An Energy Flexibility Framework on the Internet of Things

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Abstract. This paper presents a framework for management of flexible energy loads in the context of the Internet of Things and the Smart Grid. The framework takes place in the European project Arrowhead, and aims at taking advantage of the flexibility (in time and power) of energy production and consumption offered by sets of devices, appliances or buildings, to help at solving the issue of fluctuating energy production of renewable energies. The underlying concepts are explained, the actors involved in the framework, their incentives and interactions are detailed, and a technical overview is provided. An implementation of the framework is presented, as well as the expected results of the pilots.

1 Introduction

The Internet of Things (IoT) enlarges the Internet to physical objects, extending its usage to various applications such as Smart Grids. Most of these objects are pervasive and mainly interact with other Internet devices such as database servers, other objects or services. With many connected objects[1], using a variety of heterogeneous technologies and protocols, managing their interconnection is a challenge.

Service Oriented Architectures (SOA) have been developed to abstract the specificity of devices and networks and obtain consistent access to functionalities provided by the objects (e.g. [1]). In addition, a lot of effort has been put into filling the syntactic and semantic gaps that exist between networks and applications [2, 3], as demonstrated by the results of the European Connect project [4]. However, a remaining open issue is how to create smooth interconnection between service providers and consumers in the IoT. The Arrowhead project [2] aims at providing a solution to this issue, by developing a framework [5] for IoT applications, including a set of essential services, namely:

– service discovery;

[1] Cisco estimates the number of connected objects to reach 50 billion by 2020.
[2] www.arrowhead.eu

Stluka P., Le Gully T., ÅăikÅąnys L., Pedersen P., Skou A., Pedersen T., Albano M., Ferreira L. and Olsen P.
An Energy Flexibility Framework on the Internet of Things.
DOI: 10.5220/0006163400170037
In *The Success of European Projects using New Information and Communication Technologies (EPS Colmar 2015)*, pages 17-37
ISBN: 978-989-758-176-2

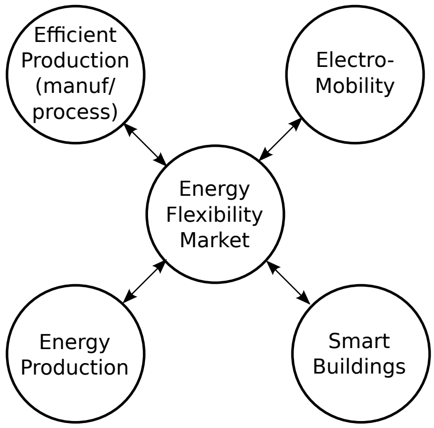

Fig. 1. The five pilot domains of the Arrowhead project.

- authentication;
- authorization.

In fact, if service discovery is sufficient to establish connection between a service consumer and provider, authorization is usually required, in particular for Cyber-Physical Systems (CPS) involving critical components. This is the case in all the pilot domains of the project, which cover the areas or production, electro-mobility, energy production, smart buildings and an energy flexibility market (or flexibility market). These five pilots provide a good sample of the diversity of applications that will be provided by the IoT. As illustrated by Figure 1, the flexibility market is the common denominator between the different pilots, and is expected to provide them its services.

This central position of the energy flexibility market illustrates well the fact that energy will be an important application domain for the IoT, as the challenges that are faced in this area are essential for the future of our society. A European Union directive from 2009 requires the EU countries to fulfill at least 20% of their overall energy needs from renewable sources by 2020 [6]. More recently, Denmark has set a 50% target by 2020 [7]. To attain these objectives, many European projects [8–10] aiming at improving and understanding the production and consumption of electricity have been conducted. Their ambition is to move the current electricity network, the grid, to a *Smart Grid* equipped with smart meters and appliances providing measurement and control capabilities [11].

A main issue with the increasing part of renewable energy sources such as solar cells and wind turbines, is that production from renewable energy sources fluctuates and is not available at all time. It is thus necessary to adjust the behavior of consumers to adapt to the fluctuating production. Solutions to these issues are known as *demand response mechanisms* [12], that provide incentives to end users to modify their consumption behavior to better match the production. A common demand response mechanism is to increase the price in periods of high demand and low production, and reduce it in periods of low demand or high production. Several European programs have been devised and dynamic prices already exist in some countries [13, 14]. Another mechanism, developed in the European project MIRABEL [15], uses the flexibility offered by some devices and appliances. For example, a Heating, Ventilation and Air Conditioning (HVAC) system can be set with a comfort temperature interval in which it can operate to adjust its consumption pattern. This flexibility can be used to adapt consumption and better match production, or to offload the grid in peak times. However, in order to make use of this flexibility, there is a need for measuring, predicting, and planning consumed and produced energy. We propose in this paper a framework for managing energy flexibility based on so-called FlexOffers, from the end user to a flexibility market where it is traded and assigned an optimal value. The objective is to enable actors of the energy domain to buy flexibility and have more freedom in distributing loads in the grid. The main contribution of this paper is to define the details of this framework, the different actors, their possible interest and their relationships, and to present the underlying ICT infrastructure enabling its deployment. Pilot demonstrations currently taking place in the Arrowhead project are also presented to discuss the applicability of the framework.

The paper is organized as follows. The concept of flexibility and FlexOffer are presented in Section 2. The framework, the actors that compose it and their interactions are detailed in Section 3. An overview of the framework implementation architecture is provided in Section 4. Pilots are presented in Section 5. Finally, related work is discussed in Section 6, and we conclude and discuss future work in Section 7.

2 FlexOffer Concept

This section introduces the concept of FlexOffer, that encodes necessary parameters of flexible loads to facilitate their management. Generation and aggregation of such FlexOffers are then discussed.

