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Industry4Redispatch

(I4RD)

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1 Introduction

The flagship project **Industry4Redispatch (I4RD)** was designed as a key project within the model region NEFI – New Energy for Industry. I4RD is the first NEFI project that develops innovative solutions enabling (i) the provision of flexibility from the demand and supply-side at distribution network level for redispatch and (ii) the demonstration of an online, predictive and site-holistic control concept for industrial energy supply systems, which optimizes a company's market participation while ensuring its energy supply. This approach enables participation of industry in redispatch and stipulated technological development within the NEFI community, especially by contributing to the central NEFI-innovation fields through *digitalization and flexibilization of the industry.*

In the years from 2013-2017, a growing need for redispatch in Austria and Germany, has been observed. This high need for redispatch remains ever since and is largely caused by the integration of renewable generation and continuing integration of the European electricity markets, which exacerbate existing grid congestions caused by a lag of critical transmission projects. This need is likely to increase more in the future. The costs for redispatch in Austria have been varying strongly within the last years between 86.5M€ and 147.8M€. Therefore, additional redispatch providers shall be incentivised to participate. For this, suitable **redispatch products** must be defined.

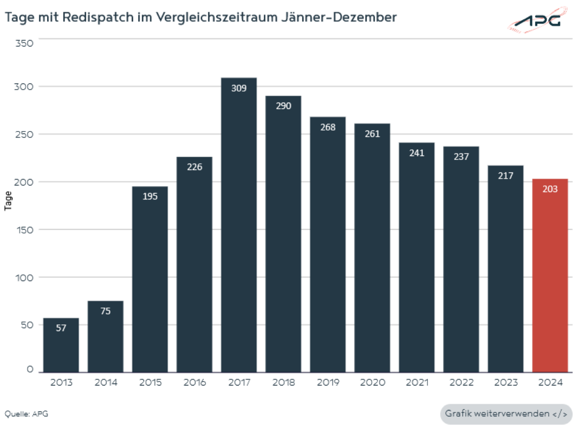

Figure 1 Days with Redispatch per Year (January-December)

Figure 2 Redispatch Costs per year (January-December)

Redispatch, that is the shift of generation and demand of electrical energy to decrease the loading of a network element, is a necessary measure for congestion management to maintain n-1 secure operation. Currently, in most cases, flexibility from generation units is utilized for redispatch. If new types of units at the distribution level are introduced, adding new types of flexibility for redispatch on the distribution grid level necessitates increased coordination between TSO (Transmission System Operator) and DSO (Distribution System Operator) to ensure that these industrial redispatch measures do not cause critical operation conditions in the distribution grid. The increase in renewable generation and an increase of concurrency factors caused by smart devices is not limited to the transmission level and could also cause congestions on the distribution level. Consequently, it can be expected that in the future, congestions are going to be managed by redispatch even on distribution levels. However, the existing regulatory framework as well as given incentives are currently not attracting industrial customers to participate in redispatch. In addition, the available capability to shift power is small compared to current redispatch needs.

At the same time, the producing industry faces challenges such as achieving energy efficiency targets and adapting to the changing energy market. The current situation shows that a highly dynamic industrial plant operation is often not possible due to a lack of comprehensive process automation. To enable flexible adaption of the industrial plants, the automation must be combined with algorithms combining industrial process optimization with automated participation algorithms in the congestion management (**industrial flexibility**). In addition, investments in plant flexibility are currently often unprofitable because of low incentives.

The primary goal of I4RD is enabling flexibility provision from both, demand and supply-side at distribution network level for redispatch at transmission system level. The project assessed all necessary technical, regulatory, economic and organisational requirements for this implementation, as well as the necessary coordination between TSO and DSOs. I4RD is the first project in Austria bringing together all relevant stakeholders to provide an integrated solution through automation and optimization of the industry, setting up a coordination process between the TSO and the DSOs, developing a novel redispatch module based on standardized requirements and demonstrating the value of the new approach by a proof-of-concept.

This report provides the key enabling factors **regarding the redispatch product and process, the TSO-DSO interaction and bid filter mechanism, as well as the industrial developments and perspectives involved**.

2 Content presentation

The project encompassed three main topics, which are presented in the following sections and illustrated in Figure 3 and Figure 4: First, the standardisation of a redispatch product and the specification of related processes (blue); second, the investigation of industrial flexibility (green) through the development of an energy demand and control system and an assessment of the flexibility potential for Austria; and third, a focus on enhancing the interaction between TSOs and DSOs (purple). Based on the outcomes, a demonstration was conducted to validate the developed concepts and methods.

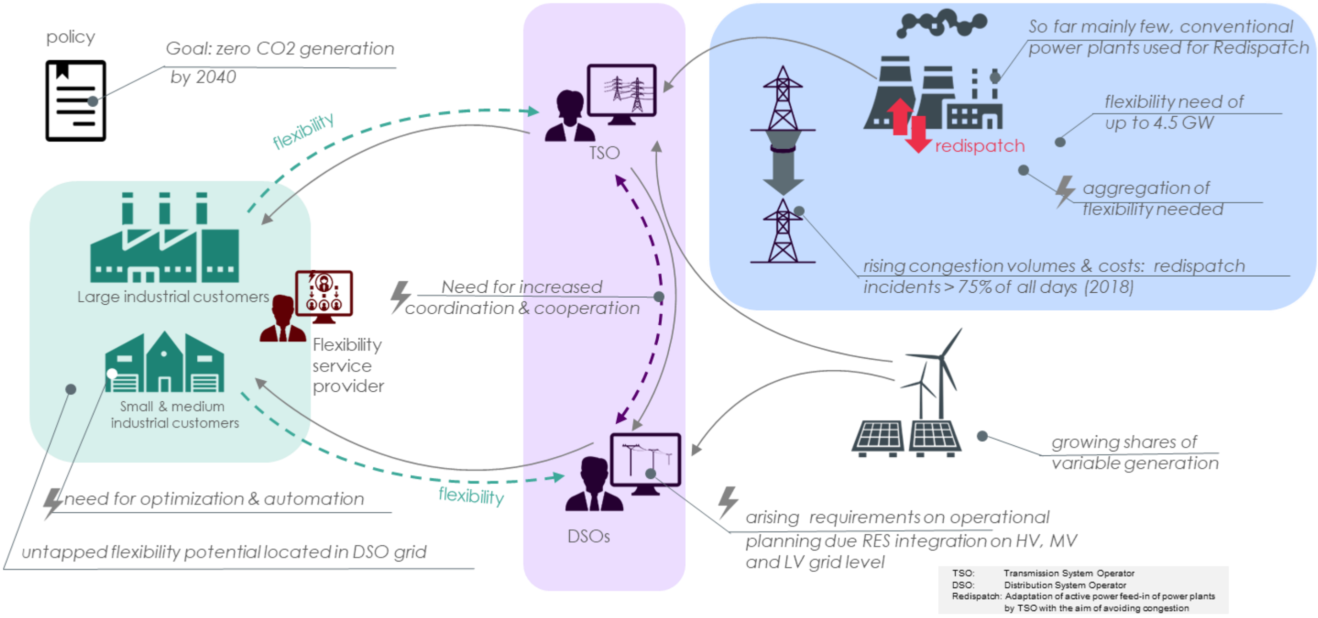

Figure 3 Increasing redispatch demand is currently being met by a limited number of conventional power plants. Simultaneously, the rising share of renewable energy sources—primarily connected at the distribution grid level—intensifies the need for operational planning at the low-voltage (LV) level. Industrial consumers, also located in the distribution grid, represent a potential source of flexibility for congestion management. This flexibility could be utilized by transmission system operators (TSOs) without violating distribution system operator (DSO) constraints, while also offering flexibility for DSOs themselves—highlighting the growing need for enhanced TSO-DSO coordination.

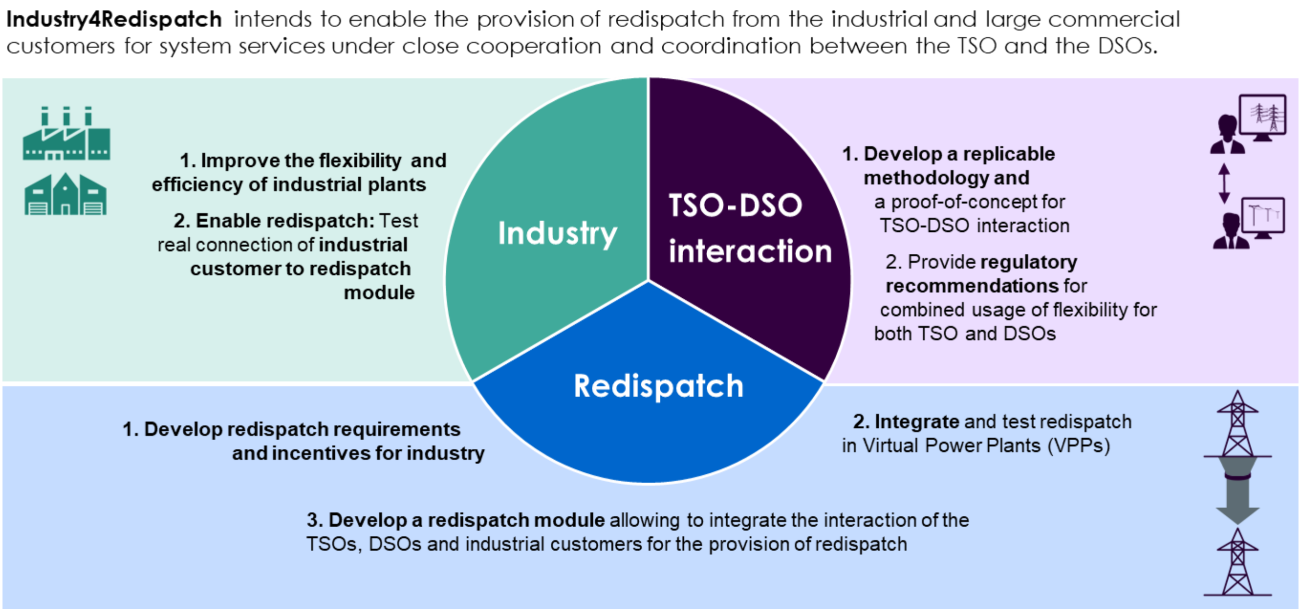

Figure 4 Overview of the research goals, focusing on three main areas: industrial flexibility, enhanced TSO-DSO interaction, and the standardisation of the redispatch product.

Figure 5 shows the project partners involved as well as their roles within the project structure.

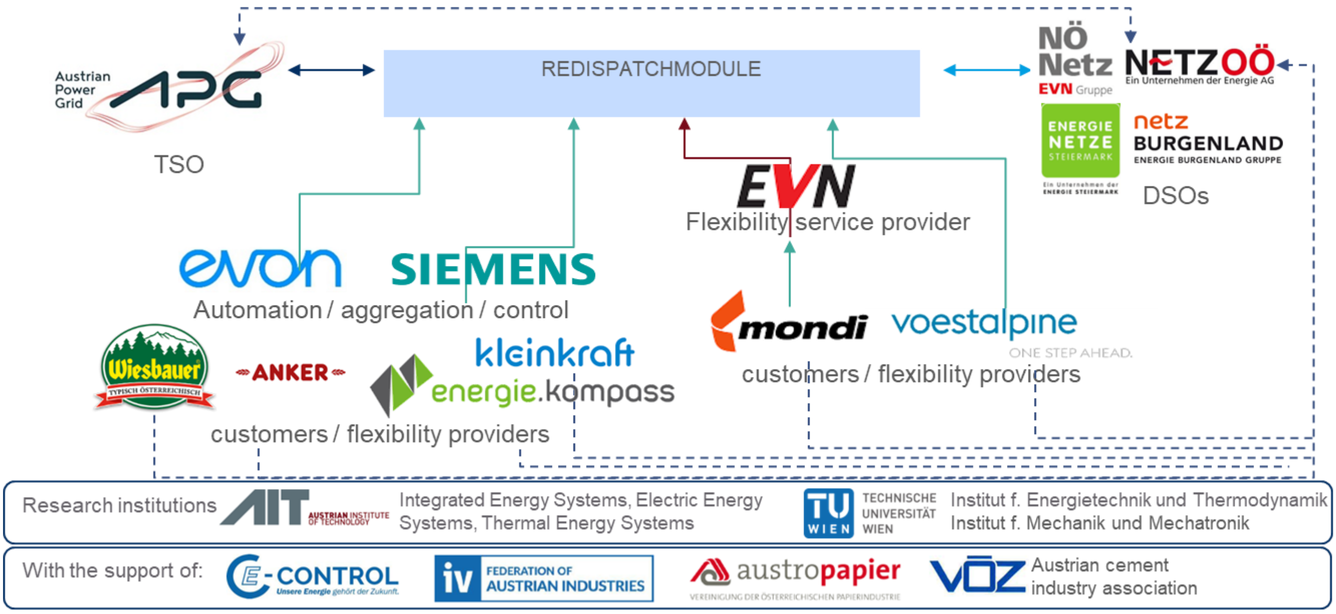

Figure 5 Participating project partners and their respective roles within the project context.

