, extrusion speed, oven settings).

Activities

- Develop a process DT for extrusion lines, using historical and real-time data to model energy consumption and process efficiency.
- Integrate oven and press data for accurate energy mapping.
- Validate DT against shop-floor measurements (energy, temperature, throughput).

Measured results

- DT accuracy > 90%.
- Enabled identification of energy-saving opportunities and process bottlenecks.

Deliverables

- Executable DT models + configuration for each line.
- Validation report (test points, deviations, confidence intervals).
- Operator-facing web UI for parameter exploration and what-ifs.

Roles

- DT model developers, SEAC process engineers (tests & measurements), OT/IT for data access.

Effort drivers

- Access to line trials at multiple speeds; temperature and energy measurements; model calibration time.

4.3.3 EFPSP (ENERGY-FLEX PRODUCTION SCHEDULING PLATFORM) INTEGRATION

Objective

Generate cost-optimal, constraint-feasible schedules and flexibility offers across extrusion lines; run fast enough for day-ahead use.



Activities

- Formalise production constraints: shared labour, set-ups, job deadlines.
- Parameterise energy demand per profile using DT outputs; include electricity costs.
- Implement three optimisation layers:
 - Baseline (weekly horizon): minimise total energy cost while meeting orders.
 - Internal optimisation: create APPs (Alternative Production Plans) for day-ahead flexibility.
 - External optimisation: hourly flexibility offers for external markets.
- Deploy EFPSP on-prem and connect to SEAC data feeds and price/CO₂ factors.

Measured results

- Run-time: <5 minutes per plan.
- Flexibility: 99.7 kWh/day average (target >20 kWh; range 17–255).
- Energy cost reduction: 7.4% average (target >5%; range 4.3–9.8%).
- CO₂ reduction: 4.4% average.

Deliverables

- EFPSP instance configured for SEAC (extrusion lines, profiles, shift calendars).
- APP generation workflow; report templates for KPIs.

Roles

- Scheduling/OR engineer, SEAC planner, IT admin (hosting, backups), EFPSP product owner.

Effort drivers

- Quality of master data (BOM/recipes), accuracy of energy coefficients, need for user training on APPs.

4.3.4 CLUSTER PARTICIPATION VIA ICFP (INDUSTRIAL CLUSTER FLEXIBILITY PLATFORM)

Objective

Offer SEAC flexibility to the cluster and (via aggregator) to external markets; ensure traceable, secure transactions.

Activities

- Connect EFPSP outputs (APPs/FOs) to ICFP.
- Use ICFP to aggregate offers, select cluster-optimal plan, and record energy/economic transactions (prototype blockchain writer as per D6.9).
- Align with cluster's operational window (day-ahead, hourly).

Measured results

- SEAC flexibility (avg. 99.7 kWh/day) becomes tradable; CO₂ and cost benefits achieved at factory and cluster levels.
- Economic transactions can be written to blockchain for auditability (pilot mode).



Deliverables

- ICFP connection/config, offer formats, operator SOPs.
- (Optional) On-meter device (F4F-OM) deployment template for verified metering.

Roles

- Aggregator ops, SEAC energy manager, ICFP admin.

Effort drivers

- Market product definition, cluster processes, and governance (who triggers which plan, when).

4.3.5 ENERGY STRATEGY PILOTS: BESS & HYDROGEN BLENDING (SCENARIO SUPPORT)

Objective

Provide levers to further reduce cost/CO₂ beyond scheduling.

BESS

- Use EFPSP scenarios to simulate BESS-assisted shifting/peak shaving.
- BESS raises offered flexibility; cost outcomes depend on tariff spread and PV availability. Add CO₂-aware charging to avoid emissions backfire.

Hydrogen blending

- Use DT + EFPSP cost/CO₂ stack to evaluate partial substitution of natural gas in ovens.
- Modelling shows significant CO₂ reduction potential; for SEAC, reductions scale with gas use and blend ratio.

Deliverables

- Scenario playbooks (cost/CO₂), sensitivity to prices, blend % and duty cycles.

Roles

- Energy manager, process engineer, finance controller.

Effort drivers

- Local gas pricing, H₂ availability, safety & burner compatibility assessments (outside EFPSP scope).

4.3.6 ACCEPTANCE, TRAINING, AND CHANGE MANAGEMENT

Objective

Ensure the tools are used daily and results are sustained.

Activities

- User acceptance tests (planners/operators) on DT UI and EFPSP screens.
- KPI dashboards for daily tracking (plant-specific metrics).



- SOPs for day-ahead APP generation and exception handling.

Measured outcomes

- High user acceptance scores; requests for usability improvements implemented.

4.3.7 TYPICAL TIMELINE & REPLICATION CHECKLIST (INDICATIVE)

- **Weeks 0–4:** Data mapping, historian access, baseline dataset preparation.
- **Weeks 5–10:** DT build, first validation runs; plant-DT aggregation.
- **Weeks 11–14:** EFPSP configuration, first baseline schedule; APP workflow.
- **Weeks 15–18:** ICFP connection, pilot cluster runs, transaction logging.
- **Weeks 19–22:** BESS/H₂ scenario runs, CO₂-aware logic refinements; training & SOPs.

Replication checklist

- Tag list + historian access (elec & gas), aligned to shifts/orders.
- Profiles catalogue with energy coefficients at relevant speeds (from DT).
- Constraint set (labour, set-up, maintenance windows).
- EFPSP instance (baseline + internal/external optimisation) with KPI templates.
- ICFP connectivity and offer formats; aggregator contact & processes.
 - Optional: BESS and hydrogen scenario templates; CO₂-aware charging rule.
 - UAT plan; roles & RACI for planners, process & energy managers.

What most influences replication effort?