2.1 FlexOffer

The flexibility framework presented in this paper is based on the concept of FlexOffer. As already mentioned, this concept was developed in the European MIRABEL project. It provides a way to formally represent flexible energy loads in terms of time and energy, and contains the information necessary to manage them. A visual representation of a FlexOffer in one of its simplest forms is shown in Figure 2. The bars in this graph represent a flexible consumption load from a component with flexible consumption that we name *Flexible Resource* (FR). Each bar represents the consumption for a given time slice. The lower area represents the minimum amount of energy the FR needs to provide its service. The upper area represents an energy interval in which it can change its consumption while ensuring predefined constraints (e.g. temperature comfort). The amount of energy consumed at each slice can thus vary within the interval given by the upper area. Flexibility in terms of energy amounts is referred to as *energy flexibility*. Note that this simple FlexOffer contains only positive flexibility, but some FRs can also contain negative one, representing flexibility in production. The second type of flexibility is time flexibility, and typically occurs when a given load can be shifted in time within a given interval, as illustrated in Figure 2. The time shift is constrained by an *earliest start*, before which the load should not be assigned, and a *latest end* at which it should have been consumed. A baseline is also assigned to each FlexOffer, that

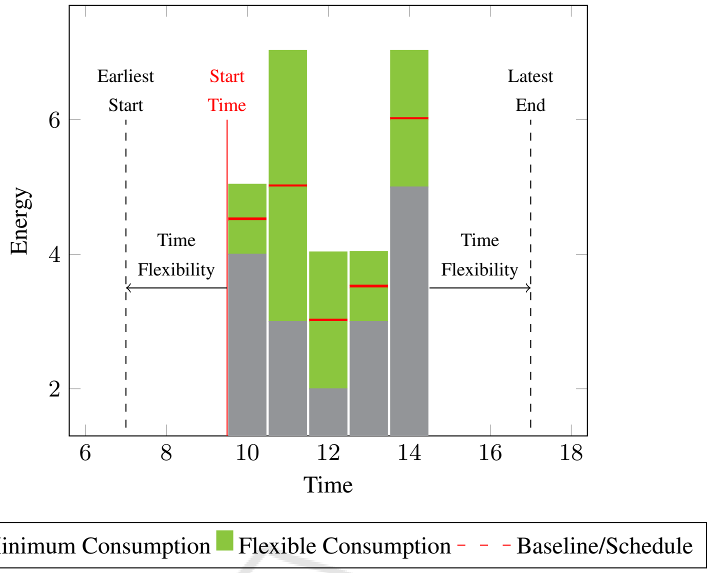

Fig. 2. Example of a FlexOffer.

represents the default consumption plan that the associated FR will follow if it does not receive any update. This baseline schedule can be updated to modify the consumption pattern within the flexibility domain.

2.2 FlexOffer Generation

Generating sound FlexOffers for FRs is not trivial. For FRs that continuously consume energy, such as heat pumps, FlexOffers are typically generated on an hourly or daily basis. Other FRs can emit FlexOffers when needed. Generating a FlexOffer with energy flexibility for FRs implies predicting the consumption (or production) of an FR required to satisfy a given set of constraints, as for example a comfort temperature interval. This is most often done using a model of the FR, its environment including relevant parameters for the predictions such as temperature or solar radiation, and environmental constraints such as comfort settings. Using the model, energy and time flexibility are estimated using various techniques, such as linear programming. Details about generating FlexOffer at the device level can be found in [16].

2.3 FlexOffer Aggregation

FlexOffers most often do not represent large flexible loads. Thus, a single FlexOffer is of little interest to balance energy loads on the grid, where required flexibility is much higher. At the same time, managing large numbers of FlexOffers is tedious and complex. A common solution to facilitate the management of energy loads is to aggregate them. Similarly, FlexOffers can be aggregated into aggregated FlexOffers with larger flexible energy loads. Once an aggregated FlexOffer is assigned a schedule, it needs to

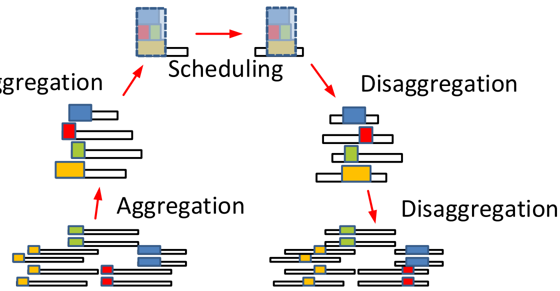

Fig. 3. The workflow of FlexOffer aggregation and FlexOffer schedule disaggregation.

be disaggregated to assign a schedule to each FlexOffer it is composed of. Note that aggregation can be performed multiple times, meaning that an aggregated FlexOffer can contain smaller aggregated FlexOffers, as shown in Figure 3. In general, the flexibility of an aggregated FlexOffer tends to be lower than the sum of the flexibility of the FlexOffers that compose it. This reduction in energy flexibility is however unavoidable to reduce the complexity of flexibility management and the scheduling problem. Note also that aggregating flexible loads is a complex task. To optimize aggregation, FlexOffers can be grouped based on similarity of consumption pattern. More details about aggregation and disaggregation of FlexOffers are provided in [17].

3 Flexibility Framework

An overview of the proposed framework is shown in Figure 4. This section describes its details with the different actors, their interactions and provide examples.

3.1 Flexibility Market

Currently, grid actors trade electricity on existing traditional *day-ahead* (spot), *intraday*, and *regulation energy markets*. In this Arrowhead pilot, we also consider a so-called flexibility market. It is based on a variation of the product-mix auction [18], in which the commodities are flexible energy loads for specific geographical areas. This model is designed to deal with the "product mix" problem, in which multiple varieties of a product with different costs are supplied, but with a constraint on the total capacity. Here the product is flexibility, and the varieties are positive and negative flexibility. Each bidder can make one or more bids, and each bid contains a set of mutually exclusive offers. Bids in the flexibility market are in fact mutually exclusive, since using both negative and positive flexibility for a given geographical area would not make sense. Two types of bids can be made, *supply bids*, offering flexibility, and *demand bids* requesting it. The auctioneer then selects the market clearing price that for each bid gives bidders the greatest surplus. Offers with negative surplus are rejected. This is visualized in Figure 5. In both graphs, a bid is represented by an horizontal segment. The length of a segment determines the supplied or demanded flexibility amounts, while its position on the Y axis shows the associated price. On the left side, "Up Bids" correspond to bids