2.1 Redispatch product: Standardization, specification and demonstration of redispatch product and process, remuneration models and regulatory feasibility

So far, redispatch is carried out based on the technical characteristics of individual power plants. Parameters such as lead times or minimum production levels of power plants are known to the grid operator and considered when planning redispatch measures. The integration of smaller units leads to an increase in the number of participants required to achieve the same impact on the transmission grid as conventional power plants. This adds complexity, as all units and their technical capabilities must be considered in the process. To address this issue, I4RD developed a standardized bidding process that eases this coordination problem, which grid operators and flexibility service providers (FSP) could follow (see Figure 6 and Deliverable 3.1 [1] for further description). Redispatch criteria and processes were developed in the project, which are outlined in the following. These specifications were then evaluated for plausibility through a questionnaire distributed to industry representatives, focusing especially on their views and requirements regarding the incentives. Additionally, a regulatory analysis was conducted to assess the compliance and feasibility of the defined product specifications and related processes. In the following, the developed concepts are presented, while the findings from the accompanying stakeholder-specific and regulatory analyses, along with the results of a practical demonstration validating the overall approach, are outlined separately in Section 3.1.

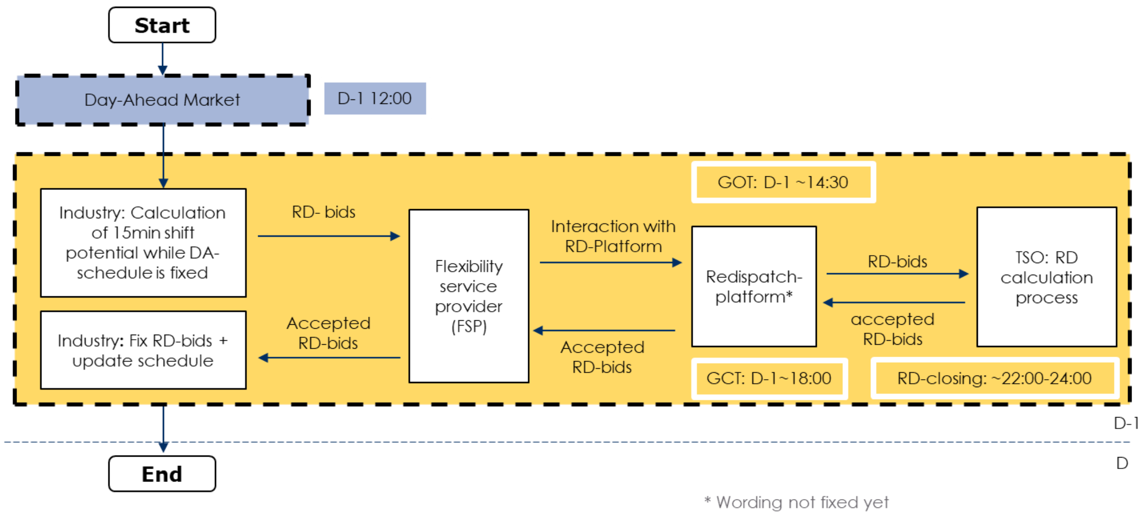

Figure 6 Exemplary redispatch bidding and activation process, see Deliverable D3.1 for further information

The suggested **redispatch process** is shown in schematically in Figure 6 and further described in D3.1 [1].

The **redispatch product** contains the technical and organisational criteria relevant for the redispatch bid (see Figure 7) and general timings related to the process.

Parameter	Value	Background
Min. bid size	1 MW	Certain size is needed to effectively solve grid congestions, also limited by computational requirements of redispatch requesters.
Min. bid increment	0,5 MW	Redispatch is activated symmetrically, therefore bids should uniform to be easily balanced.
Max. bid size	400 MW	To prevent bids that exceed the needed redispatch amounts excessively.
Min. size of single assets in a pool	0,5 MW	For this asset size observability in grid levels 5 or 6 is usually ensured.
Max. size of single assets in a pool	50 MW	Such assets are usually capable of participating in redispatch on their own, thus undesirable inefficiencies are avoided.
Aggregation level	110 kV distribution grids	Trade-off between granularity of locational information and the ease of aggregation (to be further evaluated in the course of the project).

Figure 7 Excerpt from redispatch bid and participation requirements

To participate in the redispatch provision process, flexibility providers must meet specified quality criteria. The key characteristics of redispatch delivery —observability, reliability, and shape of energy delivery—have been identified as critical factors for ensuring effective participation:

- **Observability and schedule data:** Sufficient information on schedules and measured values must be available. Schedule of asset without redispatch bid must be provided day-ahead and serves as a baseline as well as for checking plausibility of the schedule/bid.
- **Reliability/Dependability:** Once a redispatch bid has been accepted, it must be delivered with the exact timing and amplitude as offered.
- **Shape and quality of energy delivery:** Full bid activation must occur within 5 minutes. The delivered energy must fall within a range of 95% to 115% of the bid volume (see Figure 8).

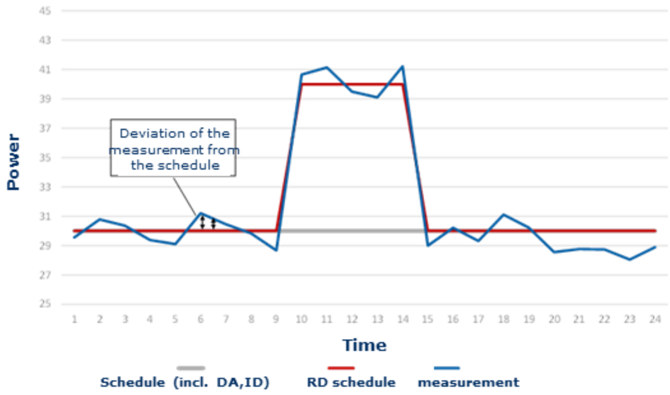

Figure 8 The original schedule is shown as a baseline in grey, the modified schedule including the bid is illustrated in red, and the actual bid fulfilment is shown in blue. The delivered power must lie within 95% to 115% of the bid amount.

Further organisational criteria encompass mainly the conditions of participation as well as possible bid types (see Figure 9) and the handling of catch-up effects (see Figure 10). To be able to participate on the redispatch platform the FSP and the corresponding assets must undergo prequalification. Both the interfaces and formats suggested in the project, as well as the process itself, shall enable a highly standardized and IT-supported bidding process that meets the needs of all involved stakeholders. Further it was considered reasonable to align with existing formats and interfaces from the balancing reserve processes to minimise implementation efforts for FSPs that want to offer both products.

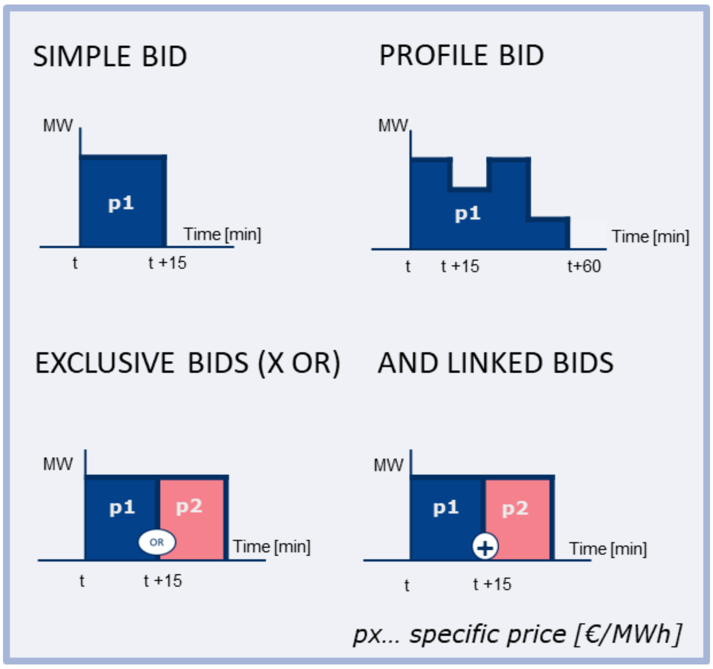

Figure 9 Possible bid types for a redispatch product

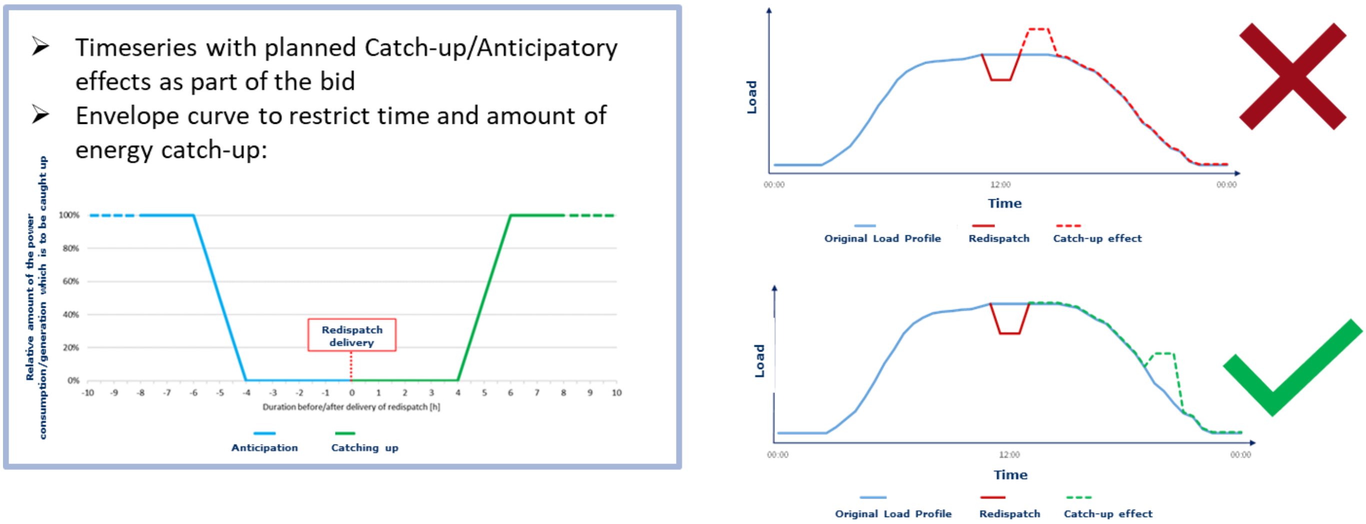

Figure 10 Handling of catch-up effects by defining an envelope curve, which restricts both the timing and the amount of energy that may be recovered after activation.

After defining the redispatch specifics, possible **different remuneration methods** were investigated by comparing existing remuneration mechanisms in European countries. The investigation reveals a clear trend in Europe towards a market-based remuneration of redispatch, as a possible result of Article 13 of the Regulation (EU) 2019/943 (Electricity Regulation). However, when comparing countries using cost-based procurement with those that have implemented markets, it can be observed that in countries without markets, the RD demand that needs to be covered is much higher. There is a variety of other country specific characteristics impacting the establishment of market-based redispatch procurement and remuneration methods, like the ability to apply network topology reconfiguration measures to solve most of the congestions, the country origin of the redispatch demand, or liquidity of the overall electricity market. This demonstrates that several factors play a significant role in the feasibility of a remuneration model in each country. These factors have been analysed in detail for Austria. Several other remuneration methods, combination of methods as well as measures are applied in different European countries:

- In some countries, **hybrid procurement mechanisms** are applied. These countries intend to procure market-based remunerated capacities for redispatch where possible, however, additional cost-based call schemes are implemented, indicating fear that purely market-based remuneration could increase socio-economic costs. A hybrid approach can be applied as a gaming mitigation measure, where market-based remuneration gets only considered where it efficiently reduces the overall costs.
- Besides market-based procurement, some countries additionally procure redispatch according to **negotiated bilateral contracts** (in addition to their market-based procurement). An approach taken to effectively limit the impact of parties with market power. In general, not only cost-based procurement must obligate participants to offer their capacities, also within market-based mechanisms it seems crucial to some countries to **oblige producers** to offer flexibilities for redispatch to ensure sufficient participation to a certain extent.

