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GOFLEX: Extracting, Aggregating and Trading Flexibility based on FlexOffers for 500+ Prosumers in 3 European cities [Operational Systems Paper]

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ABSTRACT

A demand response scheme that uses direct device control to actively exploit prosumer flexibility has been identified as a key remedy to meet the challenge of increased renewable energy sources integration. Although a number of direct control-based demand response solutions exist and have been successfully deployed and demonstrated in the real world, they are typically designed for, and are effective only at small scale and/or target specific types of loads, leading to relatively high cost-of-entry. This prohibits deploying scalable solutions.

The H2020 GOFLEX project has addressed this issue and developed a scalable, general, and replicable so-called GOFLEX system, which offers a market-driven approach to solve congestion problems in distribution grids based on aggregated individual flexibilities from a wide range of prosumers, both small (incl. electric vehicles, heat-pumps, boilers, freezers, fridges) and large (incl. factories, water pumping stations, etc.). By encompassing individual prosumers, aggregators, distribution system operators, and energy multi-utilities and retailers. It is a system of systems, where all flexibilities in electricity demand, production, and storage are extracted, (dis)aggregated, optimized, and traded using the powerful and standardized FlexOffer format, yielding a general and replicable solution with low cost-of-entry. The system has been successfully deployed in Switzerland, Germany, and Cyprus where it has controlled loads of 500+ prosumers, with a total of 800MWh flexibility offered on the market, offering up to 64% of adaptability in peak demand. In this paper, we present the overall architecture of the GOFLEX system, its sub-systems, and the interaction between these sub-systems. We then discuss the configurations, observations, and key results of using the GOFLEX system both in the aforementioned 3 demo sites – within the GOFLEX project and after the project.

1 INTRODUCTION

The increased share of electricity production from renewable energy sources (RES) is one of the key contributors to achieve the ambitious green energy targets set in the Paris Agreement [49]. However, accommodating higher amounts of renewable energy from intermittent RES is challenging and can be very costly, if not done in an intelligent way.

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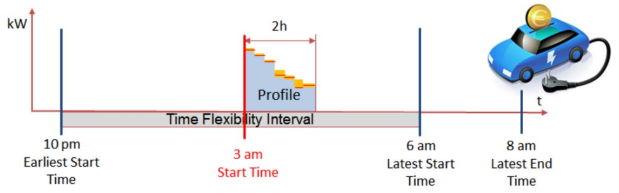

Figure 1: An example FlexOffer specifying charging of an electrical vehicle.

Electrical utilities and network operators are being exposed to excessive risks induced by uncertain, irregular and often distributed supply, causing volatility and increase in wholesale electricity prices, demand-supply imbalances, and more frequent occurrences of grid congestion. The pervasive emergence of distributed energy resources (DERs) is adding additional stress to the existing distribution grid, which was originally designed and implemented for a unidirectional top-down flow of electricity (from suppliers to consumers), which DERs are now turning upside down.

To overcome these challenges, the distribution grid needs to be more intelligent and flexible in terms of available adaptation capacity. To this end, promising solutions exist in the areas of *Demand Response* schemes, *Energy Storage and Management systems*, *Electric Transport*, *Grid Monitoring and Forecasting*, and *Energy Data Management*. Although, individual solutions in the aforementioned areas have been demonstrated to be effective at small-scale, the cost-of-entry (in terms of time, money, resources and know-how) typically prohibits deploying them at scale. Technologies that are scalable, general, and replicable are needed to deal with geographical and market diversities, as well as the heterogeneity of the potential sources of demand flexibility, ranging from heating/cooling systems, electric storage to smart appliances, and electric vehicles. Most importantly, no truly replicable and scalable integrated solution, capable of handling the full generality of demand and supply offers from different types of prosumers and offer flexibility services for the electrical grid and the energy market, has been previously deployed and tested in a real-world environment.

To address this gap, the EU Horizon 2020 GOFLEX (*Generalized Operational FLEXibility for Integrating Renewables in the Distribution Grid*) [18] project has developed a distributed ICT system, which we denote as the GOFLEX system for short. Its is an integrated, scalable, and replicable system that enables the cost-effective use of demand response in distribution grids and increases the available flexibility of consumption/generation to be included in demand response schemes.

The system supports the involvement of all kinds of DR suppliers and consumers in balancing electricity demand and supply, and optimizing energy consumption and production at the local levels of electricity trading and distribution systems, thereby supporting the integration into the existing energy markets. The core of the system is built upon the tested and proven novel *FlexOffers concept* [1, 2], to model flexibility in electricity consumption/generation in a generic, scalable, and device/prosumer agnostic way. The GOFLEX system is an example of a flexibility management solution, deployed at large scale in different pilot sites in three different European countries. In these pilots, it practically demonstrates the interplay between a number of inter-related Smart Grid technologies including real-time grid observability, automatic DR trading, dynamic prices, generalized flexibility management (including modelling and aggregation), and cloud-integration, and shows how they can be integrated and work together in large scale real-world environments. As such, the GOFLEX system practically applies and demonstrates the following:

The FlexOffer technology, which encompass flexibility extraction, aggregation, and trading processes through a common representation of flexibility, common flexibility management tools, and a data exchange protocol.

A grid observability system, based on advanced deep learning, which collects real-time measurements from different points in the grid, and actually predicts congestion problems within the grid rather than just detecting them, and finally estimates the amounts of flexibility required to mitigate these congestion problems.

Advanced data-driven techniques for extraction of flexibility (FlexOffer) from heterogeneous prosumers/loads (including, households, industrial processes, batteries).

An advanced flexibility aggregation solution, which, independent of prosumer/load type, can collect, group (mix), and aggregate flexibility offers (FlexOffers) from a very large number of prosumers, and offer such aggregated flexibility on the GOFLEX flexibility market. Successfully executed offers are remunerated based on pre-defined flexibility contracts and energy measurements.

A flexibility market system that allows large DR suppliers, aggregators, and flexibility consumers (DSOs) to make optimal use of available flexibility through active automatic trading.

Most of the content for the paper is drawn from published reports of the GOFLEX project [18]. Some of the GOFLEX system components, including the flexibility extraction and the aggregator components are available as open-source software [19].

The paper is organized as follows. We introduce the FlexOffer concept in Section 2. Section 4 provides an overview of the GOFLEX system architecture. The Automated Trading Platform and its components are presented in Section 5. Section 6 describes the distributed grid observability and management system. Demo sites and result are presented in Section 7. Section 8 presents the reflection and analysis on the the GOFLEX system deployment. Finally, we conclude and discuss future work in Section 9. A list of acronyms and abbreviations is provided at the end of the paper.