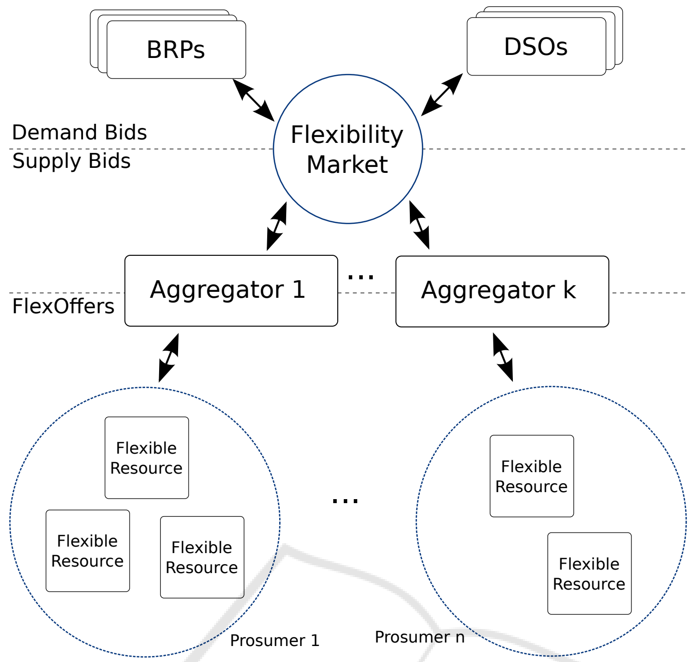

Fig. 4. Overview of the flexibility framework.

for negative flexibility, while “Down Bids” are for positive one. The market clearing price is found at the intersection between demand and supply lines. Supply bids above this line are rejected, similar to demand bids under it. All accepted bids are traded at the market clearing price. In the current implementation of the market, clearing is performed every 15 minutes, but could be adapted to match different needs.

3.2 End Consumer/Producer

The basic elements of the framework are FRs that produce and consume electricity, giving the name *prosumers* to FR owners. A first example is a household, in which we can identify a number of FRs. The Heating, Ventilation and Air Conditioning (HVAC) system is a first important one. If a user agrees to let such systems be controlled flexibly, meaning setting intervals for the different comfort settings, it is possible to generate useful FlexOffers from them. Generating FlexOffers from this type of system is the objective of one of the pilots of the Arrowhead project, which will be discussed in Section 5.1. Similarly, fridges and freezers can be operated in a given interval to offer flexibility. Another type of system that can offer flexibility is an appliance such as a washing machine, tumble dryer or dishwasher. In general, such appliances follow a fixed consumption pattern, that could thus only be shifted in time. This could be achieved by asking users to specify an interval during which they should operate, or a deadline by which a given operation should be terminated. However, at the moment, few of these appliances provide remote control capabilities, making it difficult to explore the applicability and acceptance from users.

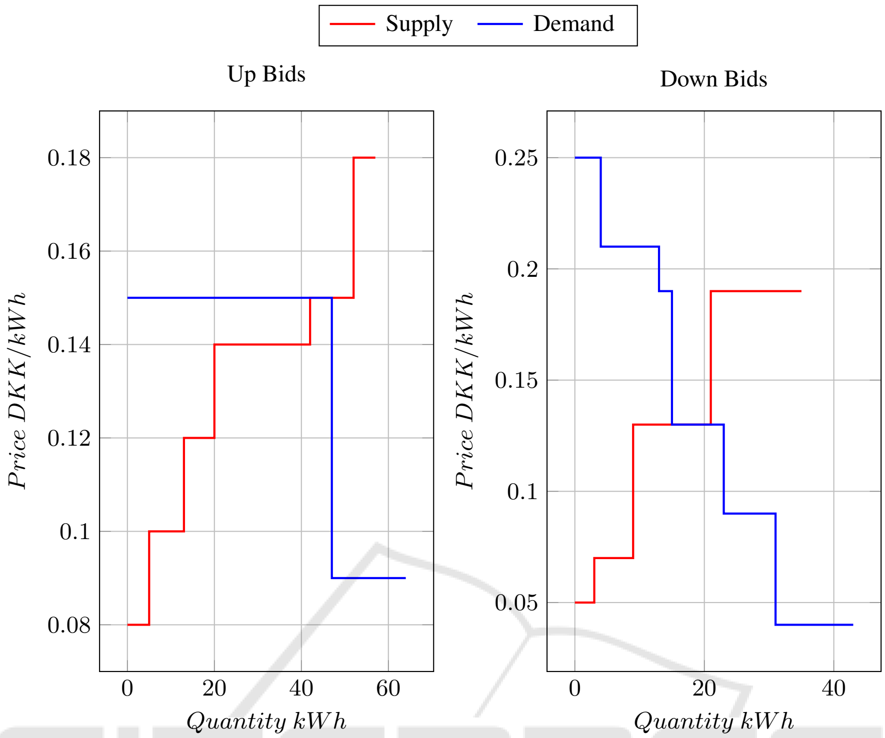

Fig. 5. Visualization of market clearing price.

Electric cars are also interesting, since their numbers is expected to increase in the near future. In fact, they can be charged in a very flexible manner, and can even be used as storage facilities. In addition, they are a real issue for existing grid infrastructures that in some cases will not support convoluted charges. It is also important that user constraints can be enforced, such as ensuring a minimal charge for emergency situations. A pilot on this topic is expected to take place in the context of the Arrowhead project.

Nowadays, houses are getting more equipped with production units such as Photo-Voltaic panels or wind turbines. These can be used to increase the flexibility offered by equipped houses. These units thus provide negative flexibility. Combining information from producing and consuming units makes it possible to generate FlexOffers with large amounts of both positive (consumption) and negative (production) flexibility. Finally, as local storage units are becoming more affordable, they could also be of interest to the framework.

Another type of FRs are public buildings that are essentially equipped with similar type of devices than houses, but with larger capacities, both in terms of production and consumption. The project includes two pilots with buildings equipped with innovative technologies that can be used to generate FlexOffers, and will be discussed in Section 5.

The last important type of prosumer are industrial actors. Industrial processes are in fact using large amounts of energy for manufacturing goods. The consumption patterns of these processes can in some cases be adjusted, by shifting production schedules or throughput. Industrial actors need to play an important role in the green transition, and tools such as FlexOffers can facilitate their integration to the Smart Grid. In the framework, only this type of prosumers are expected to participate in the flexibility market. Smaller ones will interact with it through an Aggregator.