- Another measure considered as beneficial for cost as well as market-based approaches is the **participation of DSOs in procuring redispatch**. “The European Commission estimated that the EU could save up to 5 billion Euro per year in avoided investments by 2030, if DSOs were able to solve local congestions through flexibility markets” [2] . However, in a few countries the DSOs are only partially integrated, but the trend seems to be to further improve their participation.

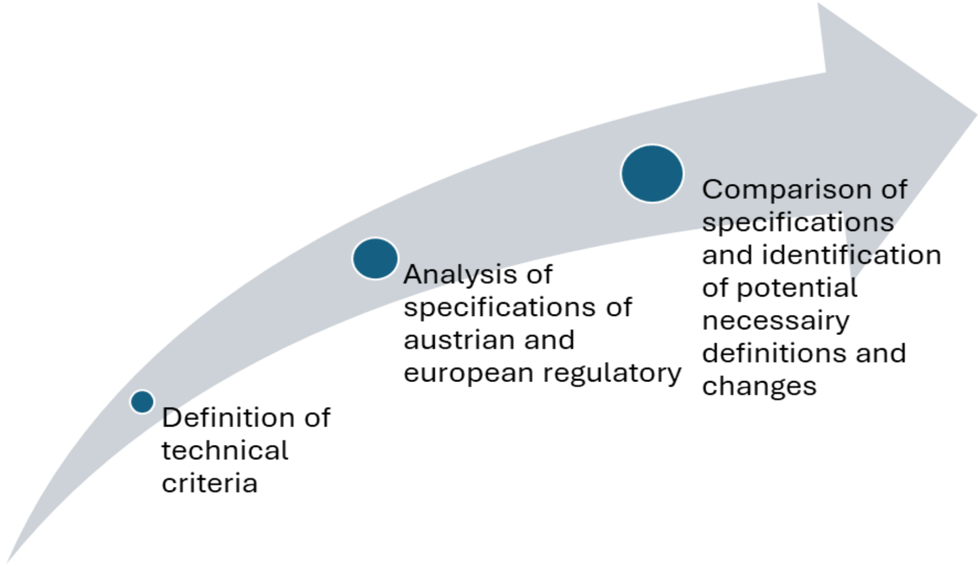

Figure 11 Schematic Overview of the Approach to the Regulatory Analysis

Finally, the **regulatory analysis** within the Industry4Redispatch project examines the legal framework regarding the roles and responsibilities regarding redispatch processes. I4RD focus is on enabling industrial facilities, including virtual power plants, to participate in the redispatch process. The analysis compares regulatory requirements with the technical needs identified in the project. The findings are presented as key legal and regulatory issues. The analysis includes a definition of redispatch, responsibilities of involved parties, data exchange requirements, and a financial compensation of redispatch services. An overview is provided on the different implementations of European countries and relevant regulations. Finally, regulatory gaps are highlighted and potential solutions provided for aligning national laws with redispatch requirements for facilitating industrial participation.

2.2 Industrial flexibility provision

Industrial flexibility has become a decisive criterion for success today. There are numerous incentives for flexibility in an industrial context. The need for this flexibility arises from several factors: on the one hand, product demand is increasingly volatile and difficult to predict. At the same time, resources such as raw materials, energy and labor are affected by fluctuations, e.g. in availability and prices. Industrial companies must also be able to deal with fluctuating process requirements - both planned and unexpected changes. Another important driver of flexibility is competitiveness, which can be significantly improved by adaptable production systems.

Energy management systems can form a significant contribution for leveraging industrial (electrical) flexibility. In this project the applied energy management system included a modular approach allowing for (1) optimal energy planning and (2) optimal realization of this planning as control system, e.g. by means of model predictive controllers. They enable real-time monitoring, analysis, and optimization of energy consumption patterns. Such systems allow industrial facilities to adjust their energy supply based on e.g. on-site renewable generation or energy prices while maintaining production requirements and transform processes from consumers into flexible assets that can participate in grid services and energy markets. In I4RD the Technology Readiness Level (TRL) of such an "energy demand and control system" (EDCS) was significantly increased. Starting from TRL4, which was realized in the project EDCSproof (2018-2021), in I4RD an increase up to TRL7 was realized. This demonstration implemented at two sites. At one of those sites, it was operated over weeks and showed significant performance increase – energy consumption could be reduced for about 8% and the number of start cycles could be reduced by 36%. At the second site, the EDCS was applied to control the energy system of an industrial plant for 72 hours and for 2 redispatch calls as part of the industrial redispatch demonstration.

I4RD determined the installed electrical capacity for industrial processes in Austria and thus, the theoretical potential for flexibility provision in Austria to be around 6,290 MW. The assessed resources include e.g. industrial processes requiring high electrical load such as electric arc furnaces, mechanical grinders in the pulp and paper sector as well as for non-metallic minerals, air separation, chlorine electrolysis or electric smelting processes, e.g. for glass. Furthermore, cross-sectoral technologies such as cooling, electricity supply or power-to-heat technologies, potentially in combination with energy storages, can provide flexibility. Such further flexibility potentials in industry are auto-electricity generation plants such as combined heat and power plants including gas turbines, steam turbines, combinations of those, engines, etc. Their capacity was estimated to be around 1,100 MW. The practical potential of these processes however turned out to be much lower at 190-410 MW (for negative and positive flexibility). Reasons for this large gap in comparison with other flexibility sources (e.g. hydropower plants) are explained together with further background information in the following sections.

The analysis of realistic bid costs for industrial redispatch bids was performed under the assumption that only cost-based bids are derived. In this chapter no further analysis of possible further remuneration schemes (e.g. establishment of a market or additional margins) to increase attractiveness for industry was done. For industrial processes hardly additional costs due to redispatch provision are expected to occur as long as the redispatch provision only includes process postponements or short-term shutdowns with no influence on the quality or quantity of the produced good. For industrial energy supply units positive or negative bid costs can occur. Comparably costs with conventional assets in redispatch provision were found for the combination of gas and steam turbines with heat-only-boilers as well as for the combination of power-to-heat boilers with heat-only-boilers.

2.3 Specification of the TSO/DSO interaction process

The initial specification of the planned TSO/DSO interaction process has been defined based on the stakeholder requirements and lessons learned from other projects. It defines the functionalities and their

distribution between the involved stakeholders as well as the necessary interfaces. Focus is on the specification of the data required to communicate the constraints within distribution networks and the efficacy of redispatch bids at the TSO/DSO intersection. The process flows are designed by addressing a set of defined requirements and the learnings from various European research projects and initiatives.
Based on extensive discussions between the Austrian network operators, the project consortium decided that a central and sensitivity-based bid set filtering approach – similar to the one used within DA/RE – is the most suitable to meet the Austrian stakeholder requirements. The functionalities and data exchanges relevant for the planned TSO/DSO interaction process are shown in Figure 12.
The major process functionalities are divided into three blocks: the *calculation of the simplified DS model*, the *filtering of bid sets*, and the *selection of a bid set*, whereby the calculation of the simplified DS model and the bid set filtering to constitute the core functionalities of the TSO/DSO interaction process. The DSO uses load flow simulations and local sensitivity analysis to calculate the simplified model of its distribution network based on the flexibility providers' schedules and other data and sends it to the platform. The platform uses this simplified DS model to filter the bid sets for redispatch at the transmission level, i.e., it identifies feasible bid sets. Finally, the TSO selects the most suitable bid set for redispatch at the transmission level and reports the selection back to the platform.
The identified basic requirements are divided into four categories, i.e., fairness, practicability, accuracy, as well as scalability & replicability.

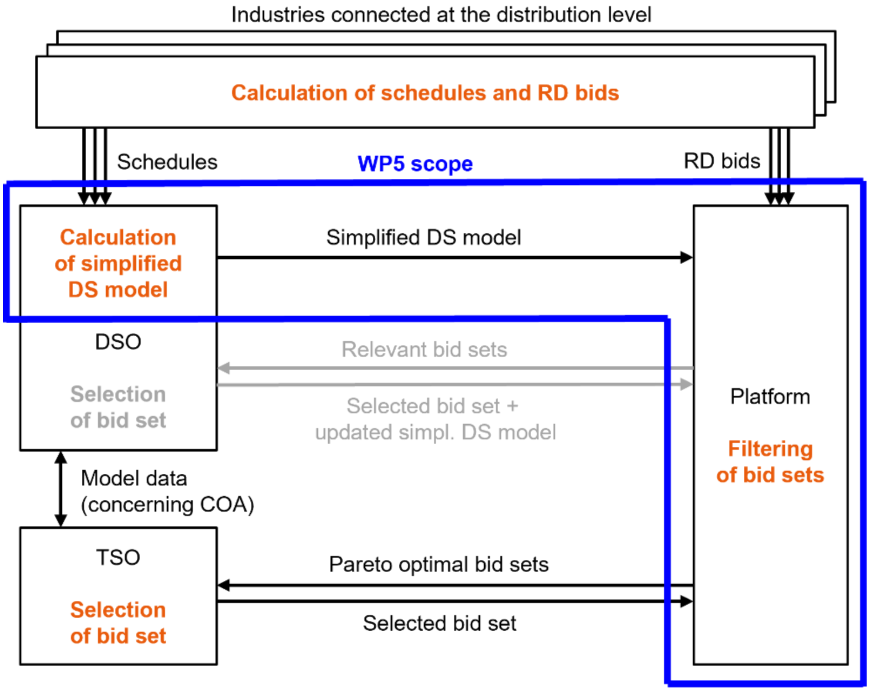

Figure 12: Functionalities and data exchanges of the planned DSO/TSO interaction process

The final specification of the planned TSO/DSO interaction process, which ensures that the activation of industrial flexibilities on request of the TSO does not lead to violations of the operational distribution network limits at the HV and MV levels, is conducted and validated through running several simulations. A simulation environment is developed for the conceptual implementation and pre-validation of the process, for this purpose. A detailed process description which provides insights into the performance of the process for specific test cases were conducted (see more in Deliverables D5.1 [3] and D5.2 [4]) and results are analysed.

3 Results and conclusions

Austria has made significant progress in developing the specifications for a redispatch product and process that allows industrial participation as well as a TSO-DSO interaction algorithm, positioning itself at the forefront of European innovation in this field. Some project results are already being implemented by the transmission system operator. The product definition for the redispatch product has been established. It incorporates input from all relevant stakeholders. This project did foster a deeper mutual understanding between the TSO, FSPs, DSOs, industrial partners and research institutes.

Distribution System Operators (DSOs) benefit from the TSO-DSO processes Distribution System Operators (DSOs) benefit from the TSO-DSO processes because their limitations are inherently considered in the way that no bids can be awarded, that would result in a congestion in their grid. The more the grids are stressed, the more important this process will be. Currently in Austria the imminent need is only just emerging. Many DSOs are interested if the TSO integrates the proposed process. A general level of acceptance of the proposed processes and incentives has been achieved in the project. Looking ahead, DSOs are supposed to actively utilize flexibility where it proves more cost-effective than traditional grid enhancements. Further improvements to the TSO-DSO platform could support and facilitate this transition.

It has been found that realizable, cost-effective industrial flexibility potential is rather limited, especially compared to both installed capacity and other flexibility sources. Still, it could be shown that automation is crucial in reducing energy consumption, demonstrating that while optimized systems may limit available flexibility under normal conditions, automation can enhance both efficiency and overall flexibility. Current framework conditions hardly attract participation and flexibility valorisation for redispatch provision. If the contribution of industrial flexibility for redispatch is to be increased, stronger incentives must be implemented for both existing and new flexibility sources in industry.

