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IDEAS: Intelligent NeighbourhooD Energy Allocation & Supervision

Deliverable 3.2
Specifications for the neighbourhood energy management tool

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LIST OF ABBREVIATIONS

ACSI	Abstract Communication Service Interface
API	Application Programming Interface
AVB	Audio Video Bridging
CAN	Controller Area Network
CBS	Credit Based Shaper
COSEM	Companion Specification for Energy Metering
DER	Distributed Energy Resource
DLMS	Device Language Message Specification
DSL	Digital Subscriber Link
DSM	Demand Side Management
EMS	Energy Management System
EPN	Energy Positive Neighbourhood
EPNAS	EPN Addressing Scheme
EPNMS	EPN Message Specification
EPNSP	EPN Service Provider
ESCo	Energy Supply Company
EU	European Union
FTP	File Transfer Protocol
GCRA	Generic Cell Rate Algorithm
GOOSE	Generic Object-Oriented Substation Event
GPS	Global Positioning System
GSE	Generic Substation Event
GSSE	Generic Substation State Event
HIL	Hardware-In-the-Loop
HPC	High Performance Computing
HTTP	Hyper Text Transfer Protocol
HV	High Voltage
IEC	International Electro-technical Commission
IED	Intelligent Electronic Device
IET	Independent Energy Trader
IGMP	Internet Group Management Protocol
IOC	Intelligent Operations Centre
IP	Internet Protocol
ISND	Integrated Services Digital Network
ISP	Internet Service Provider
KPI	Key Performance Indicator
LAN	Local Area Network
LV	Low Voltage
MAN	Metropolitan Area Network
MMS	Manufacturing Message Specification
MV	Medium Voltage
NTP	Network Time Protocol
OSI	Open Systems Interconnect
PIM	Protocol Independent Multicast
PMI	Phase Measurement Unit
PTP	Precision Time Protocol
REST	Representational State Transfer
SIL	Safety Integrity Level
SMV	Sampled Measured Value
SSM	Supply Side Management
TCP	Transmission Control Protocol
UTC	Coordinated Universal Time
WAN	Wide Area Network
XML	Extensible Markup Language

EXECUTIVE SUMMARY

An Energy Positive Neighbourhood (EPN) has been defined as one in which the annual energy demand[1] is lower than energy supply from local renewable energy sources[2]. The IDEAS project aims to illustrate how communities, public authorities and utility companies across the European Union (EU) can be engaged in the development and operation of energy positive neighbourhoods and the economic and environmental benefits of doing so. The aim in an EPN is to provide a functional, healthy, user friendly environment with high energy efficiency and small environmental impact. Achieving EPNs will require co-ordinated and optimised demand side management (DSM) and supply side management (SSM) to reduce and shift peak energy demands and smooth out the inevitable production variability of renewable energy. To facilitate this, a supporting ICT infrastructure that provides a wide variety of interconnectivity options for measurement, control and user interface equipment (e.g. smart meters, synchrophasors, weather measurement stations, grid inverters, building automation controllers, energy trading applications, etc) is needed. The ICT infrastructure envisions a ‘smarter’ grid, to enable the buying and selling of energy between prosumers[3] connected via a local grid infrastructure. This grid infrastructure is smart - in that it not only allows for the physical transfer of energy - but also supports ICTs that enable information related to energy supply/demand availability and pricing to be exchanged, along with real-time information related to the health and status of the power flows.

After discussions to set the business context and identify the main functional and non-functional use cases to be explored in IDEAS, this deliverable presents specifications for an ICT-based neighbourhood energy management system (EMS). The report includes:

- Identification and categorization of the main communication traffic types to be expected within an EPN;

- Specifications for an Internet based ICT infrastructure to support EPN functionality;

- Specifications for an optimization and decision support tool for an EPN;

- Specifications for a set of simulated DERs that may be used to virtually augment the current capabilities of the demonstration sites in order to explore future possible behaviours.

At its most generic level, the ICT architecture that is proposed covers three separate domains. These three domains of operation are: (i) the local generation and distribution (field) domain, (ii) the customer domain and (iii) the web services domain. Relevant standards are leveraged in an attempt to provide a path towards common data semantics and protocols that may be used across these domains within the context of an EPN. Although the architecture is mostly internet and hence IP-based to exploit the standardisation that this protocol brings, recent advances in non-IP-based real-time streaming media protocols are also mapped to the low-latency fundamental EPN traffic types to provide a flexible yet predictable network bridging architecture suitable for use in the field domain.

Again at a generic level, the optimization and decision support tool provides several main types of operational functionality: (i) adaptive prediction of future energy supply and demand potential, (ii) access to current market conditions and predictions of future market conditions

[1] Energy demand of a neighbourhood includes the energy demand of buildings and other urban infrastructures, such as waste and water management, parks, open spaces and public lighting (Ala-Juusela et al. 2013).

[2] Renewable energy production includes solar, wind and hydro power, as well as other forms of solar energy, biofuels and heat pumps (ground, rock or water). However, biofuels must be locally produced, i.e. within a radius of 100 km (Ala-Juusela et al. 2013).

[3] A type of energy user who both consumes energy and who also can generate some energy is called a “prosumer”.

(e.g. energy prices), (iii) receding horizon optimization to balance supply and demand given the market conditions and (iv) additional decision support and dynamic pricing incentives to prosumers and utilities within the EPN.

The specifications described within this document will be used to create prototypes of the ICT – based optimization and decision support tools to be demonstrated in two neighbourhoods: a University campus in Bordeaux, France and a newly built residential area in Porvoo, Finland. In addition, a small additional prototype will also be created to test research-level aspects of the platform which are unsuited for full-scale deployment. As such, details of the specific configurations for each site have been given in as much detail as is possible at this stage of the project. A high-level overview of the inter-relationships and functionalities of the two main demonstration sites, along with the smaller additional prototype and an urban planning tool that has been specified to support infrastructure decisions related to long-term energy positiveness is shown in the figure below, along with the wider contextual domains of a *smarter energy grid* and *smarter city*.

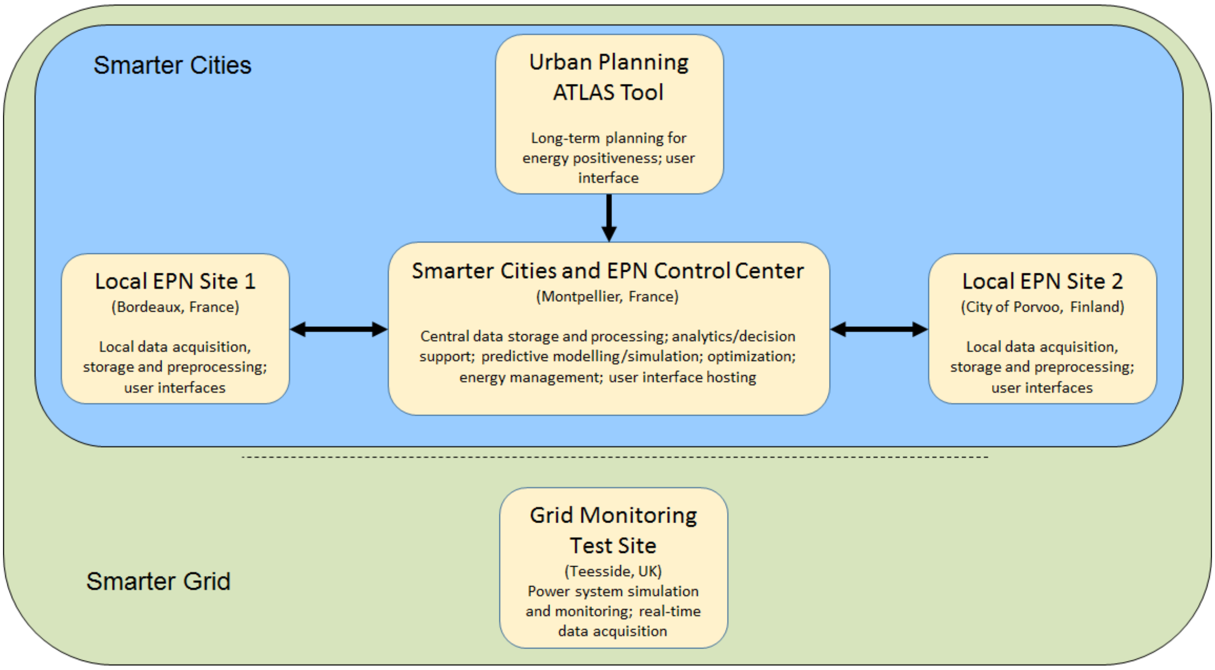

Figure I: High-level overview of demonstration sites, IT tools and functionalities in the IDEAS project

1 Introduction

1.1 Purpose and target group

The IDEAS project aims to illustrate how communities, public authorities and utility companies across the EU can be engaged in the development and operation of energy positive neighbourhoods and the economic and environmental benefits of doing so. To this end IDEAS will demonstrate how energy positive neighbourhoods can be cost effectively and incrementally implemented by designing, testing and validating:

- A neighbourhood energy management tool to optimise and balance energy production and consumption;
- User interfaces that engage communities and individuals in the operation of energy positive neighbourhoods;
- A decision support urban planning tool to optimise the planning of neighbourhood energy infrastructures;
- Business models to underpin energy positive neighbourhoods that engage end users, public authorities and utility companies.