2 THE FLEXOFFER CONCEPT

The GOFLEX system is based on the so-called *FlexOffer* (FO) [1, 2, 36, 44], which offers a common unified representation of flexibility in electricity demand and supply. A FO explicitly captures supply/demand flexibilities in both time and energy amount, e.g. an opportunity to shift demand in time and/or modifying consumption up or down. This makes it practical to exchange flexibility information between different entities. For example, in the GOFLEX system, FOs are extracted from individual flexible consumption or production resources (e.g., heat pumps, EVs, factories etc.). After a FO is generated, flexibility can be efficiently aggregated and disaggregated across various dimensions, e.g., different classes of prosumers. A single simple FO typically includes: **Energy profile**, having a number of discrete slices, which specifies electricity consumption and production options over a device's active period of operation, typically in 15min. time resolution; **Time flexibility interval**, which specifies a time period in which device's operation (profile) can be advanced or retarded; **Default profile**, which specifies a preferred / locally optimal consumption profile (a baseload); **Price data**, which specifies (discomfort) prices, e.g., associated to deviations from the default profile.

A FO can be either a *consumption* FO or a *production* FO. From the prosumer prospective, the consumption FOs (offer for energy consumption) are represented by negative flexibility value and production FOs (request for decrease in consumption) are represented by positive flexibility value. From the grid prospective, production FOs (increase in production request) is represented by a positive flexibility value and consumption FOs (request for decreasing demand) is represented by a negative flexibility value.

An example of a simple FO is shown in Figure 1. It illustrates an instance of a FO, generated by the charging station of an electric vehicle (EV). In this case, the FO specifies the intended EV charging process and expresses the EV owner's flexibility that the vehicle is available for charging from 10 PM until 6 AM with additionally provided charging profile. If needed, a price for flexibility can also be associated with a FO. Specifically, this price can be expressed as a cost paid for 1kWh of energy amount deviation with respect to the reference (baseline) schedule. The above example represents a request for consumption FO from a prosumer (EV), hence the energy profile for each timestamp is represented by a negative energy value, i.e., -kWh.

The advantage of representing flexibility as a FO is that (1) no specific knowledge about the underlying Distributed Energy Resource (DER) or a load is needed, i.e., whether the electrical loads comes from heat pumps, EVs, cold stores, etc, and (2) the same set of software tools and algorithms (e.g., for aggregation, optimization) can be used for FO management. Next, we present the related work targeted on capturing flexibility for demand response.

3 RELATED WORK ON FLEXIBILITY

This section will describe related work within flexibility models and aggregation, flexibility markets, and related projects that deal with flexibility.

3.1 Flexibility Models and Aggregation

Flexibility in energy/power systems can be seen in several ways. One way sees flexibility as *deviations* from a baseline schedule/load profile, i.e., the flexibility is the ability to change either production or consumption in a specified way (by given up/down amounts and time intervals), usually requested top-down to achieve balance between production and consumption. This is how flexibility is modeled in most balance markets. A related, but different view, is to model the *total available flexibility in time and amount* that a (perhaps aggregated) underlying load has while still meeting its internal constraints, e.g., for comfort. This view is often used for demand response. Here, many small individual loads have to be *aggregated* to meet the size constraints of typical markets (from KWh to MWh) and *optimized* to maximize/minimize a given objective, e.g., profit. The latter type of flexibility has traditionally been modelled *implicitly*, e.g. through response to price signals, or explicitly, e.g. using grey-box models [31]. Explicit models can generally capture more of the available flexibility. An early *explicit* model was the linear time-invariant (LTI) state-space model [11] which captures flexibility accurately, but where aggregation and optimization *does not scale* to thousands/millions of loads and/or dozens of time slices [27, 53]. Conversely, FlexOffers [54], the cornerstone of the GOFLEX project, represent flexibility *approximately*, can *scale aggregation and optimization to millions of loads and long time horizons*, and still handle complex state-dependent loads like heat pumps and batteries, [27, 53].

3.2 Flexibility Markets

Overall, centralized electricity markets trade either energy or power. Long term, day-ahead spot, and intra-day markets trade energy, while markets closer to real time like balance and frequency regulation trade power, specifically power regulations up or down, i.e., they adopt the "deviations from baseline" view of flexibility described above. This also holds for local flexibility markets like NODES and GOPACS [4, 5]. In contrast, FlexOffers are able to represent both energy and power, and their (possible) deviations from a baseline, within a single FlexOffer object, thus combining the two views of flexibility described above. Thus, when trading FlexOffers directly, as is done in GOFLEX, it is in some sense possible to trade both energy and power deviations at the same time. This represents the major novelty of the GOFLEX market.

3.3 Flexibility Projects

GOFLEX is part of the BRIDGE portfolio of research and innovation projects funded by the European Commission to address the challenges of climate change. A summary of the portfolio assembled in early 2019 covers 44 projects with 545 participating organizations [20] with an updated overview in 2021 [3]. Within these many projects, the distinctive features of GOFLEX are:

1. Unified (FlexOffer) data/flexibility model, all the way from energy assets to markets, including the concept of flexibility contracts designed for/based on FlexOffers.
2. Demonstrated advanced, holistic ICT solution, encompassing various energy management systems (xEMSes), aggregator tools, distribution grid observability tools, and flexibility market tools.
3. Advanced end-to-end demonstration replication in 3 sites within Europe, and with real users and loads, encompassing various aggregations of (1) complex residential (including HEMSes, smart-plugs) and industrial (including factories) energy assets/loads/generators.

4 GOFLEX ARCHITECTURE

The GOFLEX system is a market-driven ICT platform that enables active participation and flexibility trading between various energy market players: prosumers (households, tertiary buildings, industries, EV charging stations), aggregators, balance responsible parties (BRPs), and distribution system operators (DSOs). The overall conceptual architecture of the GOFLEX is shown in Figure 2.

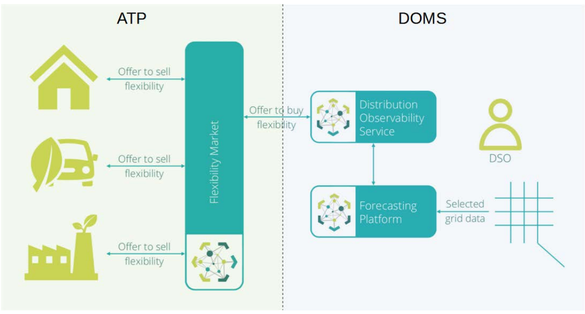

Figure 2: Conceptual Architecture of the GOFLEX Integrated Solution.