Several follow-up projects are being planned, each focusing on specific aspects:

- Further development of redispatch services as an integrated product
- Enhancing TSO-DSO interaction by refining the bid filter mechanism
- Facilitating a more robust and efficient implementation of the EDCS control system

The following table summarizes the key project achievements and remaining needs for action for the three main stakeholders on different levels (implementation, scientific, regulatory):

Table 1 Key project achievements, needs for action and their category (implementation, scientific, regulatory)

Project Achievements	Need for action	Category of Achievement and Need for Action • Implementation • Scientific • Regulatory

Successful implementation and demonstration of redispatch platform including product definition and process specification for interaction between participants and the transmission grid operator.	• Schedule exchange processes with balancing group responsible parties, especially with from the supplier independent flexibility service providers • Improve method for Proof of activation • Consideration of aggregated bids in the network filter	Implementation
Successful operation of Energy Demand Control System (EDCS) in industry, additional effects such as efficient operation of assets could be shown.	• Robustness and features of EDCS need to be further elaborated (for several asset types/industries). • Awareness initiatives for SMEs helping businesses recognize their flexibility potential • FSPs supporting in connecting assets to the redispatch platform and other flexibility markets • Further incentives for participation required • Establishing Clear Liability Frameworks: Develop standardized agreements and legal frameworks to clarify liability responsibilities among industry stakeholders, research partners, and external automation service providers • Employee awareness and clear directives from management, along with a driving force within the company and training initiatives • Incentives for design adjustments (overcapacity, FHG through storage, etc.) and input for funding programs	Implementation
TSO-DSO bid filtering process has been developed and implemented	• Non-linearities of the distribution grid (e.g. from grid control mechanisms) need to be fully incorporated • Information from industrial enterprises on their ability to adjust reactive power could be included in the method of the bid filtering process	Implementation and Scientific
Identification of trilemma between transparency, accuracy, and confidentiality, with different stakeholders having varying interests, ultimately resulting in the grid filter developed in I4RD.	• Uniform guidelines could help to standardize the identification of critical network elements.	Regulatory
Regulatory analysis has been	• New ElWG	Regulatory

carried out and adjustments were identified	(Elektrizitätswirtschaftsgesetz – Electricity Market Law) is currently pending and needs to be approved by the relevant authorities	
Evaluation of suitability of different remuneration models for Austria	• Regulatory changes concerning non-cost-based remuneration component in Austrian law is required	Regulatory

3.1 Redispatch process

In the following, the findings related to the proposed redispatch concept (Section 2.1) are presented, including the analysis of suitable incentives, the suitability of the regulatory framework, and the results of a specific practical test.

3.1.1 Findings about possible incentives for redispatch provision

Gaming of participants is an evident risk in market-based models. The smaller the market the higher the risk usually. Therefore, especially in the case of Austria, it is important to gain a better understanding of the potential liquidity of such a potential redispatch market. For this the redispatch potentials that might be offered in Austria were analysed and compared with the historic redispatch demand.
The main research questions of this analysis can be summarised as follows:

- What are the minimum and maximum redispatch potentials available in Austria?
- What is the range of redispatch demand in Austria.
- Considering these circumstances, is a market-based redispatch technically possible?

In conclusion the analysis of redispatch potentials and comparison with the historical redispatch demand shows that a majority of redispatch potential is controlled by a few market participants which might therefore have significant market power and that the freely available redispatch resources without grid reserve are of a similar magnitude as the maximum historically requested redispatch and **may thus be insufficient for a fully market-based redispatch**. At last, the necessity of the existing grid reserve mechanism is also an indication that the legal obligation to participate in redispatch was not enough to secure sufficient redispatch potentials, but additional capacities had to be reserved. These limitations must be considered when configuring options for the integration of industrial plants into redispatch processes.
With a focus on Austria, there has been analysed the applicability of different remuneration mechanisms, as shown in Table 2. The provision of redispatch may be compensated in a fully market-based model or via a more regulated cost-based model, with reimbursement of the incurred costs based on mandatory participation. Cost+, within the context of this project describes and remuneration model that is based on the cost incurred by the provider of redispatch but provides for an additional profit component to incentivize participation in redispatch. In all cases, capital expenditures (CAPEX) which are not directly connected to the provision of a single redispatch bid, e.g. to facilitate the participation in the redispatch platform, need to be covered as well. In case of a cost based or cost+ model this is subject to discussion

with the regulatory authority, in case of a market the long-term plannability of revenues is crucial for investment decisions.

COST MODEL	COST BASED	COST+	MARKET-BASED
PRO	+ lower costs + higher efficiency if there are only few participants	+ slightly higher incentive to participate + Higher remuneration could cover additional costs of industry	+ higher incentive to participate + Higher remuneration potential could cover CAPEX/addition costs
CON	- Low incentive to participate - Mechanisms to secure capacity required - Effort for supplier to justify costs - Effort for TSO/NRA to verify costs - Information asymmetries between TSO/NRA and RD supplier - Solution to cover CAPEX needed	– Tendency to increase socio-economic costs – Effort for supplier to justify costs – Effort for TSO/NRA to verify costs – Information asymmetries between TSO/NRA and RD supplier – Solution to cover CAPEX needed	– Tendency for (inc-dec) gaming – Tendency to increase socio-economic costs – Validation by TSO/NRA of RD cost probably still necessary – FSP bidding strategy to cover CAPEX needed

Table 2 Comparison of the remuneration mechanisms cost based, cost+ and market-based.

The survey revealed insights into the industry's perspective on compensation models and incentives, highlighting the preference for a cost-plus or market-based approach along with the broader importance of fair remuneration.

A comprehensive survey with over 80 questions was developed, tested with industrial partners, and distributed through various industry channels. However, due to a lack of significant responses, direct interviews were conducted with three experts from the energy supply and pulp and paper sectors. As another corrective measure, a shorter 15-question survey focusing on incentives, remuneration, risks, and organization was later designed and distributed via the same channels.

Key Insights on Compensation Models from industry perspective:

- Compensation should follow either a cost-plus model or a fully market-based approach to create a meaningful incentive for participation.
- The remuneration model should ensure no disadvantage compared to other options, such as balancing energy.
- The implementation effort should remain proportionate to the expected benefits.
- While cost breakdowns are often viewed critically, they are not seen as a fundamental barrier.
- In addition to CAPEX and (capital expenditures) (operating expenditures), key cost factors include risk compensation and personnel expenses.

Barriers:

- **Liquidity and Remuneration:** A well-functioning redispatch market depends on sufficient liquidity and an adequate remuneration structure. Compensation must be designed to provide fair incentives without distorting competition or market efficiency. Power plant operators may also weigh whether offering their leveraged flexibility in the balancing market would be more profitable, potentially reducing available capacity for redispatch.
- **Gaming:** When looking at two sequential markets, on which practically the same products can be offered, there is always a risk of potential arbitrage trading. In the case of a redispatch market, which starts after the day-ahead market, it seems rational to take advantage of opportunities between those two markets. This might lead to strategical bidding behaviour of market participants in order to raise their profits. Such behaviour can result in an inefficient market outcome and welfare losses [5]. The most popular strategy in this context is the Inc-dec gaming, as described by [6] based on game theoretical analysis. This includes the strategic behaviour for two different types of providers, those that are in regions where regulation is predominantly downward and those which are predominantly regulated upward.
- **Market power:** Market-based procurement of redispatch bears the risk of relevant power plants being in a position to exercise local market power, in particular where a congestion is structural (i.e., frequent and predictable) [7] [8].
- **Plannability of revenues:** Predictable revenues are crucial for market participants to ensure long-term engagement. Transparent pricing mechanisms and stable regulatory frameworks contribute to confidence in the redispatch market. Additionally, redispatch is highly location-dependent, and its demand can change over the years due to grid expansion, changes in generation and consumption on national and international level and evolving network conditions. If revenue streams are too uncertain, participation may decline, reducing liquidity and increasing reliance on costly emergency measures.

Aligning the national law with EU regulations and opening the door to market-based redispatch would create new opportunities for decentralized assets and incentivize their participation. The ElWOG[9] in Austria only enables the implementation of a cost-based model. Therefore, any implementation of a remuneration model beyond a cost based one is subject to discussion with the national regulatory authority. The work in the project I4RD gives a detailed base for discussion, by considering the industries perspective, the advantages and disadvantages of the possible cost models as well as the implementations in different European Countries. While a fully market-based redispatch is not yet foreseen in the mid-term due to potential liquidity issues, alternative approaches—such as the cost+ model or hybrid solutions—could help balance industry needs with socioeconomic costs for Austria. Expanding the remuneration model could thus foster innovation, improve grid stability, and increase overall system efficiency. These recommendations have been given to the Austrian regulator. Moreover, recommendations have been provided during the consulting phase of the new proposed law Elwg (implementation still pending).

3.1.2 Suitability of regulatory framework

While the definition of TSO redispatch, the TSOs and the technical units' roles and responsibilities regarding redispatch as well as the grid connection requirements are regulated sufficiently, the following subjects require adaptation:

- The **roles and responsibilities regarding redispatch, attributed to the DSO need to be defined** within the national ElWOG[9] and while some federal ElWOGs allow for DSO redispatch the legislation is not harmonised within Austria. It is suggested to extend the national definition of congestion management to applications at distribution grid level and to harmonise the congestion management obligations and responsibilities by the DSO across the federal ElWOGs.
- The definition of **Significant Grid Users (**SGU) is crucial for determining the responsibilities of grid users, in particular regarding data exchanges relevant for the system operator's grid security analysis and plays an important role in enabling the participation of industrial facilities in redispatch. While the **SGU definition** in the System Operation Guideline[10] (SO GL) was in line with the participation of industrial FSPs and virtual power plants, the definition in the SOGL Dataexchange-R came with more limitations at the time of analysis. It restricted the SGU definition to significant demand facilities providing demand response directly to the TSO with an installed capacity ≥ 25 MW. In general, all potential redispatch providers are significant grid users independent of their size. **This input has been provided to the regulator and the respective regulation has been adopted since then.**
- **An obligation to exchange schedules for demand facilities**, that are SGUs connected at the distribution level, was required as well at the time of analysis. Schedules are the basis of the system operators grid security analysis and function as a baseline for redispatch provision. The SOGL Dataexchange-R did not require demand facilities to provide schedules. The requirement to transmit schedules to the TSO needed to be added to the obligations of demand facilities with a similar wording to that of transmission connected demand facilities. **This input has been provided to the regulator and the respective regulation has been adopted since then.**
- **Financial compensation of redispatch is currently limited to economic disadvantages and incurred costs** by the national ElWOG. According to EU-Law, the default method for the procurement of redispatch is market-based procurement as stipulated in Art. 13 (2) Electricity Regulation [11]. Non-market-based redispatching may only be used, where one of the conditions listed in Article 13 (3) Electricity Regulation is met. Should the mechanism be changed to a market-based procurement, the current ElWOG [9] would not allow the TSO to compensate the participants above their economic disadvantages and costs. Therefore, any market model beyond a cost-based model is a subject to the decisions of the Austrian regulatory authority (E-Control), to ensure the costs of redispatch are acknowledged and considered within the system charges, i.e. the TSO is compensated for its expenses, if such a model should be deployed.

Without precise regulations in place, there is a lack of clarity for both DSOs and industrial participants. For DSOs, this uncertainty complicates the implementation of a unified solution across Austria, leading to potential inefficiencies and fragmented approaches. For industry, the lack of clear guidelines creates a barrier to economic planning security, as businesses are unable to rely on stable conditions for investments in flexibility measures or participation in redispatch markets. This lack of regulatory clarity prevents industries from making informed long-term decisions, which is crucial for the successful integration of industrial flexibility in the energy system.

A ministerial draft proposes a federal law to regulate the electricity industry ("Elektrizitätswirtschaftsgesetz" Electricity Act – ElWG)[12] and a federal law to define the term energy poverty for statistical purposes and to identify target groups for support measures (Energy Poverty Definition Act). The draft also includes amendments to the E-Control Act (ger.: E-Control Gesetz).
Public consultation on the draft was possible, but its progress has been delayed due to the ongoing formation of a new government. The I4RD consortium contributed feedback, and some of the identified gaps have already been incorporated into the draft:

- By harmonizing conditions and terminology for congestion management in the distribution network, there is an opportunity to create a unified framework for redispatch, enhancing efficiency and reducing complexity for grid operators. This has been included into the draft.
- Introducing clear framework conditions for the provision of schedules or baselines enables more accurate grid security analysis and an eased inclusion of smaller assets into the redispatch process. This has been also included in the draft.
- By adapting the regulatory framework to allow for adequate compensation models easily usable by DSOs and TSOs, there is an opportunity to create stronger financial incentives for participation. This could encourage more active involvement from a wider range of participants, improving overall efficiency.

3.1.3 Test of product specification and process in Demo

A redispatch platform to streamline the redispatch process for distributed flexibilities was developed and implemented at the transmission grid operator APG. It facilitates data exchange between flexibility service providers (FSPs) and grid operators, covering key processes such as registration, bid submission, and bid award information. The platform provides standardized interfaces for FSPs, simplifying their market access. By providing a code library for these interfaces in the future, the FSPs initial effort to contribute could be further minimized. Additionally, the backend provides an aggregated view of available redispatch potentials considering limitations by the DSO. Although direct connection of distribution system operators (DSOs) to the platform was not within the project's scope, it remains a viable future possibility.