The tools and business models developed will be demonstrated in two neighbourhoods: a University campus in Bordeaux, France (IUT) and a newly built residential area in Porvoo, Finland. This report presents specifications for a neighbourhood energy management system (EMS). Specifically, it includes details of requirements and specifications for an Internet-based ICT infrastructure, and an energy-related optimization and decision support tool residing in an EPN control centre. The report is mainly aimed at project partners involved in the prototyping (WP4) and operation / demonstration of the EMS (WP5). However, it also provides generic details that should enable the specifications to be adopted by external parties interested in the project. Therefore this document also facilitates the dissemination of the project.

1.2 Contribution of partners

UoT collated/edited the report and contributed much of the information it contains (Chaters 1, 2, 3, 4, and 5). Much of Chapter 3 is based on the many virtual and face-to-face meetings and discussions held by partners to define an ICT infrastructure that can be used across the demo sites, and the (non-functional) use case #12 was led by UoT. Most of Chapter 4 is based on the use cases created to capture the requirements of the demonstration sites, in particular functional use cases #5 and #8 which were led by UoT. Technical contributions, comments, recommendations and revisions to these use cases and the overall concept of the ICT infrastructure were made by most partners/subcontractors including, CSTB, POS, PE, VTT, NOBA, IBM-F and IBM-H. The stakeholders at both demonstration sites were also in the use case development. They took part in discussions and delivered presentations at the technical workshops and were involved in virtual and face-to-face meetings. IBM-F took a lead in the organization and co-ordination of many of the meetings undertaken to collaboratively develop and refine the specifications.

1.3 Relations to other activities in the project

This specifications document provides the main point of reference for the technical development effort of the EMS and ICT infrastructure elements of the project, specifically tasks T4.1 (prototyping the neighbourhood energy management tool), T4.3 (prototyping the user interfaces), T5.2 (pre-production tests: validating and debugging the tools and system for the Finnish Pilot) and T5.3 (pre-production tests: validating and debugging the tools and system for the French Pilot). The development of the specifications was informed by the work conducted in tasks T2.1 (business & community requirements analysis) and T2.2 (business models to underpin the demonstrations).

2 USE CASE IDENTIFICATION

2.1 Summary of main actors in an Energy Positive Neighborhood

In order to properly set the business context and describe the use cases that have been developed, it is first necessary to provide brief descriptions of the (main) actors that have been identified in an EPN in the context of real-time energy management.

Energy Management System (EMS): The EMS is an automated, interactive and reactive system providing services which assist the processes of energy trading, supply/demand matching and control / regulation of energy production, consumption and storage in an EPN. The EMS is operated by an EPN service provider in a central control center.

EPN Facilities Manager (FM): The EPN FM is responsible for ultimately making decisions related to aspects of energy management in an EPN, but is heavily supported by the outputs of the EMS. Although much of the operation of the EPN is expected to be automated, the FM should have a highly interactive role with the ability to override any automated behaviors as is deemed needed.

Wholesale Energy Market / Wholesale Energy Traders: A marketplace for the purchase and selling of energy by persons or companies (wholesale energy traders) involved with the trading of large quantities of energy on a near-real-time (balancing market) and/or day ahead (spot market) basis. A wholesale market provides the means for an EPN to buy or sell energy in large quantities.

EPN Residents: A person who resides some (or all) of the time within an EPN, and who may influence the energy balance (through production and/or consumption) in some way. A resident could be a private homeowner or an employee of a business within the EPN boundary. The EPN resident will also be supported in making energy-related decisions via the outputs of EMS optimization software, but may not choose to engage with the system and/or may have limited knowledge of energy-related topics: an adjustable level of interaction may be preferred. Transient visitors to the EPN may clearly also influence the energy balance, but are instead classified as IETs.

Independent Energy Traders (IETs): Independent energy traders can influence the energy balance of the EPN in a non-trivial way (through production and/or consumption), but does not necessarily reside within its boundary. An IET can buy from or sell energy to the EPN, even in small quantities (however, an IET must be involved in the physical delivery of energy in some way). An IET could, for example, be a visitor in a hybrid electric vehicle who wishes to sell some spare electrical energy. All EPN residents who produce or consume energy are therefore IETs, but the converse is not true.

Transmission System Operator (TSO): The TSO is ultimately responsible for maintaining safety and reliability of the wider power system that the EPN resides in. The TSO compensates for power flow imbalance by quickly activating pre-contracted (and normally expensive) backup power sources/sinks to maintain overall equilibrium. The TSO will retrospectively charge those parties whose deviations between contracted energy supply or demand commitments contributed to the imbalance.

The definitions of ‘EPN residents’ and ‘IETs’ are deliberately defined in a somewhat loose fashion in the above; the list could be further expanded to include, for example, home prosumers (residents), small & medium businesses (nursery), large organizations (cities), small and medium industrial sites, ESCo’s, etc. In IDEAS, only a small sub-set of these types of residents and IETs are addressed, please refer to IDEAS deliverables D2.1 and D2.2 for further specific details. In the following two sections, the key elements that influence the current report (in the sense of the business context and needs of the stakeholders which are present) that have been identified in these prior deliverables is discussed.

2.2 Business Context

The concept underpinning the EPN business approach is that energy is drawn from national grids only when there is an imbalance in neighbourhood energy supply and demand; or importantly, when it is more economically viable to buy or sell energy from/to the national grid. With the right pricing structure for renewable energy, as a neighbourhood becomes more energy positive it will rely less and less on national energy resources. On reaching energy positivity the surplus energy produced by an energy positive neighbourhood will be a source of revenue profit from intelligent energy trading with national grids. The key innovation in the IDEAS project is that it considers the potential offered by the wholesale energy trading to support the incremental implementation and financial viability of EPNs. In an EPN the amount of renewable energy generated within that neighbourhood is greater than the energy demand of the neighbourhood. However, it is not possible to provide the business, regulatory, cultural and urban environments required for EPNs 'overnight'. The approach adopted in IDEAS will support and adapt to the incremental rollout of the local energy infrastructures, energy efficient buildings and cultural and regulatory environments required for EPNs. It does this by ensuring that an energy service company (ESCo) – or a similar entity sharing many of a non-for-profit ESCo's characteristics - can increase the efficiency with which it buys energy, reducing the cost of that energy and increasing its profits, which the company or entity can then re-invest in improving the renewable energy infrastructures of the neighbourhood. This will naturally require government regulation to support pricing structures for locally produced renewable energy that support investments in local renewable energy generation. Henceforth, the EPN 'ESCo' will be referred to as the EPN 'Service Provider' in the understanding that it may be a true ESCo, a subsidiary of one, a community initiative backed by local or government investment, etc.

Achieving EPNs will require co-ordinated and optimised demand side management (DSM) and supply side management (SSM) to reduce and shift peak energy demands and smooth out the inevitable production variability of renewable energy. To help to facilitate this, the EPN service provider – who also owns or is capable of operating medium scale Distributed Energy Resources (DERs) - implements a service contract with customers which ensures that a variable price (which never exceeds more than a fixed and pre-agreed quantity of *P* Eur/kWh) is charged for energy consumed by the customers or provided by customer renewable resources. This model provides a trade-off in that on one the one hand, a tool exists for encouraging DSM and on the other hand, the customers are still able to budget for basic energy needs (heating and lighting of buildings, home cooking etc.) based upon knowledge of the worst-case price *P*. The conscientious customer may monitor for drops in the effective price, and - since the service provider is effectively not-for-profit – it is expected that not insignificant savings can be passed back to customers. In addition, the centralized service provider approach that is suggested actually provides an opportunity to standardise and more uniformly manage aspects of energy generation and distribution systems (the field and customer domains) which would normally be managed separately; this is discussed in more details in section 3. Please note that it also provides an opportunity to handle multiple energies for the same group of prosumers in one (or even multiple) EPNs.

In addition to 'independent' energy traders, in many cases the EPN would desire to partake in wholesale market transactions as such a market provides a larger domain to secure supply and offload excesses. One practical and significant issue that must be addressed in IDEAS relates to the minimum magnitude of energy transactions that are eligible to be placed on a wholesale energy market: they are normally at the MWh level (certainly within the EU). As such, the EPNs in both of the two demonstrations are not large enough to be able to effectively and eligibly trade wholesale. In IDEAS, the two main demonstration sites will explore two situations which reflect differing levels of integration between the traditional ESCo and the EPN service provider, and differing customer profiles within the EPN: two potential solutions to overcome this problem of insufficient market quantities during EPN 'startup' will be explored. In Finland, the EPN service provider is tightly integrated with a local ESCo that is itself very environmentally conscious. As such, it is willing to provide assistive services to the EPN: they are willing in principle to pass on wholesale spot market energy costs, even for small transactions, and include only a relatively small additive (subtractive) surcharge of O_s Eur/kWh to cover overheads for consumption (production). The EPN itself consists mainly of residential housing. In France, the service provider is more of a community initiative that lies as a buffer between a larger ESCo and the EPN. The ESCo currently provides a standard On Peak/Off peak fixed tariff, i.e. wholesale costs are not reflected in the prices offered to the EPN (this does not necessarily reflect unwillingness on behalf of such an ESCo, but more of a practical barrier in the real-time pricing is not a current business or technological option). The EPN itself consists of a number of buildings on a University campus.