As seen in the figure, the GOFLEX system is composed of several building blocks (sub-systems), each with own distinct functionalities and responsibilities. The sub-systems can be grouped into two main categories that separate commercial and grid operation processes: *Automated Trading Platform* (ATP) [6, 43] and *Distribution Observability and Management System* (DOMS) [47]. Here, ATP is a decentralized and automatic trading platform (for demand-response services) that encompasses all relevant market participants: active flexibility providers (prosumers), intermediaries (aggregators, Virtual Power Plants (VPPs)), and flexibility users (BRPs, DSOs, Transmission System Operators (TSOs)). The platform automatically provisions and/or collects flexibility offers (FlexOffers) from heterogeneous sources, aggregates them if needed, and finally matches them for socio-economically optimal use of flexibility in a particular (local) trading area. On the other hand, Distribution Observability and Management System (DOMS) offers functionalities to monitor, forecast, and control the state of the distribution grid – for a more active, efficient, robust, and dynamic operation of the grid. DOMS automatically generates FlexOffers as flexibility buying bids, and is the key system that takes advantage of the traded flexibility in GOFLEX. We now present ATP and DOMS in more detail.

5 AUTOMATED TRADING PLATFORM

ATP offers two general flexibility trading modes to market participants: *direct* and *delegated*. These typically co-exists in GOFLEX system deployments [43].

In **direct trading** mode, a market participant is allowed to actively price and offer their price-aware flexibility (FOs) for trading on the market. Typically, strict delivery requirements are enforced when trading in the direct mode. Therefore, this trading mode is used by medium and large prosumers (e.g., factories) capable of actively performing local energy optimization while taking energy and/or comfort prices into account.

In **delegated trading**, a market participant (e.g., household) can only offers its flexibility through an intermediary (e.g., aggregator) which takes all energy delivery risks when trading on the market. Thus, the participant delegates the trading of flexibility to this third-party, which remunerates the participant (e.g., with monetary rewards) based on (less strict) flexibility contracts. In such a case, the participants only report their flexibility, and the actual flexibility price is calculated at the level of the aggregated flexibility pool by the aggregator. Typically, this trading mode is to be used by small prosumers with weak energy delivery guarantees and/or limited support for local energy optimization.

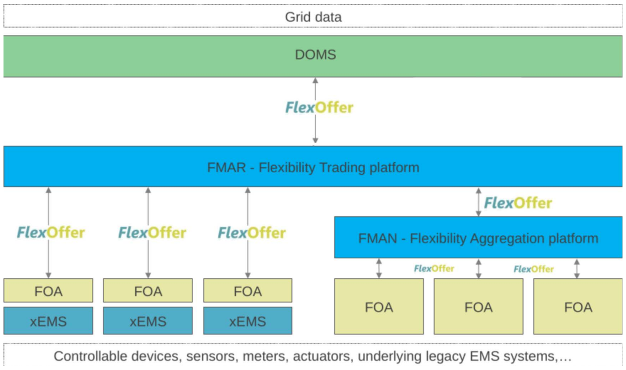

Figure 3: The GOFLEX sub-systems and their inter-connections.

The GOFLEX ATP architecture [37, 43] supporting these two trading modes is shown in Figure 3. It includes a number of components for easy replication and deployment of the platform in new or legacy environments. Namely, ATP consist of 4 main subsystems: Energy Management System (EMS), Flex offer Agent (FOA), FlexOffer Manager (FMAN), and FlexOffer Market (FMAR) [6]. We will discuss each of them individually in the following sub-sections.

5.1 Energy Management System (EMS)

Energy Management System (EMS) [6, 37] is a stand-alone system for optimizing electricity consumption and production in a particular physical environment. This typically involves monitoring, predictive control, and optimization of loads based on a specific set of constraints and objectives. In GOFLEX, such EMSes are further enhanced and tightly integrated with a so called *FlexOffer Agent*, which enables bi-directional communication and FO exchange between EMS and the other sub-systems of ATP. In addition to FOs, other auxiliary data (e.g., device state, historical electricity consumption/production) may also be exchanged. The GOFLEX system supports homes, factories, and charging stations by integrating 3 different energy management systems, 1) HEMS: Home EMS, 2) CEMS: Charging and Discharging EMS, and 3) FEMS: Factory EMS. The different EMSes are collectively known as xEMS. An xEMS is typically a prerequisite for *direct trading*, while it is optional for *delegated trading*, as discussed next.

5.2 FlexOffer Agent (FOA)

FlexOffer Agent (FOA) [37, 43] is an ATP component that ensures that a prosumer (or a particular load) is able to generate, communicate, and process (the schedules of) FOs. FOA acts as a bridge between an FMAN/FMAR and an energy management system (xEMS) or a specific legacy system. In general, as seen in Figure 4, FOA may take different forms and capabilities that depend on the functionalities of an xEMS already available. For example, FOA serves only as an FO (and schedule) gateway (interface) when the xEMS is

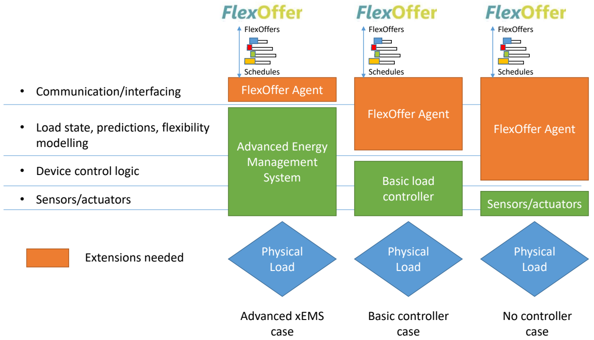

Figure 4: The general FOA cases and functionality.

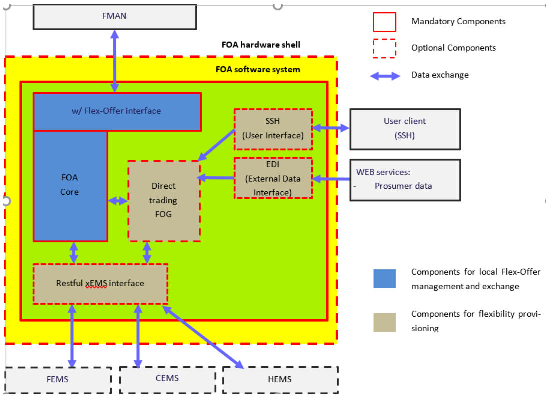

Figure 5: FOA capabilities and internal architecture.

an advanced system with built-in energy prediction and optimization capabilities. This kind of FOA is primarily used for extracting flexibility from larger sources such as industrial loads, EVs, and is preferred for direct trading, where xEMS is already capable of estimating prices for generating FOs. When no xEMS is available on site (e.g., household appliances, EVs etc.), FOA may integrate predictive and optimization logic, and perform the function of a basic xEMS. In this case, FOA is responsible for extracting flexibility and generating FOs and is mostly used for delegated trading. The FOA with the role of xEMS is the most comprehensive and can be used to control any specific type of load (e.g., industrial, EVs, household). Figure 4 demonstrates that the functionality and capacity of FOA vary according to the type and functionality available in the physical load.