- Data quality & access (biggest accelerator/slow-down).
- Line diversity (number of profiles/speeds that need DT calibration).
- Changeover complexity (set-up logic in EFPSP).
- Cluster readiness (ICFP onboarding & governance).
- Energy strategy levers (BESS/H₂—technical feasibility, procurement, safety).

4.4 INAVENTA (SOLAR COLLECTORS, NORWAY)

INAVENTA's digital twin and EFPSP delivered validated energy models, <5-minute optimised plans, ~290 kWh/day flexibility, 22.5% energy cost cuts, and >60% renewable heat coverage. Via ICFP, this flexibility is monetised and scaled at cluster level, delivering measurable economic and environmental ~~impact~~impact.

4.4.1 SITE PREPARATION & DATA FOUNDATION

Objective

Establish reliable, secure access to production and energy data for modelling and scheduling.

Inputs



- PLC/SCADA data from extrusion lines (temperatures, speeds, power, oven states)
- Energy meters (electricity), solar thermal, and BTES data
- Production plans and shift schedules

Activities

- Map and export all relevant signals and historical datasets
- Align data to shifts and production orders for baseline and KPI calculation

Deliverables

- Complete data inventory and cleaned historical datasets for baseline and KPIs

Effort Drivers

- Diversity of extrusion profiles and completeness of historical energy data

4.4.2 DIGITAL TWIN (DT) DEVELOPMENT & VALIDATION

Objective

Build and validate a multi-layer digital twin (extrusion, solar thermal, BTES) to predict energy use and maintain product quality.

Activities

- Develop process DT for extrusion, integrating real-time and historical data
- Model energy flows for extrusion, solar thermal, and BTES
- Validate DT accuracy against shop-floor measurements

Measured Results

- DT accuracy: 99.9% (die model), 82.7% (thermomechanical model)
- Enabled identification of energy-saving opportunities and process bottlenecks

Deliverables

- Executable DT models, validation reports, operator web UI

Effort Drivers

- Access to line trials, calibration time, and measurement quality

4.4.3 EFPSP (ENERGY-FLEX PRODUCTION SCHEDULING PLATFORM) INTEGRATION

Objective

Optimise production schedules for cost, flexibility, and energy efficiency; generate flexibility offers.

Activities

- Formalise production constraints and parameterise energy demand using DT outputs
- Implement baseline, internal, and external optimisation layers
- Deploy EFPSP and connect to INAVENTA data feeds and ICFP prices

Measured Results

- Run-time: <5 minutes per plan



- Flexibility: 290.5 kWh/day average (target >100 kWh)
- Energy cost reduction: 22.5% average (target >10%)
- Quality and delivery targets maintained

Deliverables

- EFPSP instance for INAVENTA, APP workflow, KPI reports

Effort Drivers

- Data quality, energy coefficients, user training

4.4.4 CLUSTER PARTICIPATION VIA ICFP (INDUSTRIAL CLUSTER FLEXIBILITY PLATFORM)

Objective

Aggregate and trade INAVENTA’s flexibility at cluster level; enable secure, auditable transactions.

Activities

- Connect EFPSP outputs to ICFP for aggregation and market participation
- Use ICFP to select cluster-optimal plans and record transactions (blockchain prototype)

Measured Results

- INAVENTA flexibility (avg. 290.5 kWh/day) becomes tradable
- Cost and CO₂ benefits realised at both factory and cluster level

Deliverables

- ICFP connection/config, offer formats, operator SOPs

Effort Drivers

- Cluster governance, market product definition

4.4.5 ENERGY STRATEGY PILOTS: BESS & SCENARIO SUPPORT

Objective

Support further cost/CO₂ reduction via battery storage and scenario analysis.

Activities

- Use EFPSP to simulate BESS-assisted shifting and peak shaving
- Model impact of energy storage and renewable integration on flexibility and cost

Deliverables

- Scenario playbooks, sensitivity analyses

Effort Drivers

- Local energy pricing, technical feasibility

4.4.6 ACCEPTANCE, TRAINING, AND CHANGE MANAGEMENT

Objective

Ensure daily use and sustained results.



Activities

- User acceptance tests on DT UI and EFPSP screens
- Daily KPI dashboards and SOPs for planners/operators

Measured Outcomes

- High user acceptance; usability improvements implemented

4.4.7 TYPICAL TIMELINE & REPLICATION CHECKLIST

- **Weeks 0–4:** Data mapping, baseline prep
- **Weeks 5–10:** DT build, validation
- **Weeks 11–14:** EFPSP config, baseline schedule
- **Weeks 15–18:** ICFP connection, cluster pilot
- **Weeks 19–22:** Scenario runs, training, SOPs

Replication Checklist

- Tag list + historian access (electricity, solar thermal, BTES), aligned to shifts/orders.
- Profiles catalogue with energy coefficients and heat flow parameters (from multi-layer DT).
- Constraint set (labour, extrusion line availability, maintenance windows).
- EFPSP instance (baseline + internal/external optimisation) with KPI templates.
- ICFP connectivity and offer formats; aggregator contact & processes.
- Optional: BESS and thermal storage scenario templates; CO₂-aware charging/discharging rule.
- UAT plan; roles & RACI for planners, process & energy managers.

Key Replication Factors

- Data quality, line diversity, changeover complexity, cluster readiness

4.5 THEBEN (PCB ELECTRONICS, GERMANY)

Theben implemented a digital twin for its production lines and photovoltaic (PV) system, enabling real-time monitoring and predictive modelling of both energy consumption and renewable generation. This multi-objective digital twin, fed by live data from the factory and PV arrays, allowed Theben to track energy use, identify inefficiencies, and optimise production schedules to maximise renewable self-consumption. The digital twin achieved high predictive accuracy (KPI 2.1 >90%), supporting reliable energy management and process improvement.