These two demonstration sites thus consider realistic situations for a 'startup' EPN within the EU, and - since the underlying technical principles optimization and decision support enabled by an underlying ICT platform) remains consistent at both sites – it provides an opportunity to evaluate the effectiveness of the approach in both situations.

2.3 Tables of Identified use cases related to Energy Management

With respect to the identification of the required use cases, two distinct classes of requirements have been identified: functional and non-functional. The functional requirements and their related use cases describe the (mainly application layer) services that the platform is required to deliver to the principal end-users (optimization and decision support mechanisms, etc). The non-functional requirements and their related use cases describe the (mainly sub-application layer) services that the platform is required to possess such that the functional requirements may be delivered in a dependable fashion (configurability and timeliness of communication services, etc). The identified use cases and a short description of their rationale is given in the sub-sections below.

2.3.1 Functional use cases

A total of 10 functional uses cases have been identified for the IDEAS project. These use cases are listed in Figure 1 below. From this list, use cases #5, #6 and #8 (highlighted in yellow) are the main subject of this deliverable. For the remaining use cases, the interested reader is referred to IDEAS deliverables D3.3 and D3.4. Note that use case #6 is deeply integrated with use case #5 (it provides the user interface), so in the following the discussion centres mainly upon use case #5. Note that use case #10 is related to use case #8 in a similar way; please refer to D3.3 for further details. The justification and motivation for use cases #5 and #8 can be broken down into several key points.

Firstly, most European energy trading pools (such as the Phelix, Swissix, NordPool and EEIX markets) operate three short-term markets (a 24h-ahead blind or spot market, a real-time balancing market and a regulation market) for buying and selling energy. Spot prices are generally cheaper than real-time prices, and in order to make sensible decisions about buying, storing or selling energy it is of vital importance to have accurate predictions regarding the likely prices to be found in these markets over a short future horizon when balancing supply and demand in an EPN. Ergo, real-time predictive models are required. Secondly, when creating a planning for buying, storing or selling energy, some knowledge of the expected load demands and renewable supply availabilities is clearly needed. However since renewable resource availability is generally less stable when compared with traditional forms of energy production, detailed models incorporating key fundamental variables are needed. These key variables may be either a-priori unknown or time-varying (e.g. seasonal effects). As above, real-time predictive models are required. Finally, even when accurate information related to the points made above is readily available, the creation of an optimal (or near-optimal) strategy for buying, storing or selling energy to minimize financial costs, emissions costs or a weighted trade-off is effectively impossible to hand-calculate and keep up to date with changing environmental conditions. Some form of reactive optimization technique is clearly needed.

ID No.	Title	Description
1	Home Energy Management (Finnish pilot site)	This use case describes how to inform home residents about fine grain energy consumption in order to help them meet Energy Positive Neighbourhoods (EPN) energy supply objectives
3	City Planner Requires Decision Support for Energy Aspects in Urban Planning (Finnish pilot site)	This use case describes how the user of AtLas tool (a city planner in first place) compares the long term effect of two planning strategies regarding energy flows on the greenhouse gas emissions, costs and energy balance
4	Public Energy Awareness Interface for Omenatarha (Finnish pilot site)	This use case aims to engage residents of Omenatarha (Finnish pilot site) into the Energy Positive Neighborhoods goals through awareness feedback of the energy consumption of their (Energy Positive) Neighbourhood
5	Decision Support for Energy Trading for ESCOs and Supply/Demand Regulation (Finnish pilot site)	This use case describes how to carry out (i) prediction of future electrical energy consumption and supply within and EPN and (ii) optimization of available resources such that operational costs and/or CO2 emissions can be minimized subject to the balancing of supply with demand
6	User Interface for Energy Service Companies (ESCOs) (Finnish pilot site).	Visualising the decision support information for energy trading and configuration of the optimizer
7	Facility Manager Acquires Decision Support on Renovation Investments' Effect on Energy Balance of the Neighbourhood (French pilot site)	This use case describes how the user of ATLas tool (a facility manger in first place) compares the long term effect of two renovation investment options on the greenhouse gas emissions, costs and energy balance
8	Decision Support for Supply/Demand Regulation within EPNs (French pilot site)	This use case describes how to carry out (i) prediction of future electrical energy consumption by the IUT buildings and PV supply potential within the IUT campus area and (ii) optimization of available resources such that operational costs and/or CO_2 emissions can be minimized through arbitrage and storage, subject to the balancing of supply with demand
9	Educational 3D Virtual Space (French pilot site)	This use case describes shared 3D virtual space for demonstrating EPN concepts to interested visitors (IUT students and others). The idea is to provide remote visitors with a venue to learn about the IDEAS project, via an immersive rich collaborative environments without the need to actually visit the project pilot sites
10	Awareness Tools Dedicated to Energy Manager and Occupants of the Site (French pilot site)	An interface to better understand how the site consumes energy, electricity, gas, water to increase occupant awareness about energy and waste, and to visualise the output of the optimization

Figure 1: List of identified (functional) use-cases in the IDEAS project[4]

[4] There is no use case #2 as it was merged with use case #4; numbering left as-is for version control.

2.3.2 Non-functional use cases

In addition to the 10 functional use cases identified above, 2 further non-functional use cases related to energy control and management in the IDEAS project have been identified. They are listed in Figure 2 below.

ID No.	Title	Description
11	Control function update or addition in an IED (Teeside pilot site)	This use case describes how an IED may have its functionality dynamically updated or extended to match changing environment or grid conditions.
12	Communication flow update or addition (Teesside pilot site)	This use case describes how communication flows between IEDs and between IEDs and control centres may be dynamically updated or extended to match changing environment or grid conditions.

Figure 2: List of identified (non-functional) use-cases in the IDEAS project

The justification and motivation for this use case (and also #11 as they are closely interrelated) can be broken down into several key points. Firstly due to changed grid conditions or topology, an update (or deletion) of one or more control functions in an IED may be necessary for optimization and/or safety purposes; in turn, this may subsequently require that one or more communication flows are re-mapped (or deleted) for the same reasons. Secondly, it is nearly impossible to visualise all future needs for IEDs involved with control and monitoring functions embedded into a smart grid that is part of an expanding and evolving EPN. The ability to dynamically add new control functions is a necessity for a flexible smart grid for optimization and/or safety purposes; in turn, meaning that the ability to dynamically add new communication flows is also a necessity, for the same reasons. Note that, in non-critical and non-real-time situations, known techniques such as code-on-demand within a REST architecture using HTTP and TCP/IP sockets could be used to provide solutions to both these use cases. However since aspects of EPN operation involves power grid monitoring and control, some of its domain of operation is both real-time and critical. From this list, use case #12 (highlighted in yellow) is a main focus of this aspect of the non-functional behaviour. With respect to use case #11, the interested reader is referred to recent work by Strasser et al. (2013). Hence, as a part of specifying a suitable ICT infrastructure for an EPN, some consideration of re-configuration for communication channels over large areas of operation will need to be given as part of use case #12, for both critical and non-critical areas.

3 INTERNET BASED ICT INFRASTRUCTURE SPECIFICATIONS

3.1 Relevant Existing Standards

In this section, a very brief introduction is given to three existing sets of standards which are of direct relevance to the ICT infrastructure considered in this project.

3.1.1 IEC 62056: Smart Metering Interface Standards

IEC 62056 is a modern European meter protocol and is a superset of IEC 61107. IEC 62056 are a set of standards published by the IEC that define the electrical connections and interfaces and also the data exchanges that are necessary for meter reading, energy tariffs and load control. In terms of data exchanges, the standards describe both a Device Language Message Specification (DLMS) and a Companion Specification for Energy Metering (COSEM). IEC 62056 and its subset IEC 61107 are relatively simple standards, and are well-accepted and now widely used in the EU. The standards include details of how DLMS and COSEM may be mapped to TCP or UDP using standard IP. Clearly IEC 62056 can provide the required connectivity using standard IP technology for smart metering that is required for IDEAS.

3.1.2 IEC 61850: Communication Networks and Systems in Substations

IEC 61850 is the worldwide standard for substation communication and automation. The standard is targeted towards high voltage and medium voltage transmission and distribution stations and systems. Its communication is based on the Ethernet protocol using store-and-forward switches to increase determinism, and operates at communication rates of up to 100 Mbps. The main purpose of the standard is not to strictly define the lower level of a protocol stack, this is achieved through the use of the existing Ethernet standards, but to define application layer features (principally data semantics) so that intelligent electronic devices (IEDs) from different vendors can interoperate and communicate efficiently. The standard principally supports operation, control and automation of sub-station equipment, and has some facilities for monitoring and control by remote stations. The IEC 61850 communication architecture is given in Figure 3.