The GOFLEX project has designed a general (internal) architecture for a FOA in its most advanced configuration. This is shown in Figure 5 and includes the following components:

FOA Core: is a component shared across a variety of FOA types. It is responsible for managing the state of FOs, securely and reliably communicating FOs with FMAN/FMAR in the correct (JSON) format, and processing FMAN/FMAR responses. It also produces keep-alive notifications, to make the status of FOA available to FMAN/FMAR.

FOA Generator (FOG): [32, 33] is a component that generates load-specific FOs and is used only in no xEMs cases. Internally, it manages instances of load-type-specific predictive models based on sensor/user data and handles their conversion to FOs. To create and maintain flexible load model instances, FOG relies on (near) real-time data collected from a number of data sources, e.g., user input, external data services (Service Platform (SP)), smart meters, or xEMS. Currently, the GOFLEX system supports individual and pool-based FO generation [32, 33].

xEMS interface: is a component used by FOG for interfacing with (and controlling) a specific xEMS, either residing locally at the Prosumer, or deployed in the xEMS provider's cloud network.

Monitoring and Control: FOA supports energy management for various types of end users (factory, household, EV charging station). It provides the following two services 1) monitoring of an operation of an individual flexible load and 2) control of an operation of an individual flexible load according to the needs of both the prosumer and the flexibility user (e.g., aggregator). The monitoring includes tasks such as checking health, recording energy consumption, etc., whereas control includes tasks such as the execution of a schedule and maintaining the normal operation.

Device/load flexibility prediction: The FO represent future energy demand from a given load. Hence, FOA includes module for predicting load for various device types and resolution. For example, the load for wet devices are predicted for next few hours whereas for thermostatic devices for only 30 minutes. The forecast horizon also depends on the configured time flexibility and constraints.

GUI : The FOA offers a Graphical User Interface (GUI) for administrators (aggregators) and load owners/users for configuration of load and flexibility parameters.

Following this architecture, the GOFLEX system includes 7 different instances/implementations of FOAs, covering several forms of industrial (FEMS), home automation (HEMS), EV (CEMS), and specialized Cloud-IO [43] and smart-plug controlled loads.

In the next section, we will discuss FMAN managing FOs, e.g., sent by a number of FOAs.

5.3 FlexOffer Manager (FMAN)

The FlexOffer Manager (FMAN) [43, 44] is responsible for all operational flexibility management tasks: (near) real-time FO collection from FOAs, (dis-)aggregation, schedule, energy optimization (e.g., demand-supply balancing), flexibility pricing, and contract handling. FMANs process and continuously optimize FOs to meet some desired objective, e.g., minimize cost or increase self-sufficiency. An FMAN is used by Aggregators, BRPs, and MGRs. The main tasks of the FMAN are describes below:

Collection of FOs from FOAs: It is responsible for FO collection from FOAs and checking their consistency. The FOs may be received from a cloud FOA or directly from an FOA located at individual Prosumers. Since each FO is identified by the source ID and a Unique ID, FMAN can receive and parse multiple FOs concurrently. The FMAN generates a new Unique ID for each received FO and sends it as a response to the particular FOA. All subsequent communication regarding the FOs uses this new ID. This is implemented based on a RESTful API available for external calls from FOAs.

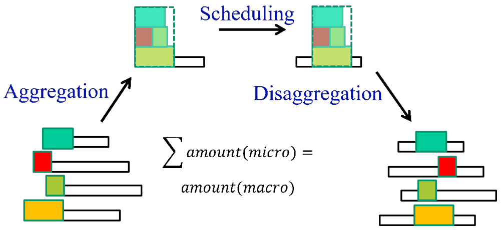

Figure 6: FlexOffer aggregation and disaggregation [54]

Aggregation/disaggregation: FOs from individual flexible resources (e.g., heat pumps, EVs) typically represent small flexible loads (specifically in indirect trading mode). Thus, a single (small) FO has low impact and is of little interest for electricity trading, and balancing demand and supply in the grid, where required balancing capacities are much higher. At the same time, managing large numbers of individual FOs is tedious and complex. A common solution is to utilize FO aggregation, where flexibilities from individual flexible loads are combined and offered in a more useful and effective aggregated form [48, 50, 51, 53, 54]. The aggregated FOs have much larger energy amounts and flexibility margins and are easier to manage. Aggregating large number of FOs, however, is a computationally hard problem, which requires dealing with many decision variables and constraints originating from many FOs.

To optimize aggregation, FOs can be grouped based on a similarity measure (e.g., consumption pattern). Aggregation is typically performed by entities called aggregators using FMANs. An FMAN receives FOs from individual FOAs and then aggregate these FOs. The flexibility of aggregated FOs tends to be lower than the joint flexibility of the FOs that compose them. This reduction in flexibility is, however, unavoidable in order to reduce FOs scheduling complexity and to increase their value (e.g., on the flexibility market). After aggregation, schedules are typically assigned to the aggregated FOs (e.g., based on energy sold on the market). By respecting all inherent aggregated FOs constraints, a schedule specifies the exact start times and aggregated energy amounts assigned to the underlying flexible resources. Such schedules are disaggregated to schedules for each individual FO it is composed of. This operation is denoted FO disaggregation. Dis-aggregated schedules are finally forwarded to the flexible resources which initially offered flexibility. The process of FO aggregation, scheduling, and disaggregation is illustrated in Figure 6 and explained in greater detail in [54].

Optimization: Highly robust and scalable FOs-based energy optimization [52, 53] techniques exist in FMAN. As such, FMAN dynamically chooses an actual solving technique depending on (1) optimization objective (e.g., demand-supply balancing, portfolio cost reduction, energy maximization/minimization within a period), and (2) types of constraints enabled and used inside FOs. For example, FMAN uses standard *linear programming* techniques to generate schedules for simple linear objectives and basic *energy amount*, *total energy constraint*, and *dependent energy amount* constraints. When *start-time constraint* is used inside FOs, FMAN uses *mixed-integer programming* (MIP) to find (semi-)optimal schedules with *start-time* parameters taking discrete values. Alternatively, the best effort techniques like *simulated annealing*, *hill-climber* can be used to cope with such discrete-value constraints. For more complex planning objectives and various combinations of FO constraints, a specialized genetics-inspired technique [48] is used. In all cases, FO aggregation is performed prior to optimization to reduce the total number of decision variables and thus the overall planning complexity. A detailed discussion on the optimization result quality and the execution time is provided in [48].

When trading is enabled, FMAN trades (bids) and except schedules for the aggregated FOs using FMAR. In the next section we will discuss the proposed FMAR architecture in detail.

5.4 FlexOffer Market (FMAR)

The FMAR [6, 37] is a stand-alone ATP system, responsible for matching the production and consumption FOs issued by active prosumers and other market actors (e.g., grid operator or an aggregator represented by the DOMS component). FMAR processes the received FOs in a number of steps as shown in Figure 7. The initial acceptance of FOs involves FO consistency checking and the maintenance of a FO pool. The subsequent steps involve FO state transitions from *accepted* over *prepared*, *locked for matching* to final *rejected* or *contracted*, and removing the expired ones.