3.3 Aggregator

An aggregator is a business entity that makes money by aggregating FlexOffers from several FRs and selling them on the flexibility market. It essentially acts as a Commercial Virtual Power Plant (CVPP), providing load-shifting options and (near) real-time control of many FRs on the energy market. As already mentioned, small Prosumers, as for example a household, do not provide large enough flexible loads to be of interest for a market. An Aggregator thus makes a contract with a number of these Prosumers, giving it the right to control their FRs based on the FlexOffers they emit. In exchange, it must reward the offered and used flexibility with a previously agreed price scheme. We propose that the actual reward be calculated based on:

- The number of FlexOffers issued by a Prosumer;
- The amount of flexibility offered by the prosumer, both in time and energy amounts;
- The amount of flexibility used by the Aggregator to balance loads in the grid;
- Other parameters such as number of actual activations, accuracy with which schedules are followed, etc.

Once a contract is agreed upon between an Aggregator and a Prosumer, the generation, aggregation and schedule of energy loads can start. The interaction between an Aggregator and an FR is shown in Figure 3.3. When an FR sends a FlexOffer to an Aggregator, the first step the Aggregator takes is to check for validity. Essentially this means ensuring that the time intervals of the FlexOffer are consistent. It then decides, based on the state of the grid and other parameters, if the FlexOffer is useful for its needs. If it is, the Aggregator accepts it, notifies the FR and aggregates the received FlexOffer with other ones, to produce one or more *aggregated* FlexOffers. During planning, the Aggregator can update the baseline of the FlexOffer by assigning it a schedule. Scheduling can be performed multiple times to react to planning changes, up to a time included in the FlexOffer. After this time, the FlexOffer is executed by the FR, meaning that it consumes (or produces) electricity following the assigned schedule. The consumption (or production) is measured to ensure that the schedule is respected by the FR. In the billing phase (every month), the Aggregator computes all of its revenues, losses and bills.

In the planning phase, an Aggregator uses the pool of aggregated FlexOffers to generate bids for the flexibility market. For each aggregated FlexOffer, it sends one supply bid with two offers. One for positive flexibility and one for negative. Recall that among these two offers only one can be accepted. Winning offers result in assignments of schedules to corresponding aggregated FlexOffer. The Aggregator can also trade on other existing power markets (e.g., ELSPOT or ELBAS) and enter into bilateral agreements with other parties such as Balance Responsible Parties. The Aggregator business model is shown in Figure 6.

Aggregators can also be specialized based on the type of FRs they handle. As already mentioned, aggregation can be optimized by grouping similar FlexOffers.

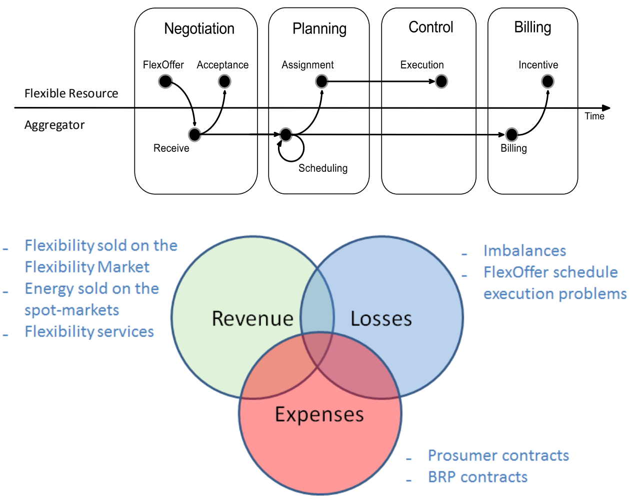

Fig. 6. Aggregator business model.

3.4 Distribution System Operators

A Distribution System Operator (DSO), is responsible for operating, maintaining, and when necessary developing the distribution system in a given area, delivering (and possibly receiving) electricity to (from) end users. This is in contrast to a Transmission System Operator (TSO) that have similar responsibilities for the transmission system, delivering electricity from large generation units to industrial consumers and local transformers. In Denmark for example, DSOs operate under 65kV while TSOs operate above.

The increasing number of energy consuming devices and appliances, including heat pumps and electric cars, lead to an increase of the load on the distribution grid. The addition of Distributed Energy Resources (DER) connected to it such as wind turbines puts even more pressure on existing installations. However, most issues arise during peak periods. To solve them, DSOs thus have two options:

– Strengthen the grid or
– Smoothen the load.

Strengthening the grid requires large investments from DSOs. Smoothening the load is more cost effective and can be used in addition to strengthening the grid. The flexibility market can be used by DSOs to that effect. They access the market by expressing interest in flexibility for specific geographical areas in which they operate. For example a DSO can emit a bid expressing interest in positive flexibility in a given area, to reduce congestion points. The interaction between DSOs and the energy market is as follows.

Step 1. Forecast of the loads on the grid and identification of possible bottlenecks. The baseline loads of Aggregators are queried and used to improve the accuracy of forecasting and congestion detection.

Step 2. During market opening time, for each bottle-neck point, a bid with several offers is generated, with different demands for flexibility at different prices. Each offer can for example represent a potential solution for a bottle-neck in the grid.

Step 3. If an offer is accepted, the DSO enters into an agreement with the wining party (for example an Aggregator) to make use of its flexibility.

Step 4. The DSO updates the load forecasts to mirror the deviations of the winning bids and re-computes bottle-necks.

Alternatively, or additionally, they can also make bilateral agreements with large prosumers to exclusively handle their FlexOffers.

3.5 Balance Responsible Party

Balance Responsible Party (BRP) is a delegated role from a TSO to ensure balance in the transmission grid, e.g. ensuring fitness between consumption and production. Today this is done by trading on existing energy markets, based on expected production and consumption. The main task of the BRP is to predict hourly energy flow up to 36 hours ahead and trade electricity accordingly. However, with fluctuating energy sources like wind turbines and PVs this is becoming more difficult. The interest from the BRP in a flexibility market is to "buy" flexibility from industrial FRs and Aggregators to balance power within their respective grid area. Interaction between BRPs and the market place is similar to the DSOs interaction.

4 Software Architecture Overview

The flexibility framework introduced in the previous section, to be put in practice, is supported by a number of software components and ICT solutions enabling information exchange, FlexOffer generation, aggregation and control of FRs. These components are implemented in Java, following a set of pre-defined interfaces. They are supported by the Arrowhead core services, a set of management services designed to facilitate the deployment of IoT applications. It aims at facilitating interconnection between systems of different application domains (e.g.: industrial automation, airplane maintenance, energy production, home automation, smart grids). The objective is to enable cross-domain applications, among which energy is a central point. Figure 7 illustrates the different system components as well and their interconnections, that will be described in this section.