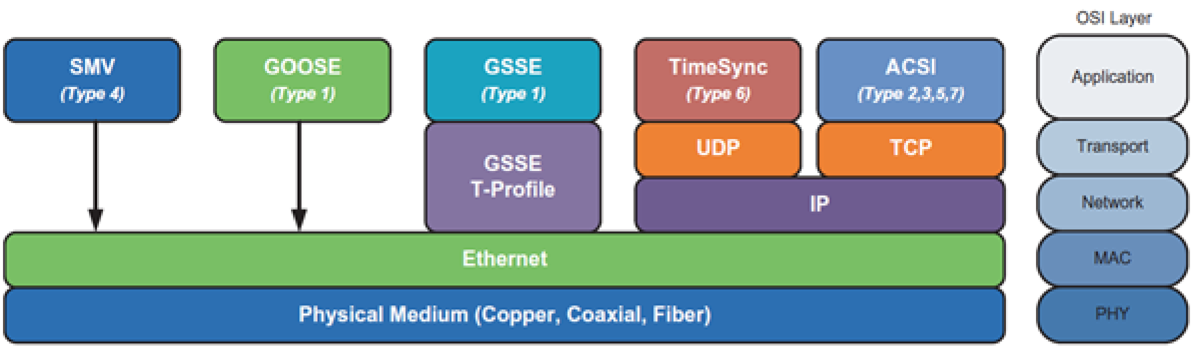

Figure 3: Communication stack mapping for IEC 61850 messages (Khan & Khan 2013)

As may be seen in the Figure 3, several of the IEC61850 traffic types are based upon IP protocols and internet technology. These types are generically defined as an Abstract Communication Services Interface (ACSI) that supports file transfers and other non-critical and high-level communication services. However, the communications architecture is only partially based upon ACSI: time-critical, low-level communications are also directly mapped into raw Ethernet frames using specific (non-IP based) protocols. These low-level communication types include GOOSE (Generic Object Oriented Substation Events), GSSE (Generic Substation State Events) and SMV (Sampled Measured Values). MMS (Manufacturing Messaging Specification) may also be mapped into the low-level communications, but MMS traffic is now generally transferred using standard TCP/IP (this is a revision to the original MMS specifications to improve easy of connectivity). The GOOSE type supersedes the GSSE type and is now becoming the preferred and dominant mapping in IEC 61850 (Brand et al. 2013; Khan & Khan 2013). GOOSE and SMV are both directly mapped into frames using ASN.1: BER (Basic Encoding Rules) and employ IEEE 802.1Q (Priority Tagging/VLAN) at layer 2 to achieve the desired fast response times. Ethernet v2 is employed at the physical layer, normally over fibre optic cabling to achieve very high noise immunity. Normally, the communication structure of the tagged, time-critical frames is simple enough that timing analysis using well-known techniques can be applied (Lee et al. 2006).

Of special interest to the IDEAS project is the recent proposal for an IEC 61850-7-420 Communications Standard for Distributed Energy Resources (DER). This extension to the basic standard is hoped to achieve a single international standard that defines the entirety of communication and control interfaces for all DER devices. Although much of the required DER interface traffic may be carried by internet protocols such as TCP/IP over a DSL or modem link, there is a lack of needed real-time support to export low-level signals in real-time. This real-time support is needed for power grid management and balancing; for example, worst-case message latencies for PMI signals (which are mapped into SMVs) are around 40 ms in a 50 Hz electrical system; clock synchronization between multiple PMIs (located in physically separate DERs) must be around be around the 1 μs level for measurements to be meaningful. Such real-time capabilities are clearly not achievable with standard IP technology over a MAN, WAN or DSL. In IDEAS, large elements of IEC 61850 will be leveraged using standard IP to provide the required interconnectivity for DERs; a solution to the problem of real-time traffic that may be suitable for multiple bridged LANs within an EPN in the form of the AVB protocols will also be investigated.

3.1.3 IEEE 802.1 AS/QAT/QAV/BA: Audio Video Bridging Standards

Audio Video Bridging (AVB) is a common name for a set of interrelated technical standards developed by the IEEE AVB Task Group connected to the IEEE 802.1 standards committee. The goal of the AVB standards is to provide the specifications that will allow time-synchronized low latency streaming services through IEEE 802 networks, and consists of four main elements:

IEEE 802.1AS: Timing and Synchronization for Time-Sensitive Applications (PTP). This standard describes how the best source of time in a LAN may be identified and distributed through the network to synchronize all end stations. When employed with suitably accurate clock sources, PTP enables fault-tolerant synchronization at sub-microsecond levels.

IEEE 802.1QAT: Stream Reservation Protocol (SRP). The SRP) is one of the core protocols required for AVB Systems. SRP is designed to allow the sources of AVB content (Talkers) to advertise that content (Streams) across a network of AVB Bridges, and users of the AVB content (Listeners) to register to receive the streams through AVB Bridges. Streams are only propagated through the network if there are enough resources to guarantee timely delivery of every stream packet. Once a stream is confirmed, VLANs along the route are automatically configured and bandwidth reserved.

IEEE 802.1QAV: Forwarding and Queuing for Time-Sensitive Streams (FQTSS). Once AVB streams are confirmed, some mechanisms are needed along the stream route to ensure timeliness is achieved and the reserved bandwidth is not exceeded. FQTSS defines the mechanisms by which this is enforced, and specifies a Credit Based Shaper (CBS) for online traffic shaping. The CBS uses information about the reserved amount of bandwidth for AVB streams, which is calculated by SRP.

IEEE 802.1BA: Audio Video Bridging Systems. Since the whole AVB scheme depends upon the participation of all devices between the talker and listener, any network element that does not support AVB must be identified and flagged. The procedures for this are defined in this standard.

Together, these standards define common QoS services for time-sensitive streams and mappings between different layer 2 technologies. They also enable a common endpoint interface for QoS regardless of the particular layer 2 technologies used in the path followed by a stream, effectively defining an API for QoS-related services that extended well beyond the transfer of audio and video (Teener et al. 2013). The principal end services that are offered to applications by an AVB network are two real-time streaming classes: the low-latency stream provides guaranteed end-to-end latency of 2 ms over 7 hops, and the medium latency stream provides guaranteed end-to-end latency of 50 ms over 7 hops. With appropriate enhancements to the domain of medium-scale energy generation and distribution, it is clear that AVB technology may be able to provide the real-time facilities for transporting low-level IEC 61850 traffic that are lacking in standard IP technology.

3.2 Internet-Based Infrastructure for Energy Management in EPNs

3.2.1 Generic Viewpoint

At its most generic level, the ICT architecture that is proposed covers three separate domains. These three domains of operation are: (i) the local generation and distribution (field) domain, (ii) the customer domain and (iii) the Web services domain. Distributed Energy Resources (DERs) exist physically in domains (i) and (ii), although they may exist indirectly (virtually) in domain (iii). Domain (ii) can be expected to contain a large amount of smart meters. Graphically, a simplified diagram illustrating the high-level view of the ICT interconnections between an EPN control centre, the DER components and the external services accessed through the internet is given in Figure 4 below. Note that, the EPN control centre is where the main optimization and decision support takes place; it is the main operating facility of the EPN service provider.

The field domain contains multiple DERs which may generate energy locally on a ‘medium’ (macro) scale, such as solar collector fields along with traditional forms of energy (e.g. coal or gas powered generators). This domain also contains high and medium voltage distribution and protection equipment, and possibly some heavy to medium industry. ICT connectivity is mainly provided by Local, Metropolitan and Wide Area Networks along with field-level automation networks such as CAN (Khan & Khan, 2013). In this domain, IEC 61850 is the standard of choice for automation and communication within each DER.

The customer domain contains homes, office buildings, small business and light industry which may have local generation on a ‘small’ (micro) scale. This domain also contains low voltage distribution and protection equipment. ICT connectivity is provided by (possibly bridged) Local Area Networks along with building automation networks such as KNX. In this domain, IEC 62056 is the dominating standard which is for communications with smart meters; however principles of IEC 61850 may still be present within the DERs.

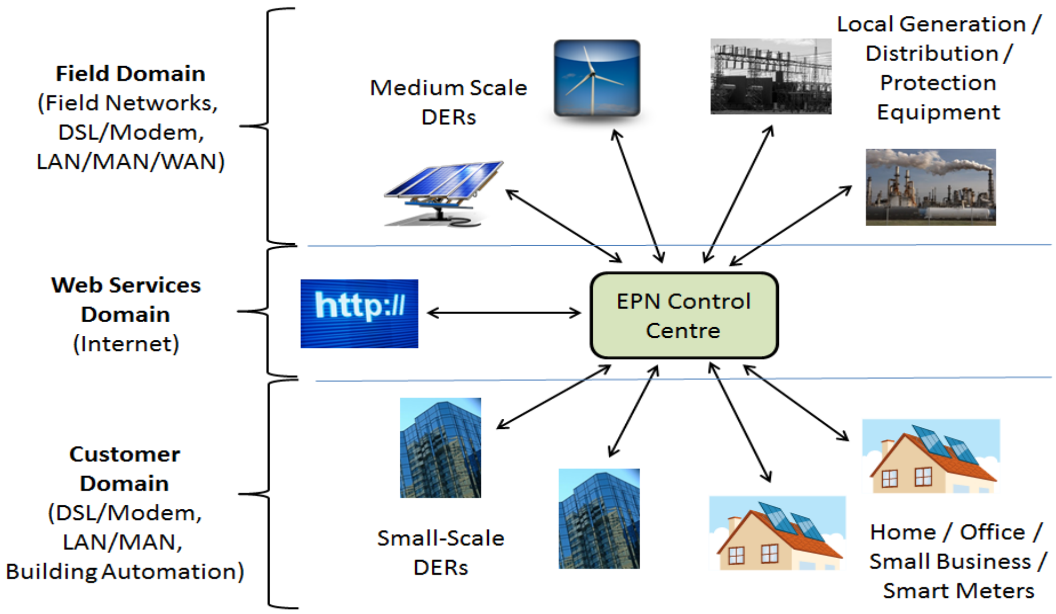

Figure 4: High-level ICT view of an EPN

The web services domain consists of a software and communication system that is designed to support interoperable machine-to-machine interaction over the internet. In the context of an EPN, we may consider that this domain provides a means for the EPN to leverage external services (weather forecast equipment, purchase of extra balancing energy from nearby DERs) that are not directly available through the equipment physically resident inside the EPN.