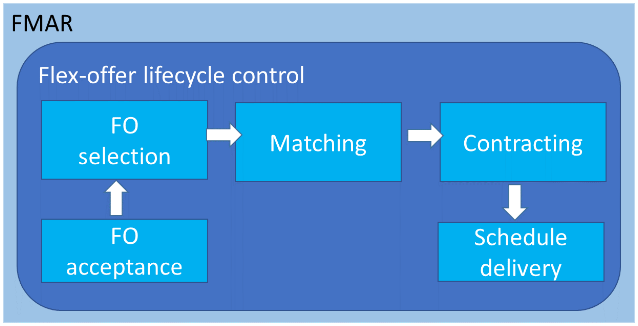

Figure 7: The life cycle of a FO in FMAR.

The matching process selects the available FOs with prices from the pool and searches the optimal combination from the total cost point of view. The matching is based on an auction process where production energy is sorted from cheapest to most expensive, and consumption energy is sorted from the most expensive to cheapest in order to define the cutoff price and amount of energy. However the selected FOs have different start times and durations, therefore the matching algorithm also provides time combinations and permutations to find the optimal solution. FMAR penalizes FOs from the distant prosumers, because it increases grid losses. This is done by introducing an energy transport cost into the FMAR's FO scheduling optimization. The so called *penalty prices* table is generated by the DOMS component according to the grid topology and sent to FMAR. The adaptation requests from DOMS include the congestion location which is used to determine the FO price in FMAR and make the distant prosumers less attractive for matching. The optimization discussed within FMAR is different from the one discussed in the FMAN. Here the optimization is done for demand and supply matching between prosumers and DOMS, whereas the FMAN optimizes consumption and production FOs from prosumers.

The FMAR component supports *many-to-many* trading where several production FOs are matched against several consumption

FOs. This trading mode is suitable for the general market organization e.g., microgrid. FMAR also offers *one-to-many* trading which was mainly used in GOFLEX for offering system services to the system operator of the grid represented by the DOMS component.

Once a FO is contracted and a schedule is assigned to it, FMAR starts evaluating the prosumer's adaptability to the assigned schedule by monitoring the prosumer's total consumption. Based on historical measurements, the prosumer's most probable consumption is calculated and compared with the measurement for the period of adaptation. The difference is taken as the adaptation realization. However, adaptation often involves rebound effects, which is the excess consumption by devices when recovering to their normal operation post DR period. It is very important to control rebound effects to ensure proper operation of the system. A long term operation is needed to correctly evaluate rebound effects and enhance the prosumers' FOs accordingly. In *one-to-many* trading, the issuer of the adaptation requests needs to define the energy and prices constraints of the rebound to 1) limit the rebound the acceptable limits and 2) to (re)fill the energy storage of the energy shift FOs and make adaptation more effectively.

The FMAR may concurrently operate several hierarchically organized markets places - typically reflecting the topology of the grid, as shown in Figure 8. Here, the prosumer's location is defined by grid connection point.

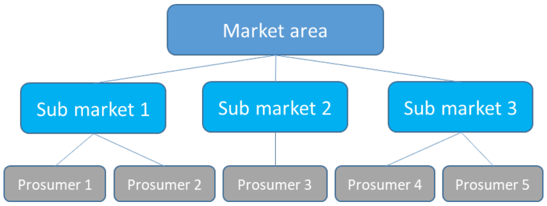

Figure 8: A hierarchical structure of a market, offered by FMAR

Many-to-many Trading Optimization: In cost based many-to-may trading, the trading process involves matching of received consumption and production FOs bids for several issuers. The matching process selects the available FOs from the pool and searches the optimal combination from the total cost point of view. Matching FOs in the FMAR is based on an auction algorithm, where matching is performed for each (15 min) trading interval and is successful if the consumption price is larger than the production price.

The optimization first matches the cheapest production offers with the most expensive consumption ones with the limit of the calculated marginal price (λ_t^D). However, the entered FOs have different start times and durations therefore the matching algorithm besides sorting also provides time combinations and permutations to find an optimal solution.

The FMAR component operates with implicit FO called "imbalance", which defines the "penalty" price when the matching between production and consumption is not perfect. The price may be internally configured by the user or may refer to the real imbalance price on the external market. The goal of the matching is minimization of the imbalance amount.

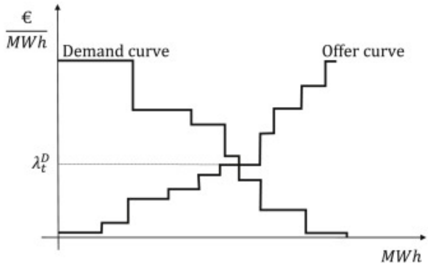

Figure 9: Auction at meeting the consumption demand and production offer (two-sided pool)

One-to-many Trading Optimization: Basically for One-to-many trading, matching means combining production with consumption FOs. However in practice prosumers often define their flexibility as an energy shift, which is more complicated for the algorithm. The energy shift FO is described as a combination of production and consumption part with the total amount equal to zero. At matching, each part needs to be matched to its own counterpart flexibility. Therefore, the energy shift FO needs to be described with production and consumption price and their difference represents the prosumer income.

The energy shift is very important at control of "rebound effect" which is essential for proper operation of the FTP. At "one-to-many" trading the issuer of the adaptation request needs to define the constraints – energy and price – of the rebound to 1) limit the rebound the acceptable limits and 2) to (re)fill the energy storage of the energy shift FOs and make adaptation more effectively.

6 DISTRIBUTION GRID OBSERVABILITY AND MANAGEMENT SYSTEM

The distribution-grid observability and management system (DOMS) [47] provides data analytics services to distribution system operators for the prediction of localised congestion events and their management by trading energy flexibility resources in the GOFLEX trading platform. Two key data services are provided by DOMS. A grid-congestion prediction service estimates the future profile over a 24-48 hours rolling window (updated every 15-60 minutes), of a number of user-defined electrical quantities of interest (e.g. power flow, voltage magnitude) at relevant grid assets (distribution substations, feeders, prosumer connections), along with the likelihood of them operating outside some user-defined threshold. Where instances of congestions are flagged, a market- bidding service generates a buy FlexOffer (see details in Section 2) based on estimates of the amount of local energy flexibility required to avoid the predicted congestions.