4.1 Arrowhead Framework

The Arrowhead core services facilitate interactions between the different systems implementing the framework. The Service Registry service allows service providers to advertise their services, and service consumers to look them up.

The Orchestration service allows to automatically connect a service provider to a service consumer. This is based on a query from the latter, containing requirements that the service should satisfy. The Orchestrator essentially performs a look up of the

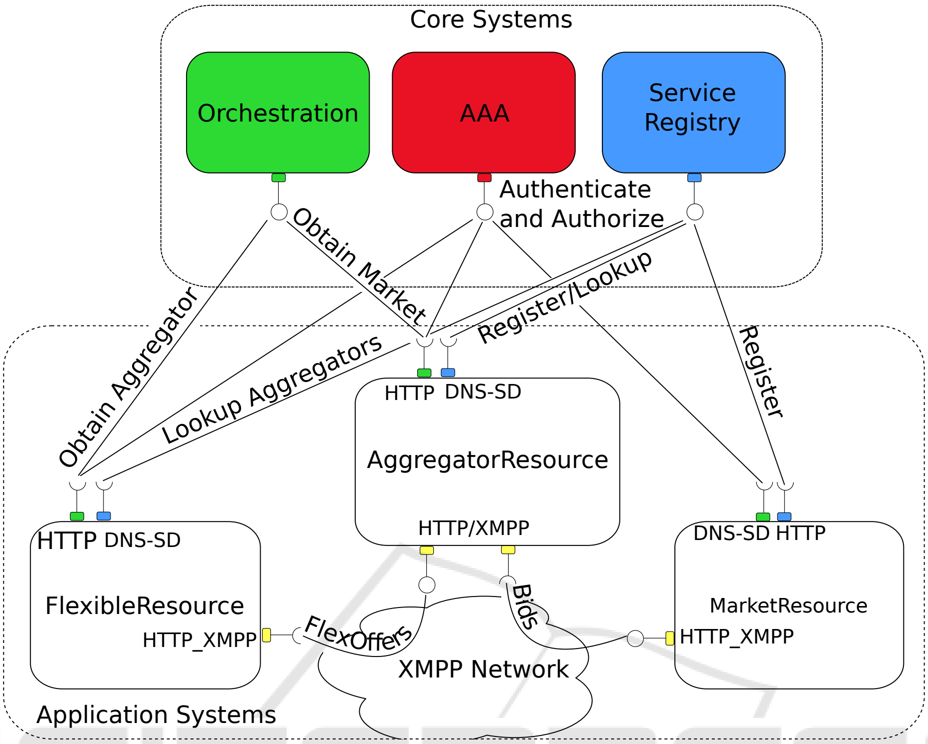

Fig. 7. Software architecture of the Virtual Market of Energy.

information stored in the Service Registry, to find the best service to satisfy a given query. Note that orchestration can return a simple service (e.g.: an AggregatorResource specialized into heat pumps) or a composed service (e.g.: a set of MarketResources to be used in round robin, or at different time of the day).

The Authentication, Authorization and Accounting (AAA) service enables verification of component identities, access control to functionalities and accountability measure in case of misuse. This is essential in the framework as malicious actions could lead to damages to grid infrastructure. As an example, criminals could impact grid operations by misbehaving in the framework, or taking financial benefit by claiming dishonest information.

The Arrowhead core services were instrumental in easing the implementation of the flexibility framework, and to ensure a good level of performance and security for the interacting systems, by providing a Service Oriented platform to support all the interactions for the functioning of the systems at hand.

4.2 Market Resource

The MarketResource component encapsulates functionalities of the flexibility market. The architecture allows for multiple markets to be defined, which could correspond to different geographical areas or type of flexibility traded. After authentication, the

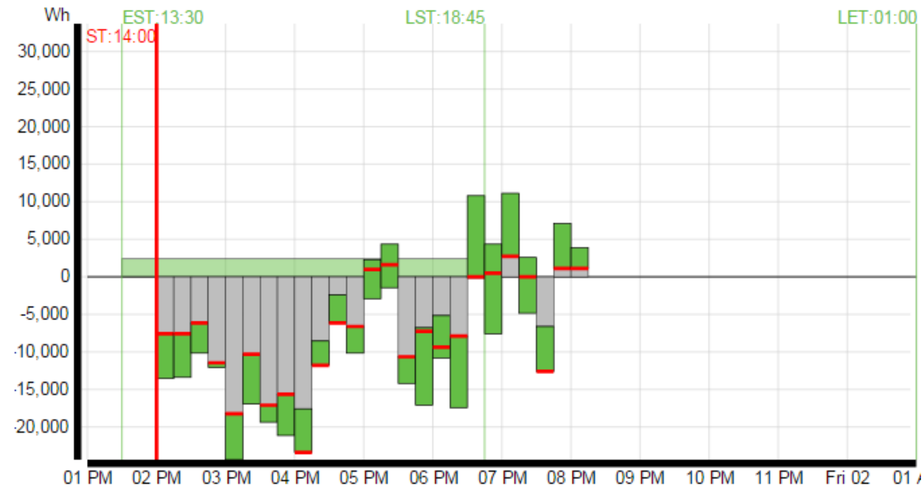

Fig. 8. FlexOffer visualization in an FR graphical user interface.

market makes its interface available to authorized bidders. It then conducts the auction as already described in Section 3.1.

The current implementation of the Market Resource provides a graphical user interface enabling its management and monitoring. It consists of a web application and includes for example the visualization of market clearings shown in Figure 5.

4.3 Flexible Resource

As already mentioned, FRs are implemented in a software component of the same name. The functionalities handled by the FR component are:

FlexOffer Generation. Sending FlexOffers to an Aggregator;
Consumption Management. Following assigned consumption schedule.

To enter the framework, an FR needs to authenticate to the AAA service, and be an authorized entity. It can then look up an adequate Aggregator with respect to its flexibility and geographical area using Service Registry or Orchestration services. The returned information enables it to connect to an Aggregator, if authorized by this one. This means that there exists an agreed contract between Aggregator and FR, as mentioned in Section 3.3.