The Energy Flex Production Scheduling Platform (EFPSP) was integrated to optimise job sequencing and energy use across production lines. EFPSP algorithms generated cost-optimal production plans and flexibility offers, allowing Theben to shift production to periods of higher PV output and lower grid prices. Key results included a 17% reduction in total energy use and a 64% increase in renewable energy share, achieved through energy-aware scheduling and maximised PV self-consumption. The platform delivered optimised plans in under five minutes, supporting day-ahead operational decisions.

A major focus was on leveraging the PV twin and energy storage scenarios to further increase renewable integration. Simulations showed that even modest battery capacities enabled significant increases in PV self-consumption and flexibility, with the most cost-effective gains achieved at moderate storage sizes. Real-time data from the PV system and production lines enabled precise control and optimisation of battery charging and discharging, reducing grid imports during peak price periods and directly lowering both costs and emissions.

The cluster concept, enabled by the Industrial Cluster Flexibility Platform (ICFP), allowed Theben to aggregate its flexibility offers with those of other factories and participate in local energy markets. Through ICFP, Theben's flexibility was traded at the cluster level, maximising economic and environmental benefits. The ICFP facilitated secure, transparent transactions and enabled Theben to interact with external energy markets via the aggregator, without direct market exposure. This approach provided additional revenue streams and supported cluster-wide decarbonisation.

Theben's digital twin and EFPSP delivered validated energy models, <5-minute optimised plans, 17% energy reduction, and 64% increase in renewable share. Via ICFP, this flexibility is monetised and scaled at cluster level, delivering measurable economic and environmental impact.

4.5.1 SITE PREPARATION & DATA FOUNDATION

Objective

Enable reliable, secure access to production and energy data for modelling and scheduling.

Inputs

- PLC/SCADA data from soldering and assembly lines
- Energy meters (electricity), PV system data
- Production plans, shift schedules

Activities

- Map and export all relevant signals (temperatures, machine states, power, PV output)
- Align historical datasets to shifts and orders for baseline and KPI calculation

Deliverables

- Data inventory and cleaned historical datasets for baseline and KPIs

Effort Drivers

- Diversity of product types and production lines; completeness of historical energy and PV data

4.5.2 DIGITAL TWIN (DT) DEVELOPMENT & VALIDATION

Objective

Build and validate a multi-objective digital twin (production + PV) to predict energy use, optimise scheduling, and maximise renewable integration.

Activities

- Develop process DT for soldering and assembly lines, integrating real-time and historical data



- Develop PV twin to forecast renewable generation and enable energy-aware scheduling
- Validate DT accuracy against shop-floor measurements

Measured Results

- DT accuracy: >90%
- Enabled identification of energy-saving opportunities and process bottlenecks

Deliverables

- Executable DT models, validation reports, operator web UI

Effort Drivers

- Access to line trials, calibration time, and measurement quality

4.5.3 EFPSP (ENERGY-FLEX PRODUCTION SCHEDULING PLATFORM) INTEGRATION

Objective

Optimise production schedules for cost, flexibility, and renewable use; generate flexibility offers.

Activities

- Formalise production constraints and parameterise energy demand using DT outputs
- Implement baseline, internal, and external optimisation layers
- Deploy EFPSP and connect to Theben data feeds and price/CO₂ factors

Measured Results

- Energy use reduced by 17%
- Renewable energy share increased by 64% through energy-aware scheduling
- Run-time: <5 minutes per plan

Deliverables

- EFPSP instance for Theben, APP workflow, KPI reports

Effort Drivers

- Data quality, energy coefficients, user training

4.5.4 CLUSTER PARTICIPATION VIA ICFP (INDUSTRIAL CLUSTER FLEXIBILITY PLATFORM)

Objective

Aggregate and trade Theben’s flexibility at cluster level; enable secure, auditable transactions.

Activities

- Connect EFPSP outputs to ICFP for aggregation and market participation
- Use ICFP to select cluster-optimal plans and record transactions (blockchain prototype)

Measured Results

- Theben’s flexibility becomes tradable, supporting cluster-level cost and CO₂ reduction
- Economic transactions can be written to blockchain for auditability

Deliverables

- ICFP connection/config, offer formats, operator SOPs

Effort Drivers

- Cluster governance, market product definition

4.5.5 ENERGY STRATEGY PILOTS: BESS & SCENARIO SUPPORT

Objective

Support further cost/CO₂ reduction via battery storage and scenario analysis.

Activities

- Use EFPSP to simulate BESS-assisted shifting and peak shaving
- Model impact of storage and renewables on flexibility and cost

Deliverables

- Scenario playbooks, sensitivity analyses

Effort Drivers

- Local energy pricing, technical feasibility

4.5.6 ACCEPTANCE, TRAINING, AND CHANGE MANAGEMENT

Objective

Ensure daily use and sustained results.

Activities

- User acceptance tests on DT UI and EFPSP screens
- Daily KPI dashboards and SOPs for planners/operators

Measured Outcomes

- High user acceptance; usability improvements implemented

4.5.7 TYPICAL TIMELINE & REPLICATION CHECKLIST

- **Weeks 0–4:** Data mapping, baseline prep
- **Weeks 5–10:** DT build, validation
- **Weeks 11–14:** EFPSP config, baseline schedule
- **Weeks 15–18:** ICFP connection, cluster pilot
- **Weeks 19–22:** Scenario runs, training, SOPs

Replication Checklist

- Tag list + historian access (electricity & PV), aligned to shifts/orders.
- Profiles catalogue with energy coefficients and PV generation forecasts (from DT).
- Constraint set (labour, machine availability, maintenance windows).
- EFPSP instance (baseline + internal/external optimisation) with KPI templates.

- ICFP connectivity and offer formats; aggregator contact & processes.
- Optional: BESS scenario templates; CO₂-aware charging rule for PV storage optimisation.
- UAT plan; roles & RACI for planners, process & energy managers.