The whole redispatch process was tested during a demonstration with industry. It involved key industrial partners (Energie.Kompass, Wiesbauer Wien, Voest, and Mondi), FSPs (Siemens and EVN), DSOs (Netz Oberösterreich, Netz Niederösterreich, and Energienetze Steiermark), as well as the transmission system operator Austrian Power Grid (APG). Furthermore, parties which were not part of the project consortium were involved or at least informed including balance responsible parties (BRPs) and a DSO.

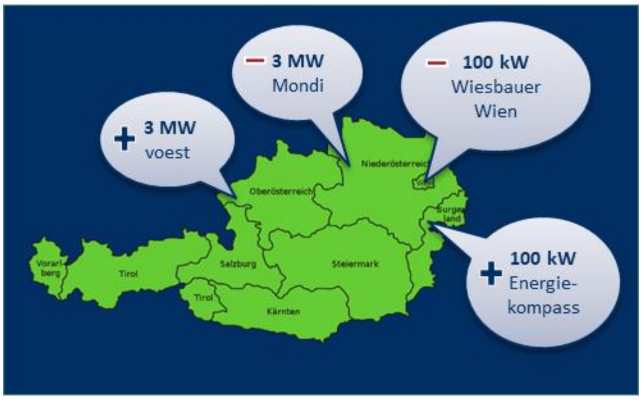

Figure 13 In demo participating industry sites

Each flexibility resource was directly linked to an FSP. The FSP collected flexibility potentials from the resources and submitted redispatch bids to the platform. In the backend of the platform the capacity management module processed the bids and the capacity information provided by DSOs to obtain possible bid combinations. When a bid was accepted, the activation signal was relayed via the platform to the FSP and finally to the respective asset. The specific communication technology and connection method between FSPs and flexibility resources were not defined within the project, leaving these decisions to the discretion of the FSPs and their associated resources.

Over two days, the following steps were executed:

1. Baseline Submission: By 14:30 each day, industrial facilities provided an initial day-ahead schedule to APG, serving as the baseline for delivery validation.
2. Bid Submission: FSPs submitted bids for three different hours of the following day via the redispatch platform.
3. Capacity Check: The bids were validated using the Capacity Management Module (CMM), based on capacity data provided by DSOs.
4. Award Process: Starting at 18:00, the APG control room operator awarded bids. FSPs received confirmation via the platform and executed the redispatch actions independently.
5. Schedule Adjustment: FSPs updated their schedules to reflect the awarded redispatch, ensuring the required adjustments to industrial production or consumption on the following day.

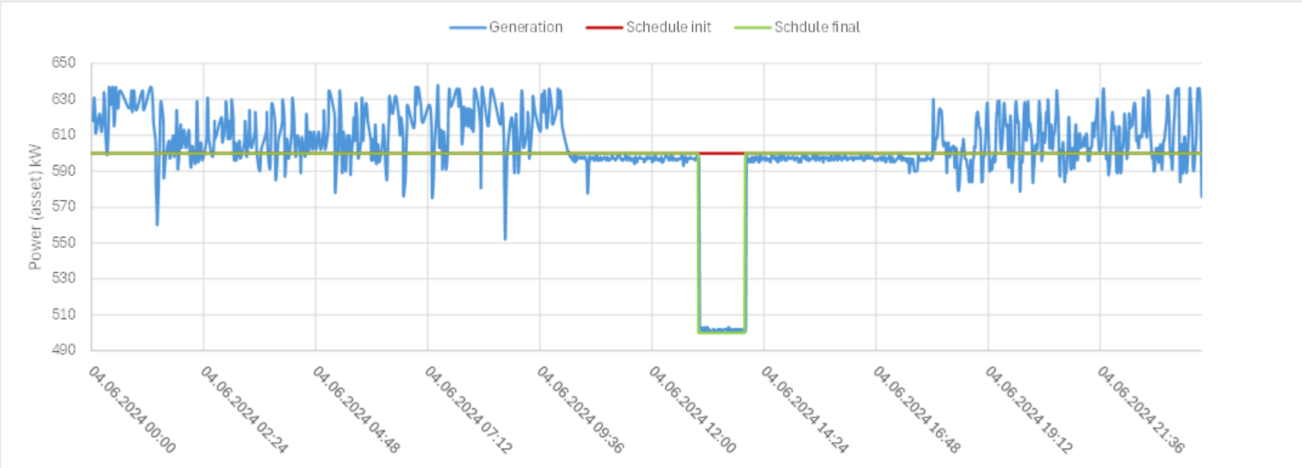

Figure 14 Initial schedule (red) and changed schedule (green) as well as actually consumed power (blue) at Wiesbauer Wien during demo day on asset level

Since the number of bids placed during the demonstration with industry partners was limited, a separate demonstration was organised to properly test the capacity management module with three DSOs individually. During each test session fictitious scenarios defined by the respective DSOs were tested with corresponding dummy bid sets. DSOs provided their grid capacities and sensitivities via a secure file transfer protocol (sFTP) server. Based on that input the capacity management identified bid combinations that respect the constraints of the DSO. In all scenarios the DSO limitations were considered correctly, and no harmful combination of bids was available.

The demonstration confirmed the viability of the process and the feasibility of participation by smaller-scale units in congestion management. The capacity management proved to facilitate a procedure that ensures that no activation of redispatch bids could lead to new congestions in the DSO grid. Additionally, the practical implementation revealed necessary developments for taking the next steps toward integrating distributed units into congestion management.

- The **process of schedule submission** and interaction with balancing responsible parties (BRPs) requires more detailed design to better accommodate the needs of suppliers, flexibility service providers and BRPs.
- If the **proof of delivery** is evaluated based on the schedule, a certain level of schedule quality is required, which cannot always be delivered by distributed resources. Even if the delivery of the resource is perfect, it is not always visible at the connection point and therefore does only have a limited effect on the grid. Therefore, the proof-of-delivery requirements **have to be further improved**.
- A significant challenge lies in **uncertainties regarding the load and generation profiles** of industrial processes. Smaller industrial enterprises, which currently have no balancing responsibility, often lack precise knowledge of their electricity consumption schedules, particularly for the following day. This represents a major shift for such enterprises. Industrial companies further place the highest priority on maintaining uninterrupted production processes. This necessitates a long-term balance between the transmission system

operator's critical need for schedule reliability and the non-disruption of production processes. The EDCS, an advanced energy management system, developed in the I4RD project, offers promising solutions in this area.

- **Aggregated participants in low-voltage virtual power plants** (LV-VPPs) face several hurdles, including the following:
  - Technical requirements currently necessitate a minimum nominal power per asset of 500 kW and above. Furthermore, redispatch offers must have a minimum bid size of 1MW. A LV-VPP might not be able to participate in the redispatch market under these conditions.
  - Applying quality criteria at the level of individual assets or metering points would significantly increase the technical and organizational complexity of an LV-VPP. An LV-VPP would likely need to adopt a stochastic bidding approach offering, for example, only 75 % of the theoretical flexibility across 100 assets while retaining a 25 % safety margin to cover any deviations during fulfilment. Consequently, both the baselining process and the proof of delivery would have to be adapted to accommodate this margin. Without such tailored solutions for redispatch provision and the aggregation of smaller assets, redispatch would cease to be a feasible business model for LV-VPPs.

A new product, which enables the participation of decentralized assets in redispatch, was designed, successfully validated within a demonstration. The final implementation is depending on the ElWG and would be executed not only by the TSO but in cooperation with DSOs. The whole process benefitted from strong stakeholder involvement and close collaboration with the Working Group "Systemführung 2.0" from Österreichs Energie. The project developments have unlocked new opportunities by enhancing the bidding, filtering, and activation process, paving the way for broader implementation and utilization. The standardization and automation of the process not only strengthens future grid stability but also sets the stage for further innovation. Valuable recommendations were submitted to the Austrian regulatory authority E-Control during the consultation phase of the planned Elektrizitätswirtschaftsgesetz (Elwg[1]), which is currently pending.

3.2 Industrial flexibility

3.2.1 Austrian industrial flexibility potential

This analysis revealed an installed electrical capacity of approximately 6,290 MW in industrial processes and cross-sectional technologies, plus about 1,100 MW in electricity auto-production plants. Three provinces - Upper Austria, Styria, and Lower Austria - account for 67.7% of the total installed capacity, reflecting the concentration of energy-intensive industries in these regions. Regarding technical flexibility potential, in the project approximately 410 MW of positive and 190 MW of negative flexibility potential for one-hour call times, including auto-production plants, were identified. The largest positive potential is found in energy-intensive sectors such as chemical/petrochemical industry, non-metallic minerals, and paper/pulp production. Negative potential was primarily concentrated in the paper sector. Auto-

[1] https://www.parlament.gv.at/gegenstand/XXVIII/ME/32

production plants contribute about 55 MW of positive and 110 MW of negative flexibility potential for 15-minute and 1-hour durations. However, their actual contribution highly depends on the actual economic situation including energy prices, order situation, etc. In comparison to the flexibility potential of other technologies (other sectors such as e.g. power plants, households, etc.), the industrial flexibility potential determined in this work is currently still very low. For example, the potential of pumped-storage and storage power plants in 2020 was 8,844 MW (positive) and 4,200 MW (negative), respectively [13].

Site based assessment but also several current developments impact the values for actual and future industrial flexibility. With an increasing need for decarbonized concepts in industrial energy supply higher shares of electrified heat supply seem possible. Nevertheless, this development could be accompanied by a reduction in industrial on-site electricity supply, especially from fossil fuels such as natural gas.

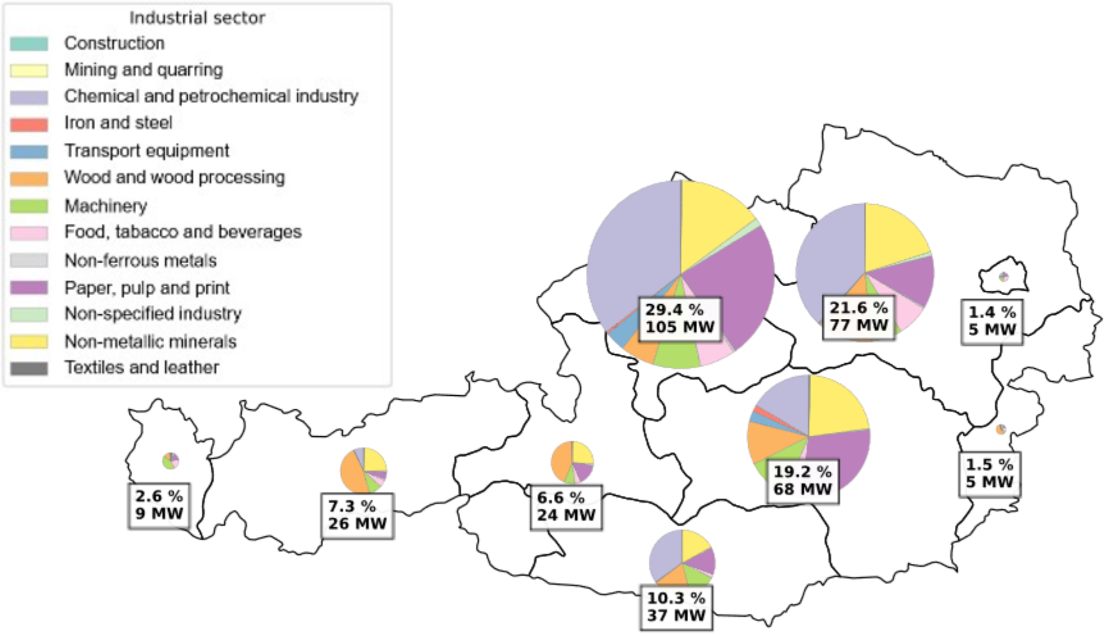

Figure 15 Distribution of the positive technical flexibility potential (excluding electricity auto-production plants) with a request time of 1h among the provinces and industrial sectors. Positive technical potential in MW and relative shares of the total available

In the following a short description is given how the quantification of the industrial flexibility potential was performed. In general, we applied a combined top-down-bottom-up method to identify positive and negative flexibility potential in the industry.