A core element of DOMS is a machine-learning model of the distribution grid expressing the spatio-temporal relationships of electrical quantities at the interconnected grid assets of interest. The model is defined as a probabilistic graph, based on the framework of graph neural networks [9, 13–15], and it is trained from a combination of topology data available from GIS and historical sensor data available from SCADA systems, IoT devices and high-resolution weather services. Grid-congestion predictions are generated by running inference on the probabilistic graph based on short-term predictions of distributed energy generation and demand profiles at different points of the grid. Estimates of required energy flexibility are also generated through inference on the probabilistic graphs where the required congestion limits are enforced [14].

DOMS depends on localised predictions of distributed energy demand and generation across the grid [9]. As part of the GOFLEX project, a scalable time-series forecasting platform was developed to deploy and execute the large number of machine-learning models required for generating predictions of electricity demand and renewable generation profiles from distributed grid assets (substations, feeders, individual prosumers) and generation plants (wind/solar farms or individual rooftop solar systems) [7, 9, 10]. The forecasting platform also provides time-series management services for the acquisition and provisioning of the raw time-series data available from the distribution grid operator (through SCADA and IoT devices), and of the high-resolution weather services driving the machine-learning prediction models. The sensor data are enriched by a semantic layer incorporating available domain expertise in the form, for example, of known relations between grid asset, variables and the sensors [7, 10]. DOMS and the forecasting platform were deployed on the IBM Cloud. Following a micro-services design pattern, the knowledge-based time-series management micro-service was hosted on a combination of relational and graph database cloud storage services. The machine-learning modelling services for energy forecasting and grid modelling relied on a combination of containerised (orchestration tasks and time-consuming jobs for training/inference on DOMS probabilistic graph) and serverless (frequent, bursty workloads such as time-series model predictions) cloud-computing infrastructure. Data ingestion and communication, both internally and with external consumers through high-level data services (e.g. the congestion predictions and market bidding), relied on asynchronous messaging based on Message Queuing Telemetry Transport (MQTT), Advanced Message Queuing Protocol (AMQP), and on serverless computing. The high-resolution weather prediction services were provisions through The Weather Company [46]. Further architecture details are provided in [7, 10].

Table 1 provides some specific figures of the deployments of DOMS and the forecasting platform at the three GOFLEX demonstration sites. The figures include number of sensors time-series data were acquired from, number of distributed energy and generation forecasting models deployed and number of grid variables included in DOMS probabilistic graph.

Site	# Sensors	# Forecasts	# DOMS variables
Germany	18	11	6
Switzerland	185	63	50
Cyprus	480	212	83

Table 1: Deployment of DOMS and forecasting platform at the GOFLEX demonstration sites.

7 DEMO SITES AND RESULTS

The GOFLEX system was deployed and tested at three different European demo sites [18, 37], where each individual demo case offers different aspects of the electricity system, aiming to include every reasonably encountered prosumer and process, so as to show the replication and scalability potential of the GOFLEX system. In all demo cases, GOFLEX was instantiated at its full scale with a number of FOA instances controlling different type of loads, a number of aggregator instances based on FMAN, and a local flexibility market based on FMAR which was connected to DOMS. Table 2 lists the different device types employed by the GOFLEX system for flexibility trading across the demo sites and the user interaction mode with the devices.

Site	Use Case	Controlled devices	User interaction
Germany	Maximize self-consumption	Heaters, boilers, freezers, fridges, and washing machines	Direct user control of flexibility
Switzerland	Reduce peak loads and corrective costs	Heat pumps, boilers	Only delegated control through the GOFLEX
Cyprus	Utilize regionally produced energy	Smart plug devices e.g., A/C, freezers, washing machines	Direct user control of flexibility

Table 2: Evaluated use cases at demo sites.

We use several performance metrics to measure how effectively the GOFLEX system is utilized in the demo sites:

- *Reduction in peak demand*: Quantified by comparing the predicted peak demand with the measured peak demand of the feeder and dividing the difference with the percentage of GOFLEX users to the actual feeder users.
- *Adaptability of energy load with respect to peak demand*: The degree that loads can vary their consumption, which is calculated as the maximum energy variation of loads over the maximum energy consumption.
- *Lessen the burden of power grids through self-consumption*: The actual flexible energy provided divided by the actual total user energy.
- Avoided costs for congestions.
- Estimated profit from supplying/activating DR.

7.1 Cyprus Demo Case

The Cyprus demo case [26, 28, 34, 35] implemented two distinct, yet complementary use cases: i) *microgrid energy community management* and ii) *local congestion management*. In the first use case, the fully functioning utility-integrated microgrid at the University of Cyprus campus plays the role of an aggregator, with the aim to optimize its energy portfolio and trade residual flexibility with the DSO. In the second use case, the DSO buys flexibility from 18 prosumers distributed across two cities, in order to increase grid balancing and mitigate grid local congestions. The DSO's business case is minimizing the cost of grid reinforcement/expansion or curtailment penalties. The second use case involved 14 HEMS, 2 CEMS, and 4 delegated trading prosumers. The main focus of the demo

Performance metric	Target value	Achieved value		
		Germany	Switzerland	Cyprus
Reduction in peak demand	> 15%	12.8%	4.7%	15%
Adaptability of energy load with respect to peak demand	> 15%	25.8%	≤ 5%	64%
Lessen the burden on power grid through self consumption	> 10%	10%	5.5%	4%
Avoided costs for congestions	€1Million/MW	NA	€30000/MW	€61862/MW
Estimated profit from supplying/activating DR	>€35,000/MW/year	€85297/MW/year	€60000/MW/year	€25080/MW/year

Table 3: Performance metrics for GOFLEX demonstration in the demo sites.

case is utilizing the GOFLEX system to maximize self-consumption through intelligent shaping of daily consumption profiles according to distributed RES generation (Figure 10). Over the trial period, EAC recorded a peak demand of nearly 9.5 MW/h and a peak physical load of 2.2 MW/h. DOMS service requested, on average, 1.42 MW/h of flexibility, which corresponds to about 15% reduction in the peak demand and to about 64% adaptability of the peak physical load of EAC. The activated flexibility lessened the burden on the grid by approximately 4% and avoided 61862 €/MW/year in congestion costs. Calculation with upscaled amount of flexibility out of GOFLEX system in connection with calculated value of flexibility resulted in 25080 €/MW/year. As before, the results are summarized in Table 3.

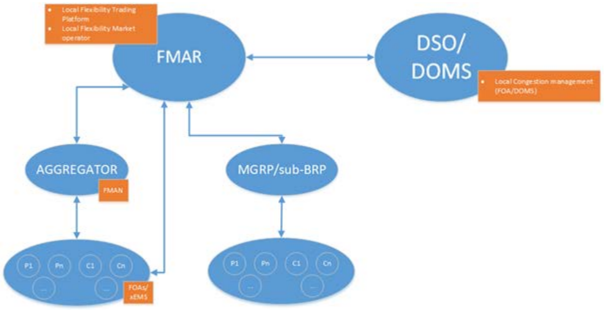

Figure 10: Use cases diagram at Cyprus demo site.