Key Replication Factors

- Data quality, line diversity, changeover complexity, cluster readiness



5 FLEXIBILITY FOR AGGREGATORS, DSOS AND TSOS

5.1 HOW TO SOURCE, VERIFY AND MONETISE FLEXIBILITY

The energy transition and the increasing share of renewables are driving a fundamental shift in how aggregators, DSOs, and TSOs manage system stability and market operations. Industrial flexibility, enabled by digitalisation, advanced scheduling, and secure market platforms, offers a powerful resource to balance supply and demand, integrate variable renewables, and unlock new value streams. This chapter provides practical guidance on how grid and market actors can source, verify, and monetise flexibility from industrial sites, and how to integrate these resources into daily system operations. Drawing on the FLEX4FACT project's validated methodologies and pilot results, it outlines actionable steps for leveraging industrial flexibility to enhance grid resilience, reduce costs, and support decarbonisation objectives.

5.1.1 SOURCING FLEXIBILITY

Aggregators, DSOs and TSOs can source flexibility by connecting to industrial flexibility platforms such as the ICFP (Industrial Cluster Flexibility Platform). Factories and clusters submit flexibility offers such as load shifting, demand reduction, or on-site generation through standardised interfaces. These offers are based on validated digital twins and scheduling platforms (e.g., EFPSP), ensuring that the flexibility is real, quantifiable, and can be activated on demand.

5.1.2 VERIFICATION

Verification is achieved through a combination of real-time data acquisition (via SCADA, IoT, or edge devices), digital twin validation, and automated measurement & verification (M&V) dashboards. Each flexibility event is tracked, with energy and process data logged for auditability. Blockchain-based transaction records (as piloted in FLEX4FACT) can further enhance trust and traceability, ensuring that delivered flexibility matches the contracted offer.

5.1.3 MONETISATION

Flexibility is monetised through participation in local and external energy markets. Aggregators or clusters can pool flexibility from multiple sites and bid into day-ahead, intra-day, or ancillary service markets. Revenue streams include direct payments for delivered flexibility, avoided grid charges, and new market products (e.g., balancing services). The ICFP supports secure, transparent settlement of economic transactions, with all parties interacting via the aggregator, reducing complexity and risk.

5.2 HOW TO INTEGRATE INDUSTRIAL FLEXIBILITY IN GRID SYSTEM OPERATIONS

5.2.1 INTEGRATION IN OPERATIONS

Industrial flexibility can be integrated into grid system operations by establishing standard communication protocols and market interfaces between the grid operator/aggregator and the industrial flexibility platform. The process includes:

- **Onboarding:** Registering industrial sites or clusters, validating their flexibility assets, and defining operational constraints.
- **Scheduling and Dispatch:** Receiving flexibility offers (e.g., via EFPSP/ICFP), selecting optimal bids based on system needs (cost, CO₂, grid stability), and issuing activation signals.
- **Monitoring and Verification:** Using real-time dashboards and automated M&V to track delivery, with fallback mechanisms for non-delivery or underperformance.
- **Market Settlement:** Ensuring transparent, auditable settlement of flexibility transactions, with economic and energy flows recorded for all participants.

Benefits

- Enhanced grid stability and resilience through rapid, decentralised response.
- Increased integration of renewables by shifting industrial loads to periods of high-RES generation.
- New revenue streams for both grid actors and industrial participants.
- Scalable, replicable model validated in FLEX4FACT pilots, with typical onboarding times of 1–3 weeks for new clusters and proven cost and CO₂ benefits.

In summary

Aggregators, DSOs and TSOs can unlock significant value by sourcing, verifying, and monetising industrial flexibility through digital platforms. Integration into system operations is enabled by standardised interfaces, real-time data, and transparent market mechanisms, as demonstrated in the FLEX4FACT project.



6 PRACTICAL TOOLS AND TRAINING MATERIALS

6.1 ENERGY FLEXIBILITY GLOSSARY

6.1.1 DIGITALISATION & DATA

Digital Retrofitting	Upgrading legacy or analogue machines to connected, digitalised devices, making data digitally accessible.
IoT (Internet of Things)	Devices with sensors, processing ability, and software that connect and exchange data over networks (e.g., Internet, WiFi, Bluetooth). A virtual representation of real-world entities and processes, synchronised with real-time and historical data to simulate and predict performance.
Digital Twin	
Big Data	Vast and complex datasets from various sources, used to enhance operational efficiency and decision-making.
Grafana	Open-source analytics and monitoring system for interactive data visualisation.
InfluxDB	High-performance NoSQL database optimised for time-series data (e.g., IoT).
Apache Kafka	Distributed event streaming platform for high-performance data pipelines and analytics.
Apache Spark	Distributed processing system for batch and stream processing of big data.
On-Premise Deployment	Running services on a company's own hardware infrastructure.
Cloud Deployment	Running services on cloud provider servers (e.g., Azure, AWS).
Containerisation	Encapsulating applications into isolated instances for deployment.
Orchestration	Efficient deployment, management, and scaling of containerised applications.
Data Preprocessing	Tasks such as missing data imputation, cleaning, and aggregation.
Feature Selection	Identifying feature subsets to improve model explainability and efficiency.
Supervised Learning	Using labelled datasets to train algorithms for prediction and pattern recognition.
Predictive Modelling	Using data to predict variables, detect faults, or analyse patterns.
Model Validation	Ensuring a model accurately represents the intended system or process.
AI Model	A program trained on data to recognise patterns or make decisions autonomously.
Circular Economy	Economic system maintaining a circular flow of resources, minimising waste and emissions.
Industrial Symbiosis	Use of underutilised resources from one company/sector by another to improve resource utilisation.
Feedstock Valorisation	Converting biomass and byproducts into valuable products (e.g., heat, biofuel).

Biomass Pyramid	Principle prioritising biomass use for high-value applications before energy or fuel.
ICT (Information and Communication Technology)	Technologies for sensing, interconnecting, and extracting information from environments.
Green ICT	ICT activities and structures that reduce environmental impact through advanced engineering and eco-friendly solutions.