3.2.2 Dependability Constraints

Malfunctions of electrical power systems are capable of causing death, environmental damage and may have significant negative impacts upon the economy. Clearly, some consideration must be given to the dependability of the ICT infrastructure of an EPN. In the context of the current report, dependability can be thought of as a measure of a system's availability, reliability, maintainability and timeliness. In the following, we briefly describe the timeliness and availability requirements that must be imposed in an EPN; note that we only consider the ICT infrastructure that is involved in the management of the generated and consumed energy sides, understanding that at the non-energy sides (typically of generation e.g. Nuclear Reactors) may have much more stringent availability requirements (e.g. SIL 4).

DER Internal Domain: there are stringent hard real-time message latency requirements as messages are involved with management of mission- and safety-critical electrical infrastructure. Clocks must be synchronized to accuracy $\leq$ 1µs within the DER to concurrently manage events with high precision. Typically, applications will be SIL 1 (Fallaize et al., 2006), and have required continuous operation mode unavailability levels $\leq$ 0.00001.

Inter-DER Domain: there are firm real-time message latency requirements (occasional deadline misses and omissions may be tolerated) as messages are involved with management of a wider range of application services, including control and management of major mission-critical infrastructure (last-gasp safety interlocks for switchgear are handled locally within the DER according to IEC 61850; so these infrastructure elopements are not safety-critical, but still important). Unavailability levels between 0.001 to 0.00001 should typically be expected. Clocks must be synchronized to an accuracy of ≈ 1μs between DERs to concurrently manage distributed events (e.g. synchrophasor sampling) with medium to high precision.

Customer Domain: there are only soft real-time message latency requirements (best-effort traffic management is the only option and is oftentimes sufficient) as a full range of non-critical application services are used. There is no management of major mission or safety-critical infrastructure. Typically, applications will have required unavailability levels of ≤ 0.001. Clocks must be synchronized to an accuracy of ≈ 1s across the area to synchronise distributed events (e.g. reading of smart meters) with a low to medium precision.

3.2.3 The need for an EPN Message Specification (EPNMS) and EPN Addressing Scheme (EPNAS)

With reference to Figure 4 and the discussion above, it may be seen that the EPN control centre has to work with many different types of traffic, including existing and well-defined data objects (e.g. IEC 61850 process data), commonly encountered objects that yet have to be defined in a structured and accepted standardised way (e.g. for energy trading) plus any custom, EPN-specific data types that may be identified (e.g. for configuration). In addition, although much of the infrastructure is based upon IP, this does not cover the entirety of the domain and cannot provide a universal and uniform means to implement an addressing scheme within the EPN. Thus, it would seem to be requirement that to create (i) a standard EPN Message Specification (EPNMS) to define a generic container class that may encapsulate the expected types of data object in a structured way and (ii) create a standard application-level addressing scheme (that may be used with appropriate gateways) such that a uniform method can be employed to route these data objects to the appropriate destinations regardless of the underlying protocol stacks.

3.2.4 EPN Traffic Types and Classes

Based upon the above discussions, and taking on board previous analyses of smart grid traffic (e.g. Khan & Khan 2013), it is now possible to generically classify the types of network traffic that may be expected in an EPN, and this is given in Figure 5 below.

Message type	Application Services	Deadlines (ms)
1A	Fast message (trip): GSE / GOOSE	3–100
1B	Fast message (other): Control, monitoring	20–100
2	Medium speed message: ACSI (MMS)	100-500
3	Low speed message: ACSI (MMS)	≥ 500
4	Periodic raw data: SMV	3–100
5	File transfer: ACSI (DLMS/COSEM, EPNMS)	≥ 1000
6	Web services	≥ 1000
7	Time synchronization TS	(Required accuracy)

Figure 5: Network traffic types in an EPN

This table of message types may be divided into three different classes based upon their latency requirements. Class 'A' traffic corresponds to the low-latency class, and consists of types 1a, 1b and 4. Class 'B' traffic corresponds to the medium-latency class, and consists of types 2 and 3. Class 'B' traffic corresponds to the high/very high-latency class, and consists of types 5 and 6. Type 7 traffic may be in either class, depending upon the accuracy of synchronization that is needed.

3.2.5 Generic Solution for the Field Domain

The generic solution architecture that is proposed for the field domain is illustrated graphically in Figure 6. The solution architecture leverages the fact that since IEC 61850 is the dominant standard for automation within DERs and is widely accepted, one may expect that the ICT architecture within them is based upon one or more LANs implemented by switched Ethernet. Although TCP/IP may be used to provide connectivity and flexibility for Class C EPN traffic, some additional means must be leveraged to provide flexible support for Class A and B traffic. This support is provided by leveraging the flexible, low-latency streaming capabilities of AVB to implement a fibre-optic MAN backbone operating at 1 Gbps or more[5] that may be used to bridge together the DERs and the EPN control centre. As direct fibre-optic links using non-buffered repeaters may be used, the distances required in an EPN may be covered (note that AVB is not yet suitable for wireless operations; however this is part of the working group's plans for extension of the protocol). EPN Class A and B traffic may be mapped into the low- and medium-latency stream facilities of AVB, and gateways used to carry low-latency traffic classes into and out from a DER/sub-station. Since an AVB network also provides TCP/IP connectivity, this provides a flexible solution for the field side of an EPN that has the potential to provide the re-configurability required of use #12 even for low-latency traffic.

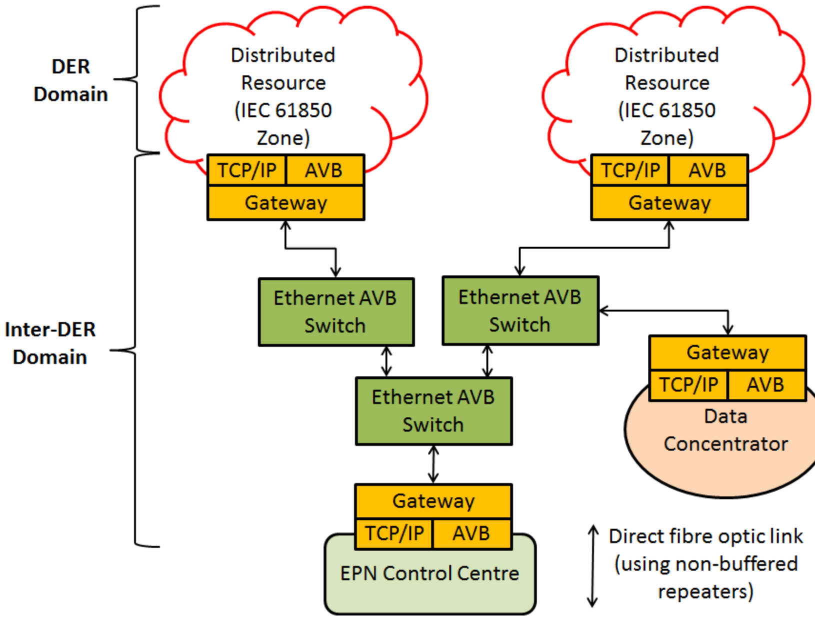

Figure 6: Generic ICT architecture solution for the field domain

3.2.6 Generic Solution for the Customer Domain

The generic solution architecture that is proposed for the customer domain is illustrated graphically in Figure 7. The solution architecture leverages the fact that most homes and small business nowadays have private internet connections that are typically implemented

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[5] Note that such fibre optic gigabit AVB switches are now commercially available: see for example, http://www.extremenetworks.com/libraries/solutions/avb_solution_brief.pdf [accessed Oct 2013].

via a fibre-optic backbone or a fast DSL/ISDN link operating at least 2 Mbps. TCP/IP may be used to provide connectivity and flexibility for Class C EPN traffic; UDP/IP and multicast protocols such as IGMP/PIM may be leveraged to provide flexible support for Class A and B traffic. However, such support is not likely to achieve the low-latencies required for these latter traffic classes as no timing guarantees can be obtained from commercial ISPs. Instead, such traffic must be operated in a soft real-time mode, which – given that customer side DERs are normally low-voltage and non-critical - may be suitable in most cases. In the IDEAS project, this aspect of the ICT platform is not investigated in depth and is mainly left for future work.