The currently implemented FR components generally provide two user interfaces (UIs), mostly through web applications. A first one is used to set configuration parameters for FRs, such as user constraints. Examples will be shown in Section 5. A second UI is used to monitor flexibility of the system, and is common to all FRs. It contains for example a visual representation of FlexOffers, illustrated by Figure 8, or information on generated FlexOffers and rewards as shown in Table 1.

Table 1. Example of information about generated FlexOffer provided in FR graphical user interfaces.

Item	Value	Price
Number of FlexOffers	20	
Fixed reward for providing flexibility		10 DKK
Total Time Flexibility	289 time units (15min.)	28.90 DKK
Total Energy Flexibility	409,137.63 Wh	40.91 DKK
Number of baseline updates	3	15 DKK
Used time flexibility	3 time units (15min.)	9 DKK
Used energy flexibility	10,232.91 Wh	21.44 DKK

4.4 Aggregator Resource

The Aggregator Resource component implements the functionalities offered by an Aggregator. It acts as a service provider towards FRs, enabling them to submit generated FlexOffers, informing them on their status, and sending back consumption schedules when FRs baseline consumption patterns are modified through wining bids and disaggregation. After authenticating, it advertises its service to the Service Registry so that it can be found by relevant FRs. If multiple markets are available, it can also use Orchestration or Service Registry to find the most relevant one for the flexibility it has to offer. It also uses AAA services to ensure that only authorized FRs can connect to it. Finally, Aggregators offer UIs similarly to FRs, offering visualization and management of FlexOffers, contracts and price information.

4.5 Communication Infrastructure

Interaction between the different components is implemented using different approaches based on communication requirements and component specificities.

Arrowhead Core Services are generally provided over the HTTP protocol. An exception is the Service Discovery that uses DNS-based Service Discovery [19].

Web Interfaces are also provided by each component over HTTP. This makes it easy to access them from any Web compatible device.

Framework Components communicate using HTTP over XMPP [20]. The reason for this choice is that as HTTP is already used for communication with the Arrowhead core services and web applications, reusing it for component communication enables reuse of interfaces, and consistent error handling. However, HTTP makes it difficult to establish two way communications. This is often in houses of buildings where FRs are located, due to Local Area Networks (LAN) and firewalls that prevent incoming connections to networked devices. Using XMPP as an underlying communication layer makes this possible, in addition to enforcing communication encryption. In addition, XMPP is being considered as a transport method for the second version of the Open Automated Demand Response (OpenADR), and the ISO/IEC/IEEE 21451-1-4 [21] standards.

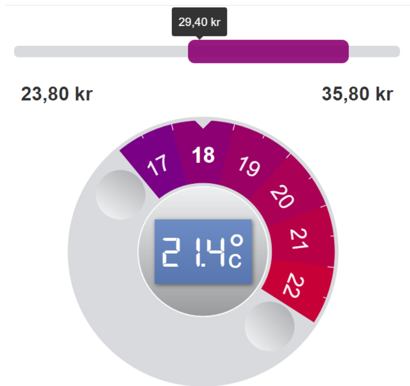

Fig. 9. Screenshot of the application to set interval comfort temperature and obtain visualization of corresponding reward.

5 Pilots

This section introduces three pilots of the Arrowhead project that are currently being developed to explore the applicability of the flexibility framework in different use cases.

5.1 Heat Pumps

The first pilot consists of an individual control of heat pumps installed in occupied residential houses. Each household is provided access to a web application through an FR component, enabling setting of comfort temperatures and visualize associated reward, as shown in Figure 9.

The idea behind the pilot is that a heat pump can be controlled flexibly both in time and energy consumption, while ensuring user constraints such as comfortable temperature interval of the house. The process used in this pilot is as follows:

- Create a model which can predict the energy demand of the house;
- Calculate day-ahead the cheapest energy plan to secure comfort using spot-price;
- Every 15 minute issue a FlexOffer describing the options for decreasing/increasing power consumption;
- Wait for an eventual FlexOffer schedule.

The data used for modelling are historical data for:

- Delivered heat in the house;
- Used energy for hot water;
- Indoor temperature;
- Power consumption of the heat pump;
- Weather data.

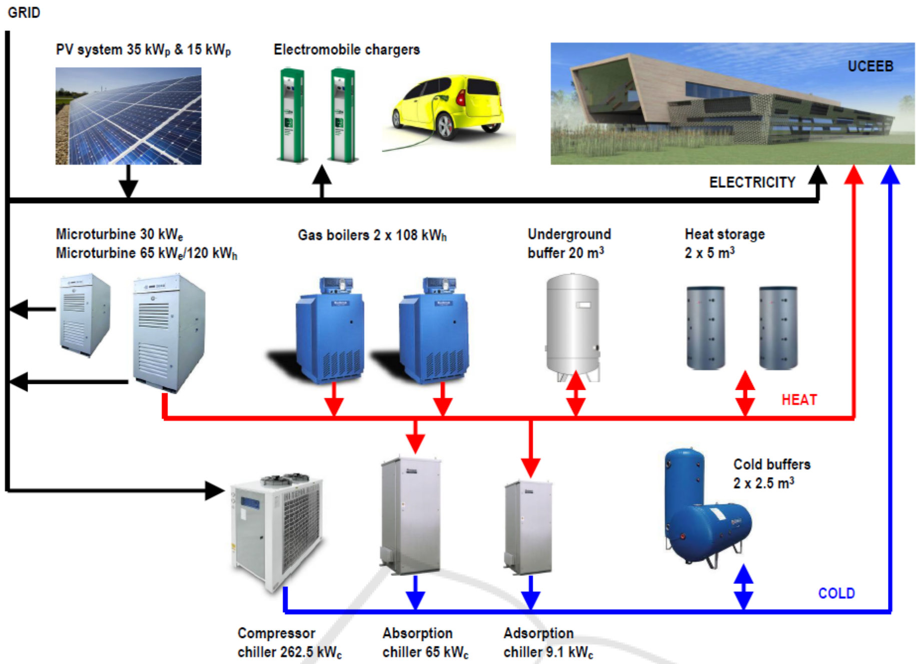

Fig. 10. Overview of the energy grids and resources in the UCEEB building.