6.1.2 ENERGY FLEXIBILITY & MARKETS

Energy Flexibility	The ability of an energy system to adapt to changes in demand or supply while maintaining service levels.
Demand Response	Strategies to balance grid demand by encouraging customers to shift electricity use, often via price signals or incentives.
Flexibility Resource	Physical resource (e.g., DER) or process operated flexibly outside its normal mode.
Flexibility Service	Abstract description of how to use a flexibility resource for a specific purpose.
Flexibility Product	Traded or contracted agreement to deliver a specified flexibility service.
Energy Cost Minimisation	Operating flexibility resources to reduce operational costs, e.g., by load shifting or increasing self-consumption.
Self-Consumption	Using on-site generation (e.g., solar) to meet own demand, minimising grid imports.
Prosumer	Entity that is both a consumer and producer of electricity, potentially providing flexibility services.
Load Shifting	Moving energy consumption from one time to another, often using storage or pre/postponed demand.
Power Purchase Agreement (PPA)	Long-term contract between electricity producer and consumer for supply at agreed terms.
Power Peak Cutting	Reducing peak power demand to lower costs and grid stress, not shifting but avoiding demand.
Frequency Control	Services to maintain grid power balance, including inertia, primary, secondary, and tertiary responses.
TSO (Transmission System Operator)	Manages high-voltage transmission networks, responsible for system security and market facilitation.
DSO (Distribution System Operator)	Manages local/regional distribution networks, ensuring reliable delivery to end-users.
Aggregator	Pools flexibility from multiple sources (e.g., factories, prosumers) to offer services to the grid or markets.
Flexibility Service Provider	Offers flexibility services based on aggregated resources.
Day-Ahead Market	Marketplace for trading electricity one day before delivery.
Non-Firm Connection Contract	Grid connection with capacity rights that may be curtailed under certain conditions.
Frequency Containment Reserve	Flexibility product for primary frequency control, procured by TSOs.
EnPI (Energy Performance Indicator)	Quantifiable metric to assess and track energy performance.

EMS (Energy Management System/Software)	Tools to monitor, control, and optimise energy consumption.
Industry 4.0	Transformation of manufacturing with smart, connected technologies.
PDCA Cycle	Plan-Do-Check-Act cycle for continuous improvement in energy management.
Resource Conservation	Sustainable management of natural resources for current and future needs.
ROI (Return on Investment)	Financial metric for evaluating investment profitability.
Sustainability	Meeting present needs without compromising future generations' ability to meet theirs.

6.1.3 TECHNOLOGIES & DIGITAL TOOLS

Asset Digitalisation	Converting physical assets into digital representations for enhanced management.
VRE (Variable Renewable Energy)	Renewable sources with fluctuating output (e.g., wind, solar).
Grid Integration	Efficiently delivering variable renewable energy to the grid.
API (Application Programming Interface)	Rules for software communication and integration.
Blockchain	Decentralised digital ledger for secure, transparent transaction recording.
Business Process Management (BPM)	Designing, analysing, and optimising business processes.
Clustering	Grouping similar data points for analysis.
Collaborative Filtering	Recommender system technique based on collective user preferences.
Dashboard	Visual representation of data analysis results.
Data Analytics	Collecting, cleaning, and analysing data for insights.
Data Schema	Organisational structure of a dataset.
Data Science	Interdisciplinary field extracting knowledge from data.
Distributed Ledger Technologies (DLT)	Technologies maintaining synchronised ledgers across networks.
Forecasting	Predicting future events or trends using mathematical models.
Graph	Data structure of nodes and edges representing entities and relationships.
Immutability	Unchangeable property, especially in blockchain.
Machine Learning	AI branch enabling computers to learn from data.
Metadata	Information about data's structure, content, and origin.
Network Analysis	Studying relationships between entities in a network.
Permissioned/Permissionless Blockchain	Blockchains with restricted/open participation.
Recommendation System	AI-based system suggesting items to users.
RESTful API	Web service API following REST principles.
Smart Contract	Self-executing contract with terms in code.

Structured/Semi-Structured/Unstructured Data	Levels of data organisation and format.
Time Series Data	Data points indexed in time order.
Web Scraping	Automated data gathering from websites.
AEM/ALK/PEM/SOEC	Types of electrolyzers for hydrogen production.
CAPEX/OPEX	Capital and operating expenditures.
LCOH	Levelised Cost of Hydrogen.
LOHC	Liquid Organic Hydrogen Carriers.
P2X	Power-to-X, conversion of electricity to other energy carriers.
COP	Coefficient of Performance for heat pumps.
CPVT	Concentrating Photovoltaic Thermal system.
PV Cells	Photovoltaic cells converting sunlight to electricity.
Thermal Collectors	Devices capturing solar energy as heat.
CCUS	Carbon Capture, Usage, and Storage.
Biorefinery	Facility upgrading biofuels and recovering chemicals.
Catalytic Cracking	Oil refining process breaking heavy fractions into lighter products.
Pyrolysis/Pyrogasification	Thermal processes converting biomass to fuels and gases.
Syngas	Gas mixture from gasification, used as fuel.

6.1.4 PRODUCTION PROCESSES & INDUSTRY TERMS

Energy Audit	Systematic procedure to assess energy consumption and identify savings.
Energy Efficiency Obligation Scheme	Policy tool for governments to deliver energy efficiency goals.
Energy Benchmarking	Comparing performance to peers or norms for improvement.
Annealing	Controlled cooling of glass to relieve stresses.
Batch	Mixed raw materials for glass production.
Blow-and-Blow/Press-and-Blow Process	Glass container manufacturing methods.
Cullet	Recycled glass used as raw material.
Furnace/Forehearth	Structures for melting and conditioning glass.
Lehr	Oven for annealing glass.
Mould	Form for shaping molten glass.
Parison	Preliminary shaped glass before final forming.
Recycling	Reprocessing waste into secondary raw materials.
Retrofit	Adding sensors/equipment to existing hardware for new technologies.
Wastewater Treatment Plant	Facility treating wastewater for safe discharge or reuse.
Anaerobic Digestion	Biological breakdown of organic matter without oxygen, producing biogas.
Dewatering	Removing water from sludge to reduce volume.
Emissions	Release of substances (gases, particles) into the environment.
Renewable Energy System	Technologies harnessing naturally replenished energy sources.