Thus, first a method for estimating installed electrical plant capacities in the Austrian industrial sector was setup consisting of three main steps. First, it determines sector-specific full-load equivalents using both regression analysis of German industrial load profiles and expert assessments. For sectors where load profile data was unavailable, the project team relied on domain knowledge from various sources including previous projects, and industry associations. Second, the installed plant capacities are calculated by dividing the annual electrical energy consumption per sector (from Statistics Austria's data) by the determined full-load equivalents. This calculation allows for both sectoral and geographical distribution of power capacities across different plant types and federal provinces. Finally, the method includes bottom-up analyses to validate assumptions and increase granularity. The study also evaluates technical flexibility potential by assessing which proportion of the total installed capacity can provide flexibility (positive or negative) for various activation durations (15 min, 1h, 4h). These technical flexibility potentials are further categorized by temporal availability (diurnal, daily, and seasonal patterns), though regulatory barriers and the realizability on-site were not considered in this assessment.

The overall potential is estimated to be 190 MW of negative, and 410 MW of positive flexibility. This is currently considerably lower compared to conventional technologies for redispatch provision. Nevertheless, industrial flexibility for redispatch poses several opportunities in the overall energy system due to its distinct characteristics compared to traditional flexibility sources on the one hand but also compared to traditional trading schemes (balancing energy and spot markets) on the other. Two key differences to conventional redispatch sources and thus opportunities – especially for grid operators - of industrial redispatch are:

1. Economics: Redispatch requires bids that specify both power quantity and associated costs for compensation. This differs from spot market trading, which primarily focuses on price prediction and cost minimization. Furthermore, industrial bids typically have smaller sizes compared to large power plants currently used for redispatch. This could even lead to reduced costs, in particular if industrial flexibility would avoid starting up big power plants.
2. Geography: Unlike balancing energy or spot markets, redispatch effectiveness depends on the facility's grid location relative to congestion points within the control area. Thus, for system operators it might be a more effective option – regarding energy and costs – to overcome congestions.

A relevant opportunity for industry is presented in the following:

- Timing: Redispatch notifications typically come the evening before or hours ahead of activation, allowing for planned operations in the industrial setting. In contrast, balancing energy activations occur with minimal notice (<1s to minutes), while spot market trading ranges from day-ahead to minutes before delivery. This allows also to include further flexibility potentials compared to spot and balancing markets. Examples can be processes such as felt change in paper machines or exhaustive cleaning activities.
- Furthermore, the analysis of flexibility potentials in industry often unlocks unused efficiency potentials leading to improved energy and cost performance of industrial systems.

In addition, costs of typical technologies were estimated. This cost analysis revealed the following key findings.

1. **Negative bid cost possible:** Industrial flexibility bids for redispatch can have negative costs. Positive costs indicate that the (transmission) network operator is liable to pay compensation, while negative costs indicate that the industrial site would pay up to those costs. A typical example is, that a fossil fuel fired steam boiler is replaced by an electric power-to-heat boiler. Assuming, that the remuneration for redispatch is cost-based, the (negative) bid costs for this case would be derived from the avoided cost for natural gas and the efficiencies of the respective technologies.

2. **Cost Range and Symmetry**: Redispatch bid costs for the considered technologies and energy price assumptions vary significantly across technologies, ranging from 26.3 €/MWh to 188.0 €/MWh for positive redispatch, and from -87.7 €/MWh to -26.3 €/MWh for negative redispatch. Some technologies, notably conventional sources such as pumped hydro storage or combined cycle plants, demonstrate relatively symmetric costs for positive and negative redispatch.
3. **Technology Comparison**: Conventional technologies generally show more balanced bidding costs compared to industrial alternatives.
4. **Industrial Applications**: Among industrial technologies, back pressure steam turbine (BPST) systems show the highest positive redispatch costs at 188.0 €/MWh, while the technology combination of heat pump and thermal storage systems demonstrate more moderate costs (-85.0 €/MWh negative, 86.7 €/MWh positive) for the given prices assumptions.

This cost analysis demonstrates that while conventional technologies offer relatively balanced redispatch options, industrial technologies present a wider range of costs, reflecting their diverse operational constraints and primary industrial purposes.

From a methodological point of view the cost analysis includes the following: average industrial energy price levels incl. fees in Austria from 2024 and typical efficiencies of considered technologies. From an industrial perspective, the costs associated with a flexibility bid encompass the difference between conventional energy consumption expenses in a base scenario and those incurred in a scenario that accommodates the specific flexibility bid.

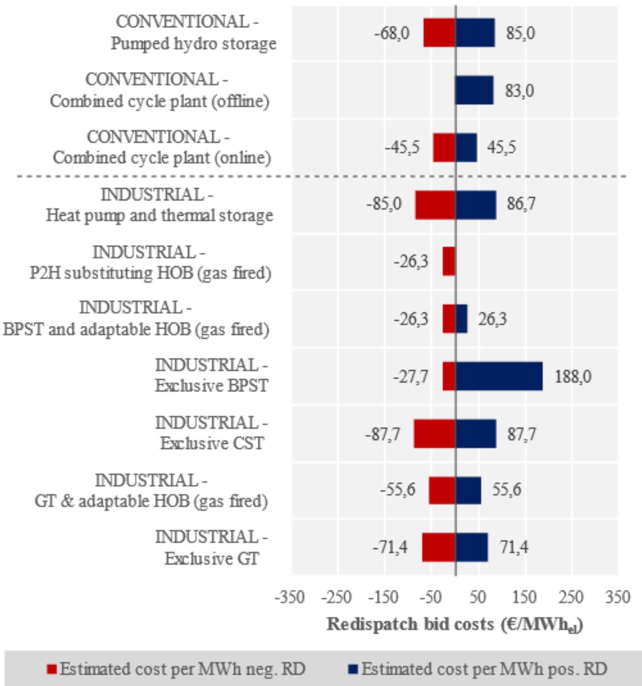

Figure 16 Overview of industrial and conventional technologies for RD supply and estimated negative and positive flexibility costs excluding changed fees for power-related grid charges. (HOB-heat only boiler, BPST-back pressure steam turbine, CST-condensing steam turbine, GT-gas turbine)

3.2.2 Barriers for industrial flexibility

In the following an overview of exiting barriers to use industrial flexibility especially for redispatch is given. Industrial facilities face multiple challenges when providing flexibility services, particularly for redispatch operations. These barriers can be categorized into four main areas: technical, organizational, regulatory, and economic constraints.

- Technical barriers primarily stem from infrastructure limitations. Many facilities lack adequate measurement systems, data processing capabilities, and control mechanisms, making it difficult to identify and utilize flexibility potential, especially for smaller sites with considerably smaller energy consumption and loads. Additionally, the coupled operation of energy supply plants, such as combined heat and power systems, can restrict operational flexibility.
- Organizational challenges are equally significant. High-capacity utilization often means that load reduction or shifting directly impacts production output. Quality concerns and production risks associated with flexible operations create reluctance among operators. Furthermore, the unavailability of qualified personnel across all shifts might limit (all-day) flexibility options. At some sites additional staff could even be required to take over the additional tasks redispatch provision brings along.
- Regulatory restrictions pose another layer of complexity. Plants must maintain compliance with noise emission limits and efficiency targets, which can prevent shifting operations to nighttime hours or utilizing alternative energy supply technologies. At the same time, they need to fulfil pre-qualification requirements which might pose another burden.
- Economic barriers are particularly crucial for redispatch services. Industrial flexibility sources often struggle to compete with conventional systems, and more attractive opportunities exist in short-term and balancing energy markets. The additional organizational burden of providing redispatch services, combined with the requirement for accurate baseline load forecasting, further complicates participation. Even energy-intensive companies with established load forecasting practices face challenges with production process fluctuations, affecting forecast accuracy.

These multifaceted barriers significantly impact the practical exploitation of theoretical flexibility potential in industrial settings.

3.2.3 EDCS demonstration

The Energy Demand Control System (EDCS) is a modelling, optimization and control framework primarily relevant for small to medium-sized industrial sites where energy consumption is important but has not been a top priority in operational decisions in the past. Within this project it was further developed from a previous NEFI project *EDCSproof*. The potential impact of the EDCS derives mainly through its expandable architecture, as demonstrated in the project through the successful implementation for different applications.

(1) On simulation level – not demonstrated at industrial scale – we were able to show its ability to be included into process scheduling. This enhancement opens additional application scenarios, showing how its core optimization framework can be adapted to address broader operational

challenges and create new value streams for industrial facilities that previously may have overlooked energy optimization opportunities.

(2) The demonstration phase for the multiple functionalities (reading of current states, optimal planning of energy supply system components and realization of a model-predictive controller to realize optimal operation trajectories) could successfully be transferred from the lab (EDCSproof project) to a real industrial plant. The EDCS was operated at one of the industrial partners for several weeks and achieved significant improvements of the energy system performance there. The application of the EDCS led not only to savings in overall energy consumptions and thus reduced energy costs. Also reduced starts and stops of the equipment could be realized providing additional monetary benefits on the long-term – energy consumption could be reduced for about 8% and the number of start cycles could be reduced by 36%. One the other side, the robustness of the running capability could be improved. Thus, also a suitable and applicable human-machine-interface was elaborated to allow efficient operation and handling on-site. This has high relevance as the successful operation of the EDCS is not possible without appropriate operation by the employees on site.

(3) The EDCS also demonstrated its advanced capabilities in supporting the demonstration of industrial redispatch services, (one main goal of the project) at one of the three included industrial sites participating in redispatch provision during the demo phase. The EDCS was applied to control the energy system of an industrial plant for 72 hours and for 2 redispatch calls as part of the industrial redispatch demonstration. Multiple functionalities of the EDCS were necessary to realize this redispatch provision. Beyond its core function of generating optimal schedules and trajectories for energy supply units, the EDCS was enhanced during the project to handle flexibility bid generation and execution. Through targeted code extensions, it gained the ability to calculate and submit flexibility bids to e.g. a flexibility service provider (as interface to any further market or platform), and upon successful clearing by external systems, it could implement the accepted bids by adjusting the operational (control) parameters of the energy supply units accordingly.

Despite successful development of the EDCS, in general the wide application range of such a tool faces several significant implementation barriers in industrial environments. Within the project the following barriers could be identified

- A primary challenge lies in the heterogeneous nature of industrial energy supply systems, where each site presents unique configurations and requirements, making standardized solutions difficult to implement. This heterogeneity still takes extensive manual effort to develop and validate site-specific models. A resource-intensive process that currently hinders broader and especially faster market penetration.
- Integration with existing automation systems presents another hurdle, as many facilities operate with systems that have evolved over decades, making seamless data exchange and control implementation complex.
- Liability concerns also pose significant challenges, particularly when the EDCS actively adjusts system setpoints, as especially manufacturers are often hesitant to delegate control of critical processes.

- In addition, often the prerequisites for the EDCS are currently not given at industrial sites including digital production plans. In those cases, the implementation of an energy demand control system might make organizational adaptions of workflows and tasks necessary. Typically, such processes require excellent communication of the benefits and needs and are thus challenging in the transition process.
- In general, to achieve wider industrial implementation, the effort required for site-specific modeling and integration must be substantially reduced, e.g. through standardization and automated model generation approaches, while simultaneously addressing security and liability concerns in a comprehensive manner.

As indicated above not only energy cost savings could be derived – an optimal operation of energy supply systems showed also additional benefits, such as reduced starting procedures of the included technologies leading to less system wear, longer service life and therefore lower costs in the long term.
The EDCS's usefulness is demonstrated through its ability to address a wide range of objectives, delivering both immediate and long-term benefits. While direct financial advantages can be achieved through reduced energy consumption, lower energy costs, and increased utilization of on-site renewable generation, the system also yields significant indirect benefits that may not be immediately quantifiable in monetary terms. These include e.g. extended equipment lifetimes and reduced maintenance costs through optimized operation patterns, particularly by minimizing unnecessary starts and stops of machinery.

3.3 TSO-DSO Interaction

During the project, a continuous cooperation and knowledge exchange took place with working groups of the Association of the Austrian Electricity Industry (Österreichs Energie), working on the definition of TSO-DSO interaction processes to be implemented in the Austrian electricity market regulations. In addition, expert interviews were conducted within the project to gain an overview of the Austrian network operators' requirements on the TSO-DSO interaction process.