Forecasting data are:

- The model;
- Weather forecast;
- User comfort criteria.

To apply assigned consumption schedules, heat pumps are operated via a relay, that can be used to stop them. However, it is not possible to force a heat pump to run.

5.2 Load Management in a University Building

The second pilot is being implemented in the new building of the University Center for Energy Efficient Buildings (UCEEB). It is located in Buštěhrad, a small town near Prague, Czech Republic. The UCEEB building serves as a complex experimental platform for all research fields related to the area of energy efficient buildings. It integrates a variety of spaces, including open space office, smaller office rooms, large halls and laboratories. It is also an experimental facility with multiple local energy sources integrated into respective distribution grids. As shown in Figure 10, it includes three energy grids, one for electricity, one for heat and one for cold. Energy resources include:

- two photo voltaic fields producing electricity (35 kWp and 12 kWp),
- a combined heat and power (CHP) unit producing heat and electricity,
- two charging stations for electric cars,
- storage units for heat and cold,
- two gas boilers, and
- two chillers.

Prior to the implementation of the FlexOffer concept, a simulation study was conducted to assess suitable scenarios, and determine how the building system could operate in combination with FlexOffers:

– Adjusting the HVAC system set points based on FlexOffers, ensuring the comfort temperature while maximizing the economic benefit for supplying flexibility to the market;
– Enable generation of FlexOffers by manipulating the temperature of hot and cold water;
– Using strategies such as *dynamic pre-cooling* or *pre-heating* to increase the flexibility of the HVAC system during periods of peak consumptions.

Following this study, several rooms with associated electric heaters and fan-coil units were selected for the pilot implementation so that experimentation could be conducted both during hot and cold seasons. An important part of the pilot is a software application connected to the Building Management System (BMS) and a database containing historical data. It is used by the building operator to control the process of FlexOffer generation. This human supervision is essential because specific adjustments of HVAC system operations can potentially lead to uncomfortable situations for the occupants of the building. The building operator is able to balance between comfort level and economic benefits. When the operator interacts with the application, the following functions are provided:

Precool: specifies a time interval in which pre-cooling of the building is allowed;
Duty Cycle: enforces a specified cycling pattern on the functioning of the HVAC system, which can be used to provide flexibility;
Full Flexibility: leaves full control of the system to the flexibility framework for a given time period, thus ignoring any comfort setting;
Adjust Set Points: allows manipulations of room temperatures in the building, but in this case the flexibility is specified by the operator himself.

The objective of this pilot is to experiment with the application of FlexOffers inline with the existing control system of the building, to assess potential benefits and application constraints. Some initial learnings are summarized here:

– The FlexOffer concept presents similarities with applications of Automated Demand Response (ADR) in commercial buildings. One possible difference is that today ADR always triggers a firmly defined load shedding strategy, while FlexOffers are assuming more degrees of freedom in building operation. For this reason it seems important to have a human operator responsible for assessing of how much flexibility may be offered under given conditions, and thus, supervising the overall process of generating flex-offers.
– Operating the HVAC system flexibly implies compromising between maximizing economic benefits and energy savings and overall comfort constraints in the building. For this reason only relatively short alterations of the default control strategy are desirable. This applies primarily to the strategies related to duty cycling and set point adjustments, which both should not span long time intervals. An example of a load shedding strategy implemented using FlexOffers, lasting over 4 hours is

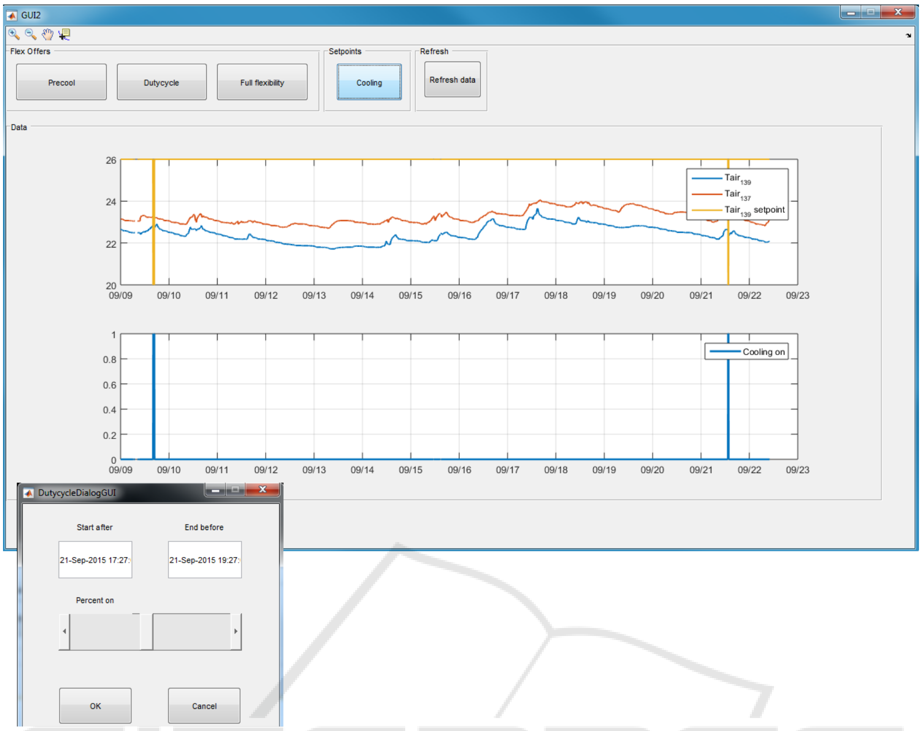

Fig. 11. User Interface used by building operators to specify flexibility parameters.

shown in Figure 12, which shows a systematic reduction compared to the estimated baseline.

– The economic benefits of FlexOffers need to be further studied. A first reason is the so-called rebound effect, already known from ADR projects. It occurs when occupants temporarily increase their heating/cooling demands after the completion of a schedule inducing reduction of comfort level to compensate the possibly experienced discomfort. This can increase energy consumption and operational costs and reduce the overall economic benefits. However, FlexOffers spanning an entire day, with relational constraints between time slices, could be used in the optimization to take into account such effects and help to determine their financial cost.
– Finally, it is important that building owners participating in the flexibility framework receive enough incentives to maintain their interest.