6.2 TRINEFLEX TRAINING MATERIALS

You are invited to take part in the TRINEFLEX project's comprehensive training programme, designed to empower professionals in energy-intensive industries with the knowledge and skills needed for the digital and sustainable transformation of industrial processes. The TRINEFLEX Training Framework offers a flexible, self-paced learning experience through a rich catalogue of e-learning modules, video lessons, webinars, and multimedia presentations—all accessible online at <https://trineflex.eu/trineflex-training-framework/>.

What does the training cover?

- **Background Knowledge:** Foundational modules on the main TRINEFLEX topics—Energy Flexibility, Digitalisation, Technologies, and Production Processes. These units provide essential insights into energy management systems (EMS), demand response strategies, digital retrofitting, digital twins, asset digitalisation, community-based energy storage, hydrogen, renewable energy-assisted carbon capture, and more.
- **Practical Skills:** Each training unit includes real-world examples, case studies, and interactive content to help you apply concepts such as flexibility resources and services, digital validation, and advanced technological solutions in your own industrial context.
- **Glossary & Resources:** The programme features a comprehensive glossary and supporting materials to ensure every participant can master the terminology and concepts used in TRINEFLEX and related EU projects.
- **Two Levels of Learning:** Start with 'Background Knowledge' to build a solid foundation, then progress to 'Results of the TRINEFLEX Outcomes' for advanced, project-specific insights as they become available.

Who should join?

- Professionals from energy-intensive industries, technology providers, consultants, energy managers, and anyone interested in industrial decarbonisation, digitalisation, and flexibility.

How to participate?

- Simply visit the [TRINEFLEX Training Framework page](#), register for free, and start exploring the training units most relevant to your interests and professional needs.

Take this opportunity to upskill, network, and contribute to Europe's energy transition, join the TRINEFLEX training community today!

6.3 CHECKLISTS

The Implementation Checklist is designed to turn your roadmap into actionable steps. It provides a clear, structured overview of the tasks required at each stage, ensuring nothing is overlooked as you progress from initial assessment to full deployment. Use it as your practical companion to streamline execution, reduce complexity, and keep your flexibility project on schedule and within scope.

NO	TO-DO	COMMENT
1	Define objectives (cost, CO ₂ , flexibility revenues, resilience).	
2	Assemble core team (operations, energy, IT/OT, finance).	
3	Collect baseline data (loads, schedules, tariffs, emissions).	
4	Select pilot line/process and KPIs; draft measurement & verification plan.	
5	Plan data connectors and security (REST, MQTT, OPC-UA; VPN; access control).	
6	Choose twin scope (physics-based, data-driven, or hybrid) and validation method.	
7	Configure EFPSP (forecasts, constraints, APPs); test scenarios.	
8	Onboard to ICFP; run internal market; prepare external offers.	
9	Develop training plan and run user acceptance sessions.	
10	Agree on O&M, SLAs, and continuous improvement cadence.	

Table 3: Implementation Checklist



Practical implementation tips

- **Start small:** Pilot digital twins or flexibility modules on a single line or process before scaling.
- **Leverage existing data:** Use what you have (ERP, SCADA, sensors) before investing in new infrastructure.
- **Engage stakeholders early:** Involve production, IT, energy, and management teams from the start.
- **Plan for integration:** Ensure new systems can connect to existing platforms (APIs, standard protocols).
- **Monitor and iterate:** Use dashboards and KPIs to track progress and adjust strategies.
- **Document and train:** Maintain clear documentation and provide hands-on training for staff.

7 BUSINESS MODELS, REPLICATION AND SCALING

7.1 SMES & MANUFACTURING COMPANIES

Why FLEX4FACT?

As a manufacturing company, FLEX4FACT offers you a proven pathway to reduce energy costs (by 7–22% in pilots), cut CO₂ emissions, and unlock new revenue streams by participating in energy flexibility markets. The digital twin and EFPSP platforms are designed for rapid deployment—new sites can be onboarded in as little as 1–10 days, with 90%+ model reuse for similar processes.

How You Benefit:

- **Direct cost savings** through optimised scheduling, load shifting, and self-consumption.
- **Operational resilience** by responding to price signals and grid requests in real time.
- **New income** from selling flexibility to local and external markets via the ICFP.
- **Scalability:** Modular architecture supports multi-site rollouts; once you've piloted at one site, replication is fast and cost-effective.
- **Checklist for Success:** Ensure data readiness, map your processes, train your team, and connect with aggregators or DSOs for market access.

7.2 DSOS/TSOS

Why FLEX4FACT?

As a grid operator, FLEX4FACT enables you to tap into validated, real-time industrial flexibility for congestion management, balancing, and renewable integration. The ICFP platform is designed for seamless integration with your systems, supporting hundreds of sites and high transaction volumes.

How You Benefit:

- **Grid stability** through access to decentralised, auditable flexibility resources.
- **Decarbonisation** by enabling higher renewable penetration and reducing curtailment.
- **Market efficiency** with transparent, automated settlement of flexibility transactions.
- **Replicability:** ICFP can be deployed to new clusters in 1–3 weeks, with near-total component reuse.
- **Scalability:** Supports expansion from pilot clusters to regional or national rollouts.

7.3 AGGREGATORS

Why FLEX4FACT?