As mentioned above the identified basic requirements for the TSO-DSO interaction process are divided into four categories, i.e., fairness, practicability, accuracy, as well as scalability & replicability:
Fairness comprises transparency, freedom from discrimination, and self-determination, which means that outsiders can easily understand and reproduce the coordinator's decisions, all flexibility providers have an equal prospect to contribute to system operation, and each network operator maintains the operational responsibility for its own network. **Practicability** implies the use of simple, robust, and quick procedures that involve low data exchanges and avoid the exchange of sensitive and confidential data. **Accuracy** promotes optimal resource utilization and **scalability and replicability** allow for the seamless process integration of additional participants and system portions without deteriorating fairness, practicability, and accuracy. Fairness, practicability, and accuracy are conflicting requirements that must be traded off against each other. Especially, resource utilization, transparency, and privacy span a trilemma in which only two requirements can be maximized at the expense of the remaining one.

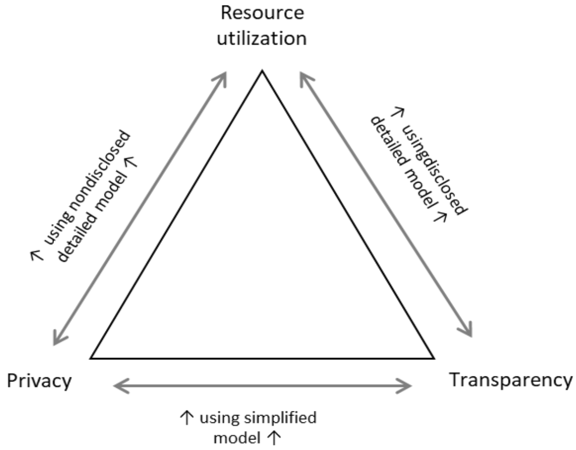

Figure 17: Trilemma of power system coordination.

The following examples correspond to the triangle's edges and shall clarify this trilemma:

a) Resource utilization and privacy are maximized by using a nondisclosed detailed system model for coordination.
b) Resource utilization and transparency are maximized by using a disclosed detailed system model for coordination.
c) Privacy and transparency are maximized by using a disclosed simplified system model (or just capacity information) for coordination.

After thorough consultations among the Austrian network operators, the project consortium concluded that a centralized, sensitivity-based bid set filtering method is the most appropriate to address Austrian stakeholder needs. The resulting core process flows reflect a balanced compromise aimed at achieving a suitable trade-off between fairness, practicality, and precision. Although simplified distribution system models reduce the accuracy of calculations, the resulting errors are considered minor considering existing modelling and forecasting uncertainties.

The final TSO-DSO interaction process involves three major functionalities that are executed by different parties:

- calculation of the simplified Distribution System (DS) model
- filtering of bid sets, and
- selection of the final bid set.

Figure 18 depicts the functionalities (orange fonts) and data exchanges (arrows) of the planned TSO/DSO interaction process (blue box).

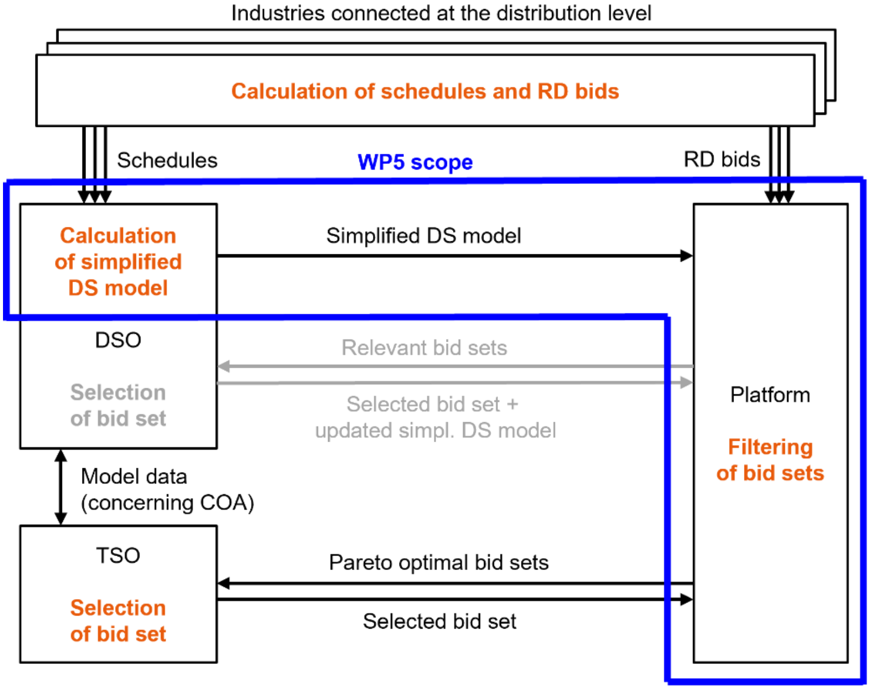

Figure 18: Functionalities and data exchanges of the planned DSO/TSO interaction process.

The calculation of the simplified distribution system model includes initial calculation of the simplified DS model and its re-calculation after bid set selection (if redispatch at the distribution level is necessary). The DSO re-calculates the simplified DS model after receiving relevant bid sets from the platform and after selecting the most suitable bid set. This re-calculation is optional and happens only if the platform detects violations (or approaching limits) of the distribution network's operational voltage or current limits based on the initially calculated baseline network state. In contrast to the initial calculation, the re-calculation is based on the modified industry schedules, which reflect the effects of the selected bids including the corresponding anticipatory and catch-up effects.

The bid set filtering is the core task of the planned TSO/DSO interaction process. If redispatch is necessary the platform uses the simplified DS model to identify pareto optimal bid sets, i.e., sets with low cost and high power that do not cause any limit violations at the distribution level. These bid sets are then provided to the TSO.

The TSO receives these bid sets and selects the most suitable one by solving an optimal power flow problem that respects the transmission constraints. Pareto optimal bid sets give the optimal solution of DSO level for any specific TSO redispatch demand and can therefore be used at the transmission level without violating distribution network constraints.

nd can therefore be used at the transmission level without violating distribution network constraints.

The proposed data exchange between different parties is a vital part of the planned TSO-DSO interaction process. Sets of data must be transmitted between the participating project partners and the data exchanges must be facilitated within a suitable IT infrastructure. The main exchanges for this process are the DS capacities, i.e., the simplified DS model, the redispatch bids provided by the flexibility service providers, and the communication of the pareto optimal bid sets to the TSO.

These bid-sets should be generated for every distribution grid area. The interaction process should bundle the bid sets in a data-exchange format which contain information about

- the distribution grid area associated with the list of bid-sets
- the respective price-volume curve of bids-sets ranging from the maximum power reduction up to the maximum infeed
- the list of bids associated with each point in the price-volume curve

Besides the consideration of grid capacity constraints, the TSO-DSO interaction also requires other data exchanges that are outside the scope of the project but should be listed, nonetheless.

- Schedules of power generation and load are the basis for grid security analysis and capacity calculation. Any schedules required to perform the capacity calculation are exchanged within the existing framework for the exchange of schedules in accordance with Austrian electricity market rules (Sonstige Marktregeln - SoMa[2]).
- Measurement data for ex-post validation will not yet be harmonized but exchanged manually after the demonstration was completed.

The recommendations and conclusions on the proposed TSO-DSO interaction process are presented in chapter 4.3

4 Outlook and recommendations

The following section presents the key findings from the different thematic parts of the project, from which the recommendations are derived:

4.1 Redispatch process

The process defined for the demonstration in general proved to be instrumental to a successful incorporation of distributed resources into the redispatch process. Nonetheless, a couple aspects have been identified that require further development. This chapter summarises the main lessons learned on both technical and organisational level which are clustered into the topics schedule exchange, registration and prequalification process, RD platform, TSO-DSO coordination, validation, procedure in the event of failure and measurements. Furthermore, difficulties from industry perspective regarding the delivery are summarised.

Schedule exchange: Since the schedule functions as baseline for the redispatch delivery, a Production Responsible Party Schedule (PPS) announcement and update, reflecting the planned generation of a powerplant or consumption of a significant load, are required. Usually, the PPS announcement is done by the BRP. However, the BRP do not model small scale assets in such detail. This means that a schedule announcement would need to be executed by the plant operator themselves or the FSP. However, this proves to be challenging, since even the plant operators themselves do not always have a

[2] „E-control SoMa“ [Online]. Available: https://www.e-control.at/bereich-recht/soma-strom.

reliable schedule in the day-ahead timeframe. In any case the correction of the balance groups of the redispatch providing assets needs to be considered to account for the schedule change due to the redispatch activation. The correction of the internal schedule of the BRP works well when the redispatch providing assets have a size considerable enough, that they are modelled by their BRPs. In the RD Demo the correction of the balance groups with Energie AG (for VOEST) and GEN-I (for Mondi) worked, because the industrial sites were explicitly considered by their BRP. However, in case of small-scale assets a model (similar to the "Datenkarussell" used for balancing) needs to be developed to facilitate the necessary data exchange between FSP, the original supplier and the BRP for the purpose of correcting balances but also for potential economic exchange between FSP and supplier. Furthermore, the consumption records (i.e. the measurements used for settlement) need to be adapted, to allocate the volumes accurately to the BRP of the supplier and the BRP of the service provider. Finally, the distribution of grid fees in case of multiple BRPs also needs to be considered.

Registration and prequalification process: The registration should be easily accessible for FSPs and process wise as similar as possible to the balancing process. So far there is no prequalification procedure for redispatch established. This needs to be developed and to be included in the overall onboarding process of new FSPs and their redispatch providing groups and resources. The onboarding should involve the following steps: Initial registration of the FSP (including technical connection to the RD platform), data provision for registration of resources and the configuration of pools and prequalification. Part of this procedure has to be the correct assignment of feed-in nodes of the DSO and the transmission substation to the respective resources for the correct modelling in the capacity management module. While the technical aspects of the registration and the required data were developed as part of the project and successfully tested during the pilot, the exact procedure still needs to be defined. The aim is to create a process that minimises barriers to new market participants while also ensuring high quality of the service.

RD platform: The platform configuration in general fulfilled the required functionalities and the developed and used JSON interfaces facilitated standardised data exchange during the registration and bidding process. In the future APG will use an API Gateway facilitating the authentication on APG side, however FSPs still will need to implement an authentication mechanism for their own interfaces. Furthermore, the need for additional feedback has been identified. Service providers would like to receive additional information on why their bid was not accepted (i.e. because of the merit order or because of DSO restrictions). Finally, FSPs suggested the provision of modules/code snippets for the implementation of the interface by the TSO to reduce implementation efforts for FSPs. The difficulty with such an approach lies within the variety of local systems: providing a template for implementation that could be applied universally might prove to be challenging.

Validation of delivery: In the Deliverable 3.3 [14] it is clarified that the delivery of redispatch is evaluated based on the schedule. Therefore, a certain level of schedule quality is required. This schedule quality cannot always be delivered by FSPs, especially since most distributed resources currently do not send a schedule at all. The possibility to handle a lack of schedule quality by correcting the schedule based on the calculated error was analysed. However, the most effective method could not be concluded. Furthermore, it has become evident, that even if the delivery of the resource is perfect, it is not always visible at the connection point. In such cases the measure does only have a limited effect on the grid. A mechanism when and how this is treated and potentially penalised needs to be developed, to establish a sufficient quality of service delivery.

Delivery by Industrial sites/ Procedure in the event of failure: In general, the control of industrial sites works well. However, contrary to conventional powerplants there are more dependencies affecting actual generation or load. In case of distributed renewable energies behind the metering point this involves the potential risk of volatilities due to the weather dependency. In case of industrial procedures there may not only be the difficulty to plan the production sequence that would allow the generation of a reliable load profile but also the added complexity of the use of process steam or gas which is dependent on the industrial demand. In case the industrial process doesn't go as planned there may be less or more gas/steam available, which affects the capability to follow the schedule and provide the service. Since this may happen with a certain probability, it is important to plan for it: there is a need to develop a process that can be followed in the event of failure. In Deliverable 3.3 [14] three options were outlined. Another option would be to allow FSPs to aggregate geographically similar assets and to account for securities (including more flexibility in their pool than is offered). In this case all recourses would need to be sent as part of the bid to be evaluated in relation to DSO restrictions. This would add the benefit of better quality of delivery while increasing the risk that the bid will be limited due to DSO restrictions. Such an option needs to be further investigated to ensure the modelling of such a concept for all process steps is clear.

Measurements: Currently the measurements are exchanged ex-post manually in various formats. This makes an automated validation more time consuming. In the future a clear data format should be used, that is easily machine readable.