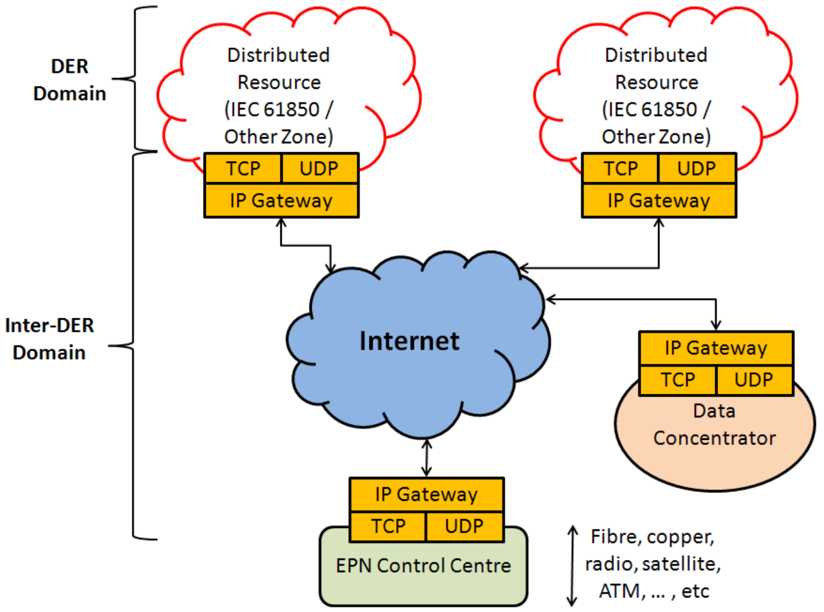


Figure 7: Generic ICT architecture solution for the customer domain

3.3 Implementation for the IDEAS Project

As mentioned, the two main demonstrating sites for the IDEAS project are located in France and Finland. In addition, there is another smaller demonstration site implemented in the UK for testing some of the communications concepts defined in section 3.2. Before detailing the specific ICT layouts and extensions needed at each site, some generic implementation specifications are described. Note that the following legend is used for IT interface diagrams:

3.3.1 Generic Specifications for all Demo sites

3.3.1.1 Implementing the EPN Control Centre: The IOC

Many organizations require efficient operational supervision and coordination. All have in common the need for the right information to be brought together so that the right people can make fast, accurate decisions and track the effect of those decisions. IBM® Intelligent Operations Centre is a software solution that is designed to facilitate effective supervision and coordination of operations. Authorities face common challenges in their core systems and in making improvements to systems that are interconnected. Authorities that are forward-looking want to use the improvements in efficiency and effectiveness of smarter core systems. They adopt new ways of thinking about and using these systems. The application of advanced information technology can help authorities better understand, predict, and intelligently respond to patterns of behaviour and events. For example, an intelligent city is defined in terms of the improvements in quality of life and economic well-being that are achieved through applying information technologies (IT) to plan, design, build, and operate the city infrastructure. An intelligent city is not primarily about "the latest technology." It is about finding ways to use technology to make the most effective use of the existing resources, to improve the life of the citizens of the city.

IBM Intelligent Operations Center (IOC) uses the power of the real-world data that is generated by computer systems by performing the following main tasks:

- Collecting and managing the right data;
- Integrating and analysing that data;
- Facilitating easy and timely access to information;
- Presenting related information in a coherent way.

An operation can be divided into individual domains, which generally match with the organization structure and the expertise of the people involved. In a city, the expertise is held in departments, for example, in transportation, energy, water, public safety, urban and space planning. As the complexity of operations in a domain increases, a more customized solution is required. IBM Intelligent Operations Center has a number of different integration points where customization can take place to build a broad and powerful solution for multiple actors. In IDEAS, the IOC is not only the data repository for most data (city and sites data, energy management and urban planning ones), but also a strong analytics, optimisation and decision support system. It also provides user interfaces, notifications and reporting capabilities that can be leveraged by all partners and used by all end users.

In the context of this specific deliverable, the IOC provides a central control centre to implement the EMS, and the following main features are to be used: database and data management, geographical information systems, web hosting and internet interfaces, performance metrics/analytical engines and optimization tools. Please refer to Figure 8 for an overview of the IT infrastructure of the EPN control centre.

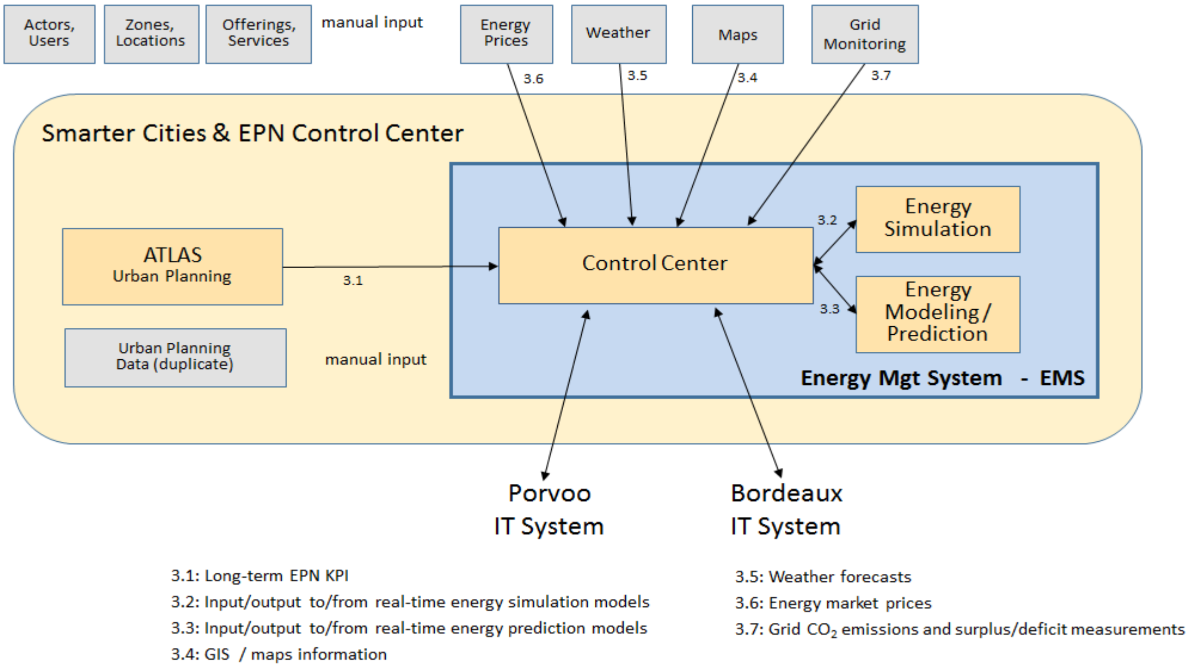


Figure 8: IT interfaces at the IBM-F control centre

3.3.1.2 IOC REST API

In order to realise and manage the remote interface capabilities required for the demonstrations, the IOC Representation State Transfer (REST) Application Programming Interface (API) will be employed. The REST API may be implemented using a standard HTTP connection via TCP/IP. General details of the API may be found from: http://pic.dhe.ibm.com/infocenter/cities/v1r6m0/index.jsp?topic=%2Fcom.ibm.ioc.doc%2Frest_overview.html. Note that the database elements described in the various appendices will be exposed via this interface, with appropriate permissions granted to the various partners and their respective ICT equipment during prototyping.

3.3.1.3 EPN Message Specification

The need for an EPNMS and EPNAS was discussed in section 3.2.3. For the French and Finnish demonstration sites, IP addressing suffices to implement all aspects of the ICT infrastructure. Although it is beyond the scope of the IDEAS project to provide a fully working specification for EPN messages, some initial considerations for a common semantics for Energy Positive Neighbourhoods is suggested by providing an initial high-level mapping of the required data objects into a common EPN data object. An incomplete high-level viewpoint of the required encapsulation is shown in Figure 9 below:

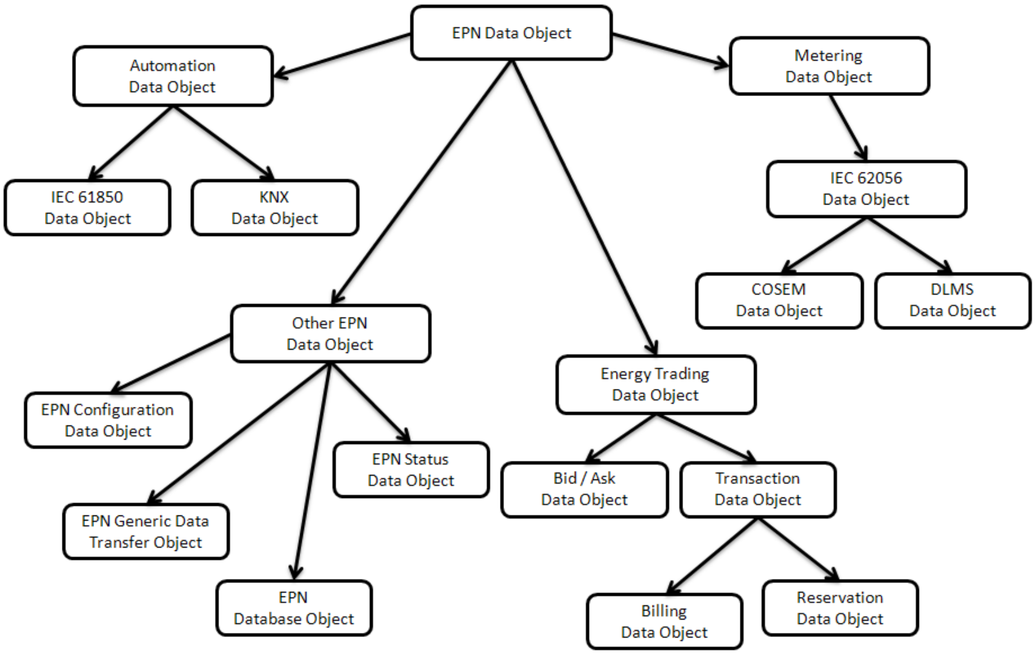


Figure 9: Initial overview of data objects required in an EPN

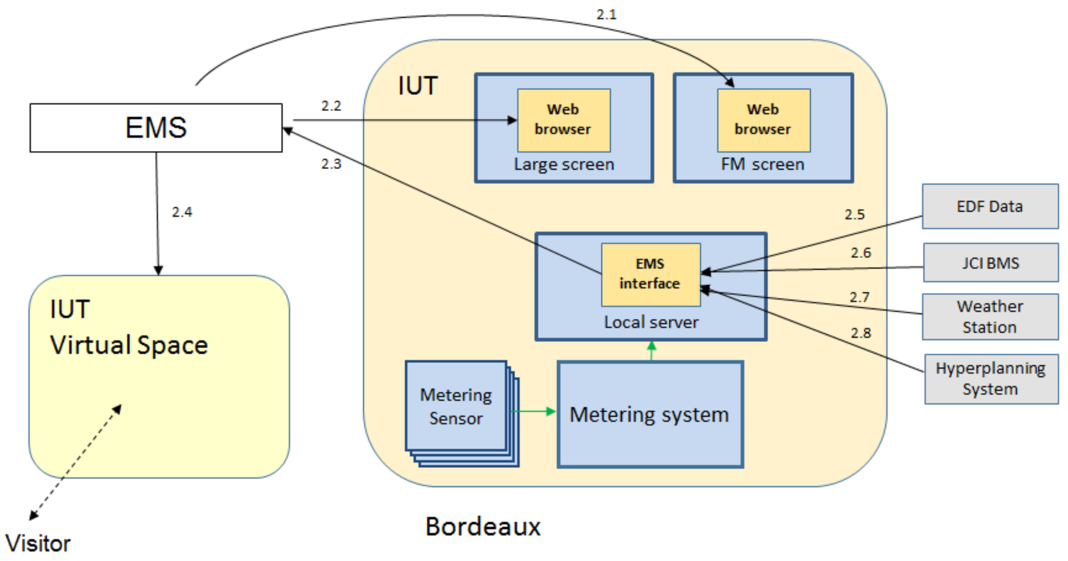
In Appendix 'A' an XML-based specification for containing EPN database read/write request objects along with a file naming convention suitable for the IDEAS project is given. This is used to transfer data between demonstration sites where the REST API of the IOC is not suitable to be employed directly. Although this is a simple (but functional) approach, it is easy to observe how it may be extended to cover other objects, and adapted to provide a suitable hierarchical approach.

3.3.2 Description of the French demo site

This demonstration site is intended to provide a suitable platform to explore how aspects of use case #8 may be implemented within an EPN.

3.3.2.1 ICT Infrastructure

The overall ICT architecture employed at the French demo site is as shown in Figure 10.



2.1: EMS status and summary information for FM interface
2.2: EMS status and summary information for IUT public display
2.3: (Energy, Weather, Occupancy) hourly information summary
2.4: EMS status and summary information for IUT virtual space
2.5: Energy measurements (summary data: retrospectively from EDF server)
2.6: Information from JCI BMS (interface reserved for future expansion)
2.7: Information from local weather measurement station
2.8: Occupancy information from IUT hyperplanning system

Figure 10: IT Infrastructure at the French Demo site

With respect to Figures 4, 7 and 8, the main elements of this demo site may be viewed as: (i) an EPN control center located at IBM-F; (ii) customer domain smart meters, (iii) a weather measurement station, (iii) a building occupancy planning system and (iv) a local server (data concentrator) for local interface to items (ii)-(iv) hosted by NOBA.

3.3.2.2 Specific Requirements

1) Data transfers shall consist of only EPN class C traffic (file transfers, web services).
2) IP addressing is sufficient to be used.
3) The REST architecture (implemented via HTTP) and FTP will be used to implement the data transfers via TCP/IP.
4) Clocks at the NOBA and the IOC sites will be synchronized to UTC +/- 0.5 second using NTP.
5) All sites will use the same time server (TBC) for this synchronization.

3.3.2.3 Protocol Stack

The required protocol stack (with reference to the 5-layer ‘internet’ version of the OSI 7-layer model) for the EMS and the EMS local server is as shown in Figure 11 below. Note that at this time, it is not known how the interfaces (2.6-2.8 in Figure 10) shall be implemented due to a lack of information. This will be investigated and solved during prototyping.

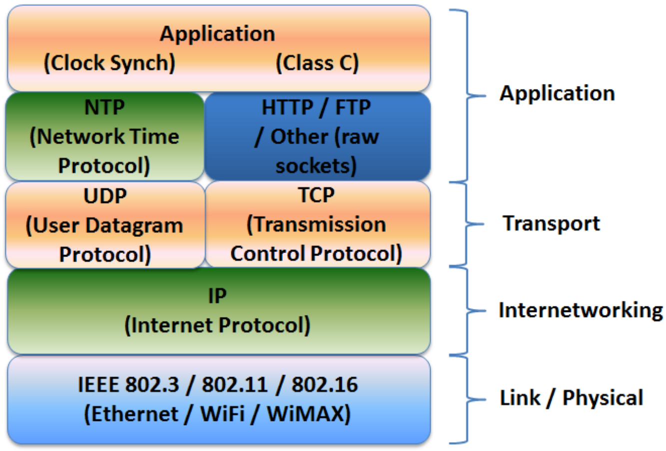


Figure 11: Protocol stack for the French (Finnish) Demo site

3.3.3 Description of the Finnish demo site

This demonstration site is intended to provide a suitable platform to explore how aspects of use cases #5 may be implemented within an EPN.

3.3.3.1 ICT Infrastructure

The overall ICT architecture employed at the Finnish demo site is as shown in Figure 12.

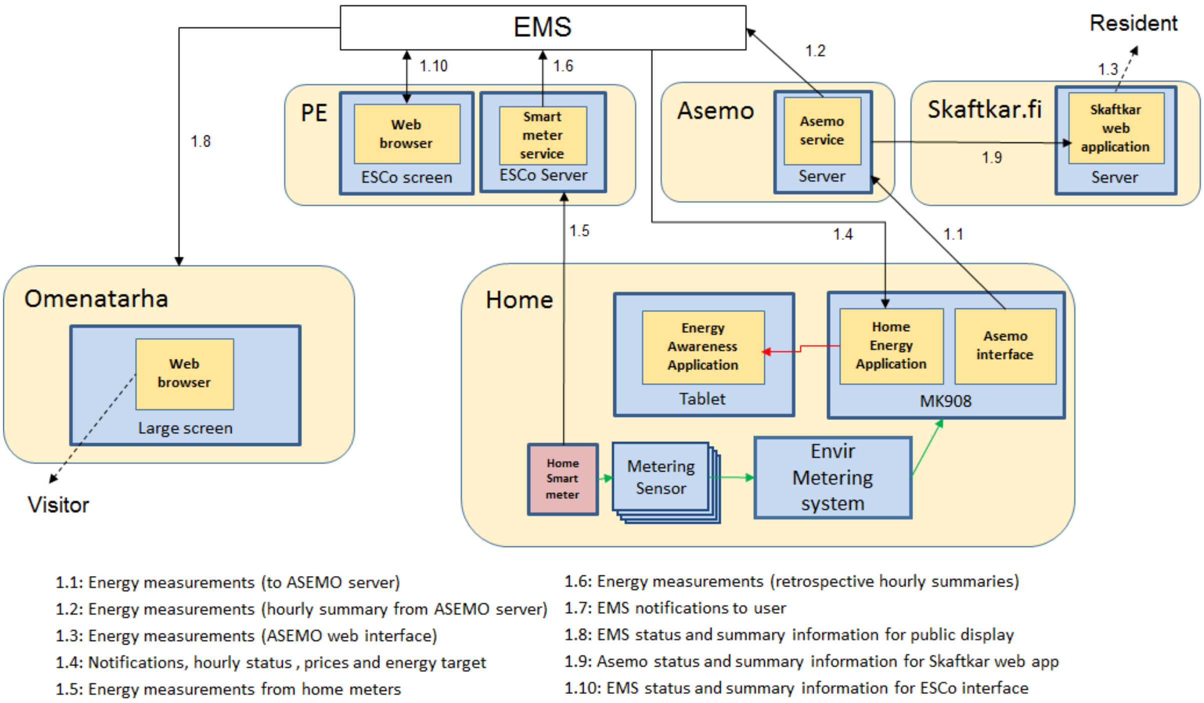


Figure 12: IT Infrastructure at the Finnish Demo site

With respect to figures 4, 7 and 8, the main elements of this demo site may be viewed as: (i) an EPN control center located at IBM-F; (ii) customer domain smart meters connected to data concentrators hosted by POS and PE and (iii) a home energy application embedded in each of the residents' homes.