As an aggregator, FLEX4FACT gives you a turnkey solution to aggregate and monetise flexibility from multiple industrial clients. The EFPSP and ICFP platforms enable rapid onboarding, standardised offer generation, and access to new ancillary service and balancing markets.

How You Benefit:

- **Portfolio monetisation** by pooling flexibility and bidding into multiple markets.
- **Rapid scaling** with cloud-native platforms and standard connectors.
- **Diversified revenues** from shared savings, market participation, and integration fees.
- **Replicability:** New clients can be onboarded in days to weeks, leveraging templates and APIs.
- **Scalability:** Modular architecture supports portfolio growth and integration with diverse client systems.

7.4 TECHNOLOGY PROVIDERS & CONSULTANTS

Why FLEX4FACT?

As a technology provider or consultant, FLEX4FACT is your platform for delivering digital transformation, decarbonisation, and flexibility solutions to industry. The modular, API-driven architecture allows you to customise, extend, and integrate solutions for a wide range of clients and sectors.

How You Benefit:

- **Market differentiation** by offering validated, scalable solutions.
- **Customisation opportunities** for sector-specific needs and advanced analytics.
- **Recurring revenues** from integration, training, and support services.
- **Replicability:** Standardised deployment templates and documentation enable rapid rollouts.
- **Scalability:** Expand your offering from single-site pilots to multi-client, multi-sector portfolios.

GROUP	REPLICATION	SCALABILITY	KEY ENABLER
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	TIME	MECHANISM	
Manufacturing/SMEs	1–10 days/site	Modular, multi-site rollout	90%+ model reuse
DSOs/TSOs	1–3 weeks/cluster	High-volume, native	cloud- Standardised onboarding
Aggregators	Days– weeks/client	Portfolio growth, APIs	Templates, connectors
Tech Providers	Days– weeks/project	Multi-client, multi-sector	Documentation, modularity

Table 4: Summary Table: Replicability & Scalability at a Glance

In summary:

FLEX4FACT’s solutions are designed for your context whether you’re a factory manager, grid operator, aggregator, or technology consultant. The platforms are proven, modular, and ready to scale, enabling you to capture value from energy flexibility and support Europe’s industrial transition.

8 FLEXIBILITY CONCEPT, DRIVERS AND POLICY CONTEXT

8.1 CONCEPTS OF FLEXIBILISATION

Flexibilisation in the industrial and energy context refers to the ability of manufacturing processes, energy systems, and entire industrial clusters to dynamically adapt their energy demand and production schedules in response to external signals—such as electricity prices, grid constraints, or renewable generation availability—while maintaining operational performance and product quality.

Key concepts include:

- **Energy Flexibility:** The capacity to shift, modulate, or curtail energy consumption or production in response to market or grid signals.
- **Demand Response:** Mechanisms enabling consumers (including factories) to adjust their energy use in real time or ahead of time, often incentivised by price signals or contracts.
- **Digital Twins and Data Integration:** The use of virtual models and real-time data to simulate, predict, and optimise energy and production flows.
- **Aggregation:** Pooling flexibility from multiple sites or assets to create a marketable product or service for grid operators or energy markets.
- **Market Participation:** Factories and clusters can offer flexibility as a service, monetising their ability to adapt operations.



8.2 DRIVERS OF FLEXIBILISATION

The push for flexibilisation is shaped by a combination of technological, economic, and regulatory drivers:

- **Decarbonisation and the Energy Transition:** The EU Green Deal, Fit for 55, and REPowerEU all set ambitious targets for reducing greenhouse gas emissions and increasing the share of renewables. As renewables are variable by nature, system flexibility is essential to balance supply and demand.
- **Rising Energy Prices and Volatility:** Volatile electricity prices and grid congestion create both risks and opportunities for industrial consumers. Flexibility allows companies to reduce costs and generate new revenues.
- **Digitalisation and Industry 4.0:** Advances in IoT, data analytics, and digital twins enable real-time monitoring, predictive maintenance, and automated optimisation of energy use.
- **Grid Stability and Security of Supply:** As more renewables are integrated, grid operators require new sources of flexibility to maintain frequency, manage congestion, and avoid curtailment.
- **Market Innovation:** The emergence of new market products (e.g., local flexibility markets, ancillary services) and business models (e.g., aggregators, performance-based contracts) incentivises participation from a broader range of actors.

8.3 POLICY CONTEXT

The FLEX4FACT project directly supports and advances several core European Union policy priorities by addressing the twin green and digital transitions in the manufacturing and energy sectors. Its outcomes contribute concretely to the objectives of the European Green Deal, the REPowerEU Plan, the Circular Economy Action Plan, and the Net-Zero Industry Act, reinforcing Europe's global leadership in sustainable industrial innovation.

8.3.1 ALIGNMENT WITH THE EUROPEAN GREEN DEAL

FLEX4FACT contributes to the European Green Deal's overarching goal of achieving climate neutrality by 2050 by enabling the decarbonisation of energy-intensive industries. Through the deployment of digital twins, predictive control, and energy flexibility algorithms, the project allows industrial sites to:

- Reduce CO₂ emissions through optimized energy use and waste-heat valorisation,
- Increase the share of renewable energy integrated into manufacturing operations, and
- Support resource efficiency and circularity through reduced energy waste and improved process control.

By demonstrating scalable, replicable solutions in five industrial pilots, FLEX4FACT provides a concrete pathway to achieving greener and more competitive European manufacturing.

8.3.2 SUPPORT TO REPOWER-EU AND ENERGY INDEPENDENCE

In line with the REPowerEU Plan, FLEX4FACT develops digital and organizational mechanisms to

reduce reliance on fossil fuels by:

- Integrating renewable generation and storage systems at factory and cluster level,
- Promoting the use of hydrogen and other low-carbon energy carriers in industrial processes,
- Enabling industries to provide demand-response services to the power grid through the Industrial Cluster Flexibility Platform (ICFP).