4.2 Industrial flexibility

The work in the project Industry4Redispatch revealed promising pathways for industrial companies to adopt flexibility and capitalize on emerging opportunities. Also, it was elaborated how optimization-based tools can support this process.

Opportunities arising through flexibilization are e.g. the fact that automatization of energy supply and control can uncover unlooked potentials. It can be understood as baseline to increase process understanding and awareness, lead to increased efficiency and unlock new business options such as participating in energy markets. Furthermore, synergies with reporting activities might be realized due to more exhaustive data collection and advanced data handling. Additional non-monetary benefits could be higher product quality, better unit performance or unit conservation, e.g. through reduced starts and stops of a unit.

For **future developments** several interesting aspects can be discussed.
First, flexibility as a service represents a potential new business model evolution that could lower barriers to entry, allowing companies to access flexibility markets without significant in-house expertise.

Electrification as significant decarbonization measure for a wide range of industrial activities will offer new flexibility potential, particularly through integration of electrified kilns, electric boilers or heat pumps. Furthermore, new potentials might rise through refrigerated transport fleets and electric vehicle fleets owned by industrial enterprises. These mobile storage systems could participate in grid services when not actively in transport use.

However, the ongoing energy transformation introduces not only opportunities but also challenges. As conventional (fossil fired) natural gas-fired boilers, turbines, and CHP plants are gradually phased out in favor of electrified heat generation, many traditional flexibility potentials will disappear while new ones emerge. This development brings additional complexities, particularly in batch production processes transferring to electrified methods, requiring new approaches to flexibility management.

Retrofitting existing infrastructure presents another opportunity, though challenges around warranties and performance guarantees must be addressed to make this approach more efficient. Industrial heat pumps face an interesting optimization challenge, balancing the preference for constant operation against fluctuating waste heat availability and demand patterns.

Meanwhile, deeper collaboration with equipment manufacturers to optimize ramping sequences, start-up procedures, and operating parameters could unlock additional potential and significantly increase cost savings.

A not exhaustive list of **potential future steps** for different stakeholders (research, industry, consultants, technology suppliers, etc.) in this field are:

(i) Improved forecasts and realizing better compliance with the calculated operating schedules
(ii) Fast and easy assessment tools for industrial flexibility to reduce the temporal and monetary effort for the task *modeling and simulation studies.* A challenge here is the heterogeneity of industrial sites, which typically requires specific models and assessments for every single site.
(iii) Realize easy integration of suitable exploitation options with low burdens suitable for the respective site (e.g. industrial redispatch provision might not be realizable for all industrial sites due to challenging pre-requisites)
(iv) Assessing and realizing flexibility in commercial sites
(v) Facilitate implementation and overcome burdens such as risking warranty reduction by ensuring compliance for determined operating strategies from higher-level control concepts. Particularly in the case of interventions by higher-level control concepts, liability issues often arise with the manufacturers of the individual components in the system in the case of existing installations and complex systems. Here, collaboration regarding the required interfaces of technology suppliers, automation experts and industrial sites, shows potential for further improvement.

4.3 TSO-DSO Interaction

A set of recommendations should be considered by TSOs and DSOs to be able to join the proposed redispatch process and facilitate the interaction between TSOs and DSOs. These contribute to the further enhancement of the interaction process on the long term.

Forecasting: Forecasting procedures for industrial loads need to be established and introduced by the FSPs. They are already established at 100-kV-level and need to be extended to medium voltage level connected loads with increasing numbers and capacities of flexibility providing resources located there.

At medium voltage level it needs to be a combination of forecasts provided by FSPs (both at individual customer level and aggregated starting from medium voltage level) as well as DSO forecasts for non-flexibility providing loads and generators including aggregation.

Network, load and generation models: Respective grid models need to be made available and a procedure to collect and process the corresponding data needs to be established. At medium voltage level this will be simplified and aggregated modules. The requested degree of detail of the grid model is going to depend on the number and capacity of flexibility providing industry and existing grid capacity in the specific grid area. Capacity data must be transmitted for an entire business day. Depending on the resolution of congestion forecasting processes, capacity data can be calculated at different time resolutions. At the moment an hourly resolution is foreseen and a change towards 15-minute intervals needs to be anticipated for the future, which is unlikely to happen any time soon even at transmission level. The future international procedures only foreseen 1h resolution.

A data format for capacity exchange should consider that the interaction process may benefit from a transmission of bundled timeseries, describing the entire business day or a selected period thereof, instead of individual files. In case of I4RD, already used data format for capacity information which exists in the international TSO processes.

Identification of constraints: Distribution system operators need to be aware of the most critical situations and actual constraints in their supply areas. The data format shall cover asset loading and voltage constraints. Additionally, the format should be able to represent general linear constraints by a DSO to account for any constraints that cannot be directly attributed to a loading or voltage constraint but that might yet be necessary to ensure secure grid operations. Such limits can be required due to stability or other system constraints and could be realized by applying safety margins.

Contingency States: TSOs and DSOs that adhere to the n-1 criterium in their grid, or in a part of their grid, must calculate any security constraints of network elements for certain contingency cases. This may for example be the outage of an equipment like a line, a transformer, or other equipment. This means that the simplified DS model must be calculated and transmitted for the base case and all relevant contingencies. To ensure transparency in the application of constraints the resulting n-1 or n-m constraints should be labeled regarding the outage the constraint is associated with.

Transparency: To facilitate a functioning market both the FSPs and TSOs share a vested interest in knowing why bids were not selected due to constraints at distribution system level side. This enables FSPs to provide better bids or in the case of TSO understand which steps are necessary to enable more flexibility use. The process should therefore be transparent and reproducible.

Visualization: Redispatch at the transmission level requires a visualization that provides a comparative geographic overview of available redispatch capacities, giving the operational planner an immediate picture where the most optimal capacities are available. The graphical user-interface should also allow the selection of bid-sets from the price-volume curves and the and automatic selection of the associated bids. After selecting the bids, the activation by the operator then triggers the communication to the requested FSPs.

The developed TSO-DSO interaction process for providing redispatch services from industry located at distribution system level has been proven as feasible. The proposed process can even be extended to other flexibility products requiring a TSO-DSO coordination. The approach proposes a redispatch process workflow which includes:

- **Initiation of Redispatch**: Definition of clear criteria for when a TSO can initiate redispatch actions, including thresholds for grid stability and congestion.
- **Coordination Protocol**: Develop a step-by-step protocol for coordinating redispatch actions, including timelines for notifications and responses.
- **TSO-DSO coordination procedure**: It should be designed in a way, that ensures that at the time of the bid award by the TSO all DSO restrictions are considered and thus no award/activation can harm the DSO grid. Therefore, the DSOs must provide their restrictions in a timely manner before the award of the bids.
- **A centralized, sensitivity-based bid set filtering:** Currently, it is the most appropriate method to address Austrian stakeholder needs, regarding transparency, fairness and feasibility.
- **Further methods analysis:** They should be analysed to further mitigate the short comings of the chosen approach, as needed for the actual network situations.

The developed process successfully identifies cost-effective bid combinations in the analysed scenario when voltage limits are neglected, of which approximately 95 % respect the loading limits of the synthetic distribution network.

The consideration of distribution network limits can be achieved through different enhanced actions which can be the cornerstone of the future work, especially when considering the availability of more flexibility located at medium voltage level. The more flexibilities become available at distribution system level in the future, the more the optimizer for bid selection must be adjusted accordingly. For the near future, the developed configuration of the optimizer is sufficient. When the number of flexibility providers to going to increase in future, it is going to reach its limit.

With increasing number and capacity of provided flexibility at distribution level, the simplified DS model will no longer adequately reflect reality. The limits defined in the optimizer must be reduced and safety margins need to be introduced. After the safety margins are introduced, the configuration will be sufficient again for a certain period until the same pattern reoccurs, and stricter safety margins need to be applied. This process repeats itself continuously as flexibilities in the distribution network continue to increase with time.

In addition, the performance of the interaction process and the bid filter optimizer can be enhanced by set of actions, which can be considered in future work: Improving the load and generation forecast quality. Further analysis of bid power factors and the effect of their sensitivity-based consideration on the filter performance. It should also enable the consideration of distribution network voltage limits within shorter runtimes. This can be achieved, by increasing the speed of constraint calculation (e.g., through carefully selecting a low number of critical elements and nodes of relevant impact) and by reducing the number of generations that must be calculated by the filter optimizer to find a proper solution (e.g., by using another heuristic algorithm for two-objective optimization).

4.4 Economic viability of the concept

To assess key performance indicators for the overall concept a further investigation was performed. This investigation, described in detail in Deliverables 7.2 und 7.3, conducted a cost–benefit analysis for the exemplary year 2030 to assess the impact of integrating industrial flexibility into the redispatch process. The analysis was based on the sector-specific flexibility potentials, typical bidding patterns, and the geographical distribution of industrial assets within the Austrian electricity network. Different markup schemes — both uniform across all participants and targeted solely at industrial assets — were examined to evaluate their effects on system costs and flexibility utilization.

From the transmission system operator's perspective, incorporating industrial assets into the redispatch model leads to a reduction in total system costs of approximately 1—1.5% and a reduction in curtailed renewable electricity by up to 7.5%, with persistent curtailment reductions even under high participation markups. While the integration of industrial assets leads to modest absolute cost reductions, their systemic value extends beyond immediate economic gains. In a future with significantly expanded renewable capacity and increasing grid congestion, industrial flexibility presents a viable lever for enhancing operational efficiency and minimizing renewable energy losses. However, unlocking the full potential of these assets may require regulatory adjustments, particularly concerning the remuneration of curtailed renewable generation. Results indicate this curtailment of renewable generation to almost triple (from 57.4 GWh during 2024, cf. to around 150 GWh), reflecting the planned expansion of renewable capacity by around 11 GW — an increase by more than a third of the currently installed capacities (around 25 GW). Within this context, the participation of industrial flexibility enables a reduction of curtailment by about 7.4%, lowering the total to around 139~GWh. This reduction corresponds to roughly 20% of the observed curtailed renewable energy in 2024 and underscores the substantial potential of industrial participation in facilitating more efficient domestic utilization of renewable electricity. Even if the absolute savings remain modest in relative terms, the potential of industrial participation to contribute to overall system efficiency is made evident by that, which suggests that industrial flexibility might also play a significant role in reducing the need to curtail clean energy, thereby supporting broader decarbonization and energy system transition goals.

The impact of industrial assets is most notable on the provision of negative redispatch, effectively substituting curtailed renewable generation and enabling a more efficient use of domestic clean energy. While the overall contribution of industrial flexibility to redispatch volumes remains limited in absolute terms due to spatial and technical constraints, the targeted use of such assets can address specific structural limitations in the Austrian transmission network, especially in reducing reliance on conventional generation for negative redispatch. The sensitivity analysis also reveals that increasing industrial markups quickly erodes the economic benefits, underlining the importance of well-calibrated incentive structures. In the light of the overall macro situation, it is further interesting to observe that activations are increasingly triggered to counteract East-to-West (and North-to-South) flows, which aligns with empirically emerging trends but shows a clear shift to historic information that shows that costs were incurred by countering predominantly West-to-East flows. In summary, integrating industrial flexibility into redispatch planning offers a feasible and beneficial pathway to improving decentralized support for congestion management, reducing system costs, and enabling higher renewable integration. The design of market mechanisms or regulatory frameworks that allow for cost-efficient and reliable activation of industrial assets will be crucial for realizing this potential in practice.

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6 Glossary

APG
: Austrian Power Grid

API
: Application Programming Interface

BPST
: Back Pressure Steam Turbine

BRP
: Balancing Responsible Party

CAPEX
: Capital Expenditures

CHP
: Combined Heat and Power

CMM
: Capacity Management Module

DA/RE
: TSO-DSO Platform for Redispatch 2.0 in Germany

DSO
: Distribution System Operator

EDCS
: Energy Demand Control System

ElWG
: Electricity Act in Austria ,"Elektrizitätswirtschaftsgesetz"

FHG
: Firm Heating Generation

FSP
: Flexibility Service Provider

GT
: Gas Turbine

HOB
: Heat-Only-Boiler

I4RD
: Industry4Redispatch

JSON
: JavaScript Object Notation

LV
: Low Voltage

MV
: Medium Voltage

NEFI
: New Energy For Industry

PPS
: Production Responsible Party

RD
: Redispatch

SGU
: Significant Grid User

SOGL
: System Operation Guideline

TRL
: Technology Readiness Level

TSO
: Transmission System Operator

VPP
: Virtual Power Plant

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