7.2 Swiss Demo Case

The second demo site [38–42] is in Valais, which is located in southern Switzerland with ample sunshine throughout the year. The utility company Energie Sion Region (ESR) serves as both energy provider and DSO. The demo case objectives include using flexibility for optimising the balance for the DSO to reduce corrective costs and using demand-side management to reduce peak loads on the distribution grid. The demo case involved 9 FEMS, 9 HEMS, 197 direct control (no HEMs), and 7 EV charging stations.

Over the trial period, ESR recorded a peak demand of nearly 101 MW/h and a similar peak physical load. DOMS service requested, on average, 4.8 MW/h of flexibility, which corresponds to about 4.7% reduction in the peak demand as well as adaptability of the peak physical load of SWW. The activated flexibility lessened the burden on the grid by approximately 5.5% and avoided 30000 €/MW/year in congestion costs. Calculation with upscaled amount of flexibility out of GOFLEX system in connection with calculated value of flexibility resulted in 60000 €/MW/year. The results of the Swiss demo case are also summarized in Table 3. Below are the key points in the Swiss demo case:

- Average of about 500 W flexibility per household. It can vary greatly between winter (up to 1.8 kW) and summer (down to 200 W).
- Considerable flexibility potential early morning and evening, with up to 70% of total consumption.
- Most people did not notice that flexibility was controlled.

7.3 German Demo Case

The German demo site [16, 17, 29, 30] is located in Wunsiedel, Germany. The utility company SWW plays the role of both energy provider and DSO, ensuring supply to Wunsiedel city and several other municipalities. The main energy goal of the Wunsiedel city and SWW is meeting energy needs of residential and commercial customers with 100% renewable and regionally produced energy. The demo case involved 209 prosumers covering all supported types of energy management systems including 21 FEMS, 22 HEMS, 6 CEMS, 154 home appliances with direct control (not connected to xEMS), and 6 EV charging stations.

Over the trial period, SWW recorded a peak demand of 21.8 MW/h and a peak physical load of 10.8 MW/h. DOMS service requested, on average, 2.79 MW/h of flexibility, which corresponds to about 12.8% reduction in the peak demand and to about 25.8% adaptability of the peak physical load of SWW. The activated flexibility lessened the burden on the grid by approximately 10%. No situation of grid congestion occurred during the trial period because of copper cables of larger diameters. Calculation with upscaled amount of flexibility out of GOFLEX system in connection with calculated value of flexibility resulted in 85297 €/MW/year. The results are summarized in Table 3. The adaptability level tends to be higher because SWW mostly controlled heat pumps and water heaters, which may offer higher flexibility because the underlying process can be fully controlled due to its simplicity.

The results from the demo sites presented in this section and summarized in Table 4 evidence that flexibility can be cost effective. For example, GOFLEX system facilitated a safe increase of installed capacity for renewable energy of 20-59% with respect to existing renewable capacity. In order for this capacity to be used effectively, adaptability of electricity loads is crucial. GOFLEX demonstrations estimated load adaptability of 5-64% of peak demand. Hence GOFLEX shows strong progress towards the Paris

Agreement's 2030 target of a 27% share for renewable energy in Europe [49].

Active prosumers	500
Number of FlexOffers generated	100000
Number of FlexOffers activated	6000
Flexibility offered (MWh)	800
Flexibility activated (MWh)	30
Safe increase in installed capacity with respect to existing renewable capacity	20-59%
Adaptability with respect to peak demand	5-64%

Table 4: Demo sites stats for a typical month.

7.4 FOA Performance Analysis

FOA performance was evaluated in terms of throughput of flexibility extraction, schedule execution, and accuracy of the flexibility forecasting as a function of the number of electric loads. A highest throughput of 800+ FOs per hour was extracted from 500+ loads while also simultaneously executing 100+ schedules. No degradation in FOA performance was noticed even under such high load. The average duration for flexibility forecast task was less than a minutes for 500 loads. FOA is running live for 2+ years without any performance issues.

7.5 FMAN Performance Analysis

FMAN performance was evaluated in terms of throughput of FO (dis-)aggregation, portfolio optimization, and market bidding as a function of the number of FOs collected from FOAs. For a highest throughput of 800+ FOs per hour collected from FOAs, FMAN successfully aggregated all FOs under the chosen optimization objective and submitted market bids in time for consideration in the next bidding cycle. FMAN never took more than a few seconds to optimize and aggregate FOs. FMAN is also running live for 2 years without any performance issues.

7.6 DOMS Performance Analysis

DOMS Performance was evaluated in the Cyprus use case by comparing actual and predicted voltage on the system using models trained with 1 year of historical data (27137 samples), with one month of cross-validation (July 2019). The evaluation shows a mean absolute percentage errors were between 0.70% to 0.82%. Similarly, root mean square error varied between 2.13 and 2.45 for the same models. [14] provides further details on the experimental results.

Predictions of grid congestion rely on load and generation forecasts throughout the system. Experiments results on one year (2018) of training data and one month of evaluation period, showed an Mean absolute percentage errors ranged from 2.76% to 6.37% . Average durations for end-to-end forecast rose from 6.4 seconds, with ten forecast task in parallel to 27 seconds with 200 parallel jobs. Highest throughput of 27,600 jobs per hour was achieved with 175 jobs in parallel for an average duration of 22.8 seconds. This reduction in performance on the deployed system was mainly due to back-end database operations at high throughput. Scalability and accuracy of the forecasting system are detailed in [7].

8 REFLECTION AND ANALYSIS

In this section, we analyze and reflect on the development and deployment of the GOFLEX system.

8.1 Achievement and Impacts

The GOFLEX system has the impact of improving the use of local flexibility in the local energy system. Experiences in the demonstration phase showed reductions in peak demand in the region from a few percent up to 13%. An increase in the level of self-consumption of 5-10% was also observed during the demonstrations. Evaluation of the forecasting systems showed an accuracy in the range of 91% for the substation level and 98% for the utility level. These forecasts, used together with an AI based observability system, led to 91% overall observability of the local grid, which is 33 percentage points up from from 58% in the previous situation. These enhanced capabilities of the DSOs and enabled the smarter use of the flexibility.

A key aspect of the evaluation of the GOFLEX system in the demonstration sites was a cost-benefit analysis carried out by local DSOs. Of course, each analysis was specific to the local conditions and comes with certain assumptions. Nonetheless, the numbers reported by the demo sites indicate that each site witnessed a benefit of using the GOFLEX system [18]. In the Cyprus demo, the benefit for the grid operator was estimated to be 9.7M EUR/year. In the Switzerland demo, avoided grid costs were estimated at up to 150,000 EUR/year. In the Germany demo, an extra gross profit of EUR 5M/year was estimated for bringing prosumer flexibility to the market. By demonstrating that energy flexibility can be cost-effective, GOFLEX helped to drive the market uptake for flexibility.