5.3 PVCC

PhotoVoltaic Comfort Cooling (PVCC) is a Danish project that aims at combining technologies with an innovative energy management system to improve the current cooling system of a bank building in Hadsund, Denmark. An overview of the setting is shown in Figure 13. The system is composed of:

Photovoltaic Panels: (PVs) producing electricity from solar energy.

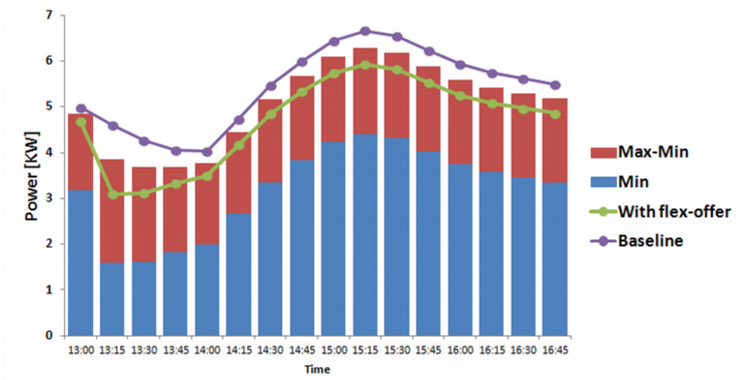

Fig. 12. Example of load shedding implemented using FlexOffers compared to estimated baseline.

A Heatpump: converting the electricity produced by PVs into cool air.
An Ice Bank: that can be used to store thermal energy in the form of ice.
A HVAC: used to control indoor climate.
A Controller: monitoring the different components and control energy production from the PVs and consumption from the heat pump. Its objective is to ensure system stability and improve energy consumption while maintaining a comfortable climate for building workers.

The controller receives information from the Danish Meteorological Institute to better anticipate PV production, thermal changes and optimize energy consumption. It can also receive external control commands from remote clients through the Internet. The system has been deployed for more than a year, and has drastically improved the comfort level of the building. In fact, due to its outside being composed mainly of glass, the sun heating it rapidly increased indoor temperature in summer. Due to the presence of both consuming and producing components, as well as energy storage, this pilot is now being investigated to generated interesting FlexOffers from it, that could be traded on the flexibility market.

6 Related Work

There has been a number of projects exploring the use of flexible loads to solve balancing issues on the grid. Already mentionned, the MIRABEL project [15] introduced the notion of FlexOffer reused in the presented framework. A similar flexibility market has previously been proposed in the iPower project [22]. It provides an overview of the possible interactions between DSOs and Aggregator, detailing their interaction process using a market and contracts to ensure application of the assigned schedule. Here we have provided a more general overview of the components and actors that constitute our proposed framework. Our approach also differs by the use of the FlexOffer concept, as well as the application and implementation of the product-mix auction in the market. In addition, we have provided details about concrete implementations of an ICT infrastructure enabling the deployment of such a market.

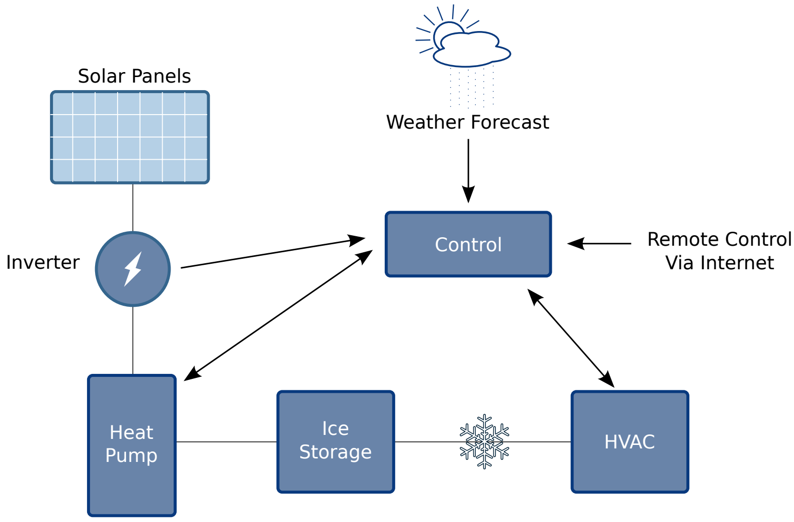

Fig. 13. Overview of the PVCC pilot.

Powermatcher [23] is also an auction based framework for energy balancing using load shifting. FRs are referred to as device agents while Aggregators are referred to as concentrators. It provides an open source library to implement the framework using web sockets over HTTP for communication. Here the integration with the Arrowhead core services and the use of XMPP aims at providing necessary services for facilitating interconnection of the components and security and accountability measures. The CITIES project [24] explores energy flexibility at the city level, and has shown interest in the presented framework.

There is in general active research in the area of energy flexibility. Neupane et al. evaluate the value of flexibility on current regulation markets. Valsomatzis et al. [25] discuss how to compare energy flexibility, a useful technique for managing FlexOffers at the FR or Aggregator level.

Finally, a technical overview of the framework was presented in [8]. Here we have presented a more general overview of the framework, and more details about the flexibility market.

7 Conclusion and Future Work

In this chapter we have presented a framework to leverage flexible energy loads from consuming and producing devices, aggregate them and make them available on a flexibility market for interested parties. We have described the different actors of the framework and detailed their interactions and interest in it. The software components and ICT infrastructure enabling the deployment of the framework were also presented. This includes interaction with the Arrowhead core services, that facilitate integration into the Internet of Things. Finally, we have presented three pilots where the presented framework is currently experimented, that provides a perspective of its possible application in concrete scenarios.

Further work will first consist in consolidating the framework, trying to converge to a standardized approach to trading flexibility and finding synergies with similar approaches. This also includes the ongoing standardization process of the FlexOffer concept, as well as in the interaction between the actors, in collaboration with industrial partners to ensure feasibility of the approaches. The underlying ICT infrastructure is still ongoing further development, with a goal to release an open implementation of the framework providing all necessary services. Research in generation, aggregation and improvement of the flexibility market is also expected to continue to increase flexibility offered by FRs and Aggregators, thus strengthening the interest of the framework. Finally, the flexibility market will also be improved, both from a theoretical and application point of view.

Acknowledgements. This research was supported by the European project Arrowhead.

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