These solutions strengthen Europe's energy resilience, enhance grid stability, and contribute to the creation of industrial energy communities where manufacturing plants, utilities, and local stakeholders collaborate to balance supply and demand.

8.3.3 CONTRIBUTION TO THE NET-ZERO INDUSTRY ACT

FLEX4FACT supports the objectives of the Net-Zero Industry Act (NZIA) by delivering enabling technologies for clean industrial transformation. The project's modular digital platform and data-driven architecture serve as key enablers for:

- Energy-efficient production systems and decarbonised industrial processes,
- The creation of new industrial value chains based on energy flexibility and digitalisation, and
- The upskilling of the workforce with digital and sustainability competencies, thus supporting the EU's industrial competitiveness.

8.3.4 CONTRIBUTION TO THE CIRCULAR ECONOMY ACTION PLAN

The project's approach to energy valorisation, waste heat recovery, and closed-loop optimization reflects the principles of the Circular Economy. By leveraging data analytics and digital twins, FLEX4FACT improves the resource efficiency of manufacturing systems, reducing both energy and material waste while supporting sustainable business models at the industrial cluster level.

8.3.5 IMPACT ON EU INDUSTRIAL AND DIGITAL STRATEGIES

FLEX4FACT exemplifies the vision of the EU Digital Strategy and Industry 5.0 framework, which emphasise the integration of digital technologies to achieve resilience, sustainability, and human-centric industry. The project strengthens Europe's capacity to deploy AI-driven, interoperable, and secure digital infrastructures for industrial and energy applications, aligning with the goals of the European Data Strategy and Digital Europe Programme.

9 CONCLUSION

The FLEX4FACT project confirms that industrial energy flexibility is both technically feasible and strategically necessary for Europe's transition toward a resilient and decarbonised energy system. Through its pilots, digital twins, optimisation algorithms, and integrated flexibility platform, the project has demonstrated how industries can adapt their operations to energy price signals, renewable variability, and grid stability needs. However, the most significant insights emerged not only from internal experimentation but also from extensive networking with technical experts, energy system

actors, European partnerships, and policy stakeholders.

Networking activities provided a broader context for interpreting FLEX4FACT's technical results. Interactions with DSOs/TSOs and aggregators emphasised that industrial flexibility will increasingly become a core component of local energy systems and future flexibility markets. Exchanges with sector associations and innovation clusters highlighted the need for improved data granularity, interoperable systems, and new business models, especially for SMEs that often lack dedicated energy management resources. Dialogue with policy actors and research platforms confirmed that regulatory frameworks are evolving, but industry still faces uncertainty in monetising its flexibility potential.

Technically, the project learned that flexibility modelling requires a balance between accuracy and generalisation. Networking with other Horizon Europe projects showed that the challenge of heterogeneity - across processes, energy carriers, and control systems - is a common obstacle. FLEX4FACT's modular and interoperable architecture responds to this challenge, and its scalability has been validated through interactions with multiple stakeholders. The project also confirmed that the combination of digital twins, real-time monitoring, and AI-driven optimisation significantly reduces the complexity typically associated with industrial flexibility.

Looking beyond the project, the exploitation potential of FLEX4FACT is reinforced by the strong interest expressed by industrial and energy actors during networking events. Opportunities exist for further developing flexibility-as-a-service models, replicating the platform across industrial clusters, supporting local energy communities, and contributing to emerging standardisation efforts. Continued engagement with European partnerships such as Processes4Planet, EFFRA, and A.SPIRE will help ensure the project's results feed into long-term research agendas and industrial strategies.

In conclusion, FLEX4FACT's legacy rests not only on its technological achievements but also on its ability to synthesise diverse insights gathered through networking and stakeholder engagement. The project demonstrated that industrial flexibility requires both advanced digital solutions and coordinated actions across technology providers, energy actors, regulators, and end users. By integrating these perspectives, the project provides a robust pathway toward large-scale industrial participation in Europe's evolving energy markets

9.1 LESSONS LEARNED

Some learnings from the Flex4Fact project:

- Learning 1: Modelling and scheduling industrial flexibility is complex

Flexibility is a change in planning a production process to vary the industry load profile, i.e., the electric energy that the industry exchanges with the main electricity grid; the change in planning can cover the whole day or part of it. It can be achieved by activating product, volume, process, routing, and time flexibilities or a combination of them. Electrical energy storage systems can also be used as industrial flexibility resources.



- Learning 2: Flexibility markets are complex
In Flex4Fact, two interrelated markets were implemented, Internal market and External market. In particular External markets are complex and their regulation is constantly changing.
- Learning 3: Flexibility has a (potentially high) value. Potentially high monetary value of marketing flexibility.
- Learning 4: Capturing, managing and marketing flexibility requires sophisticated approaches. AI can provide those and create new business models.

Modelling Flexibility

Challenge: Industrial flexibility varies by machine, crew, and energy setup – making standardized modelling difficult.

General idea: Why spend time on modelling production processes? Let AI do it!

Possible solution: Use AI to generalize process-specific constraints and learn plant-specific patterns.

Valuing Flexibility

Challenge: Monetary value of industrial flexibility is hard to quantify, especially under dynamic market and asset conditions.

General idea: *Why spend time on estimation long-term value of our energy assets? Let AI do it!*

Possible solution: Use AI to value flexibility across different setups, timeframes and future scenarios.

Marketing Flexibility

Challenge: Selecting the optimal market channel (internal, day-ahead, intraday, balancing power, etc.) is highly complex and dynamic, particularly because they are correlated with each other.

General idea: *Why spend time on **developing and executing** short-term marketing strategies? Let **AI agents** do it!*

Possible solution: AI-based agents learn to optimize market participation and maximize value from flexible assets

10 CONTACT

For further information, inquiries or feedback regarding this guidebook, please feel free to get in touch.

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