8.2 Challenges

Developing a scalable, general, and replicable system inevitably poses known and unforeseen challenges. Some of the prominent challenges faced during GOFLEX project are.

1. It has not always been easy to involve the end-user, as they were sceptical that the financial gain might not be sufficient for them compared to their investment costs and comfort losses. In the Swiss case, for example, the cost of installation is still high compared to the actual potential revenues.
2. In some case, the quantity of flexibility offered by the GOFLEX prosumers was not sufficiently large to counteract problems in the distribution grid. This is due to the nature of loads connected and/or used too conservative flexibility extraction techniques. Flexibility aggregation was helpful integrating such small flexibility assets.

8.3 Prosumer Survey Evaluation

After the deployment of the GOFLEX system, we evaluated how residential prosumers experienced interacting with the system. To do so, we conducted a survey study at all three demo sites. The survey was devised to measure; 1) how residential prosumers experienced the GOFLEX system, 2) the ease with which they interacted with GOFLEX technology, and 3) if the GOFLEX system was used as it was intended to be used. We organized the survey with both open- and closed-ended questions. The survey was distributed to 304 GOFLEX participants from the three demo sites, and a total of 167 provided responses during January 2020. Participants had experienced the GOFLEX system running for two to five months at this point. All data were anonymously collected.

When asked, survey respondents reported they experienced the GOFLEX system as easy to learn, and simple and fun to use. The GOFLEX system was dominantly seen through an energy information management lens, with over 70% (agreeing or strongly agreeing), the GOFLEX system provided more information about personal energy usage. In contrast, 57% saw the system as an enabler to manage energy use. When asked about what information was of importance for future use, 75% responded with information about household energy use and comparison of personal energy use over time, while 71% responded with information about how GOFLEX controls appliances and influences energy usage. Such experiences were detailed by respondents as; "an improved understanding on self-consumption for customers with PV production" and "detailed information about the power consumption of the devices".

While GOFLEX was predominantly experienced as an energy information management system, 58% of respondents perceived the main purpose of the GOFLEX system to help them use *less* energy (which was not an intended impact). At the same time, only 33% saw GOFLEX helping to use *clean* energy (flexibility; which instead WAS the intended impact). Other user studies [21, 22] on flexible energy management systems illustrate that the concepts of flexible energy and flexibility trading can be difficult for end-users to understand and conceptualize, and that such systems are often misinterpreted to lower energy use [23]. The survey results illustrate that GOFLEX end-users had similar difficulties understanding flexibility as a concept, with some respondents stating a "lack of details on the technology" and "lack of information on the functioning and the ultimate goal of the GOFLEX project".

The survey also included questions on specific demo site use cases. At the Swiss demo site, we asked questions about the control of the indoor climate and hot utility water. 67% of respondents reported they experienced no change to their indoor comfort and water supply during the trial period, while 17% stated an actual improvement of their comfort of both the indoor climate and water supply. At the German demo site, users with direct control of GOFLEX devices were asked in which activities the GOFLEX system was convenient to use. Conveniently, 59% stated battery charging, and 24% stated keeping food cold. In contrast, 6% agreed that washing dishes and washing clothes were more convenient accomplished through the GOFLEX system (68% and 72% respectively disagreed with this).

To conclude, the implementation of the GOFLEX system in the demo sites has been able to actively engage prosumers, DSOs, and the public to think about the energy system from the bottom-up instead of the top-down.

8.4 Lessons learned

Overall, important lessons can be learned from users interacting and experiencing the GOFLEX platform. Foremost, these platforms have to support users in their daily energy-consuming activities as it increases their active participation. Studies show that both consumers [24] and prosumers [25] can experience EMS technologies as engaging, fun, and playful if the use of the technology relates to their context and interests [45]. In addition, experiences with the GOFLEX system have proven that the user interaction with the software has to be user friendly and as informative as possible. For example, giving users the ability to easily control their devices, providing detailed information on what the control means in their daily lives, and for what purpose the control is applied. However, it should be noted a majority of GOFLEX users were extraordinarily cooperative and carefully following the given guidelines.

Further, the system must be designed in a more modular way to accommodate various heterogeneous loads in a plug and play fashion. Users (flexibility providers) have different expectations and needs of their flexibility. Hence a system must be suitable to adapt to user requirements and maximizes flexibility extraction.

Lastly, the FlexOffer concept (including its underlying sub-systems) has demonstrated its great potential for being a general, robust and scalable technology for process-independent flexibility management. It is sufficiently mature to be immediately exploited by both commercial products/services and new projects, as well as start a new line of FlexOffer-ready end-user products and services with plug-and-play rapid integration. New projects, including the recent Horizon 2020 projects FEVER [12] and domOS [8], are already taking advantage of this technology.

9 CONCLUSION AND FUTURE WORK

We have presented the GOFLEX system for flexibility management and trading, which encompasses 500+ prosumers ranging from simple household appliances to complex processes in operational industrial facilities. The GOFLEX system consists of a number of inter-connected sub-systems, including those for load control, flexibility extraction, flexibility management/aggregation, flexibility trading, and grid monitoring and management. Here, the FlexOffer is used as a common format/representation for capturing and exchanging explicit flexibility offers and requests between relevant GOFLEX sub-systems (parties).

The GOFLEX system has been successfully deployed in 3 demo sites in Germany, Switzerland, and Cyprus. The use of the GOFLEX system in these demo sites has shown that it is a scalable solution, which enables an active prosumer participation and a cost-effective use of flexibility for integrating more renewables and mitigating problems in the distribution grid. By offering a total of 800MWh flexibility on the market, the GOFLEX system facilitated a safe increase of installed capacity for renewable energy of 20-59% with respect to existing renewable capacity and an estimated load adaptability of 5-64% of peak demand, thus showing strong progress towards the Paris Agreement's targets of renewable energy in Europe for the year 2030.

In the future, we will capitalize on all the achieved results and harvested field experience in new projects. The recent Horizon 2020 projects *FEVER* and *domOS* are already taking advantage of this technology. There is also a 3-year extended observation period in the German demo site, where the system will be further tested.

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ACRONYMS AND ABBREVIATIONS

Abbreviation	Definition
ATP	Automatic Trading Platform
BRP	Balance Responsible Party
DER	Distributed Energy Resources
DOMS	Distribution Observability and Management System
DR	Demand Response
DSO	Distribution System Operator
EMS	Energy Management System
FMAN	FlexOffer Manager
FMAR	FlexOffer Market
FOA	FlexOffer Agent
GUI	Graphical User Interface
MGR	Micro-grid responsible
RES	Renewable Energy Sources
SP	Service platform
TSO	Transmission System Operator
VPP	Virtual Power Plant
xEMS	One of energy management systems used in GOFLEX

Table 5: List of acronyms and abbreviations.