3.3.3.2 Specific Requirements

1) Data transfers shall consist of only EPN class C traffic (file transfers, web services).
2) IP addressing is sufficient to be used.
3) The REST architecture (implemented via HTTP) and FTP will be used to implement the data transfers via TCP/IP.
4) Clocks at the PE, POS and the IOC sites will be synchronized to UTC +/- 0.5 second using NTP.
5) All sites will use the same time server (TBC) for this synchronization.

3.3.3.3 Protocol Stack

The required protocol stacks (with reference to the 5-layer 'internet' version of the OSI 7-layer model) is to be the same as shown in figure 11.

3.3.4 Description of the UoT demo site

This demonstration site is intended to directly explore how aspects of use case #12 may be implemented for class A, B and C traffic within an EPN. In addition, it may be observed that the *specific* ICT infrastructure employed at the two main demo sites (standard 'best effort' connections using home/leased internet connections) may not be scalable to larger EPNs, but merely provides a-proof-of-concept platform for demonstrating the developed functional tools. To address this issue the potential of AVB and 3G/4G technologies are being investigated to provide re-configurability and scalability over the entire EPN domain: AVB provides a potential means to also maintain predictability in the field domain, whilst wireless 4G technology (or advanced 3G if not available) provides a potential means to quickly and efficiently gather remote smart meter data without relying on home/leased internet connections without installing new cabling (Anderson, 2010).

3.3.4.1 ICT Infrastructure

The overall ICT architecture employed at the UoT demo site is as shown in Figure 13.

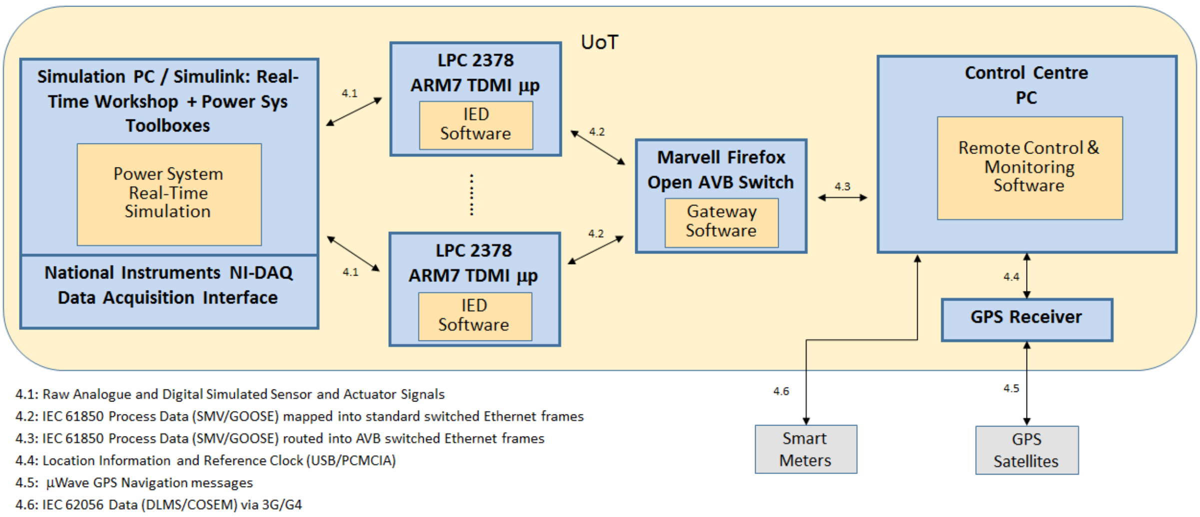


Figure 13: IT Infrastructure at the UoT Demo site

With respect to figures 4 and 6, the main elements of this demo site may be viewed as: (i) a simplified EPN control center implemented on a PC; (ii) a PC-based environment for the real-time simulation of multiple DERs and distribution / protection equipment, (iii) a wired communications infrastructure based upon standard Ethernet and AVB-based packet switched Ethernet links, (iv) a high-precision GPS radio clock, (v) a number of test smart meters located physically off the UoT site and (vi) a wireless communications infrastructure based upon 3G and/or 4G technology. Note that the basic equipment setup is shown in the above; the test facility is flexible in that the amount of IEDs, gateways and externally located smart meters may be modified to suit the particular scenario or scenarios under test.

3.3.4.2 Specific Requirements

1) Data transfers shall consist of EPN class A, B and C traffic.
2) Class C traffic will be implemented via raw TCP/IP sockets.
3) Clocks between physical devices in the field domain will be synchronized to UTC +/- 0.5 µs using PTP.
4) A single GPS radio clock will be employed as the 'grandmaster' for this synchronization.
5) Class A and B traffic will be dynamically mapped into AVB streams to be transferred into the EPN control center.
6) Clocks between physical devices in the customer domain (the test smart meters) will be synchronized to UTC +/- 0.5 second using NTP (the main server for this synchronization is TBC).
7) A specialized time-series database[6] will be hosted on the control center PC for gathering and storing the generated data.
8) Connections to the off-site test smart meters will be implemented via 3G or 4G wireless broadband technology.

3.3.4.3 Protocol Stack

The main additional protocol stack (with reference to the 5-layer 'internet' version of the OSI 7-layer model) that is required for the transfer of class A and B traffic is as shown in figure 14 below.

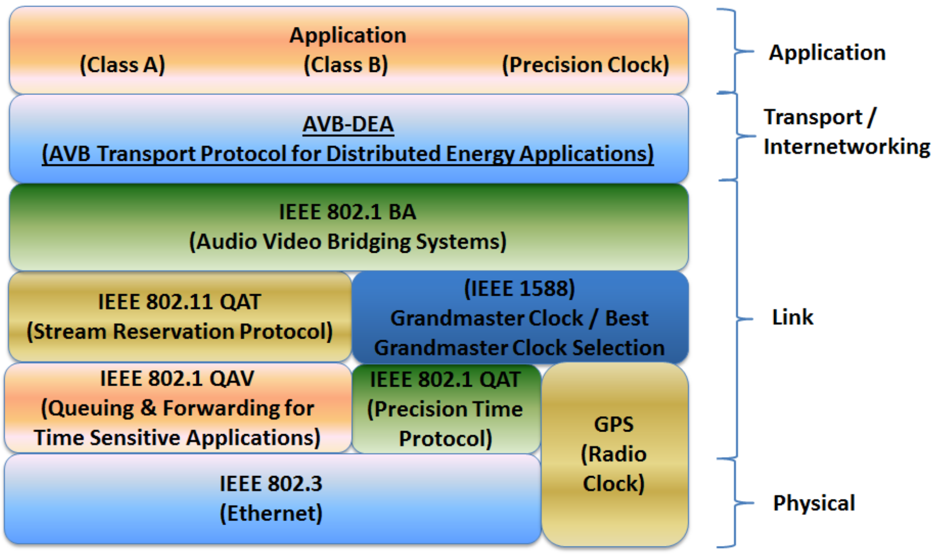


Figure 14: Additional protocol stack for the UoT demo site

The AVB-DEA element of this protocol stack is required to be created during prototyping. At this stage, the full specification of this layer of the protocol stack cannot be stated clearly and unambiguously as research is needed to examine the exact requirements it must possess. Research prototyping will be employed for this development. However it can be stated that the services that must be exposed to the application later include:

[6] At the time of writing, it seems that the Apache 'Cassandra' database seems most suited to this purpose, see: http://cassandra.apache.org/ [Accessed Oct 2013].

1) A transparent high-precision clock interface to provide local timing control to drive the scheduling of critical activities;

2) A means to dynamically map EPN traffic types from Class A and Class B into low- and medium-latency AVB streams and to both advertise and discover these EPN class streams;

3) Ingress and egress temporal firewalling and security and integrity checking.

In particular, prototype gateways will be constructed using the protocol stacks to test these basic services and provide a working interface between two IEC 61850 switched LAN sub-domains and an EPN control center implemented as an embedded PC. The suggested structure of such a remotely configured gateway is as shown if figure 15. TCP/IP and EPNMS will be used in combination to allow the remote configuration of the gateways in order to meet the needs of use case #12. Temporal firewalling will be implemented in the form of Generic Cell Rate Algorithms (GCRAs) operating as ‘leaky buckets’ to prevent the arrivals of any erroneous messages creating an instantaneous network load that is beyond its stated requirement (Le Boudec & Thiran, 2012). The simulated power grid is employed for the purposes of Hardware-In-The-Loop (HIL) testing of the embedded communication system using specific scenarios that will be developed and fine-tuned during prototyping. HIL testing has been found suitable for a wide variety of applications, including critical ones (e.g. transportation and nuclear, e.g. see Short et al. 2008) and hence should provide a suitable environment for the testing and evaluation dependable smart grid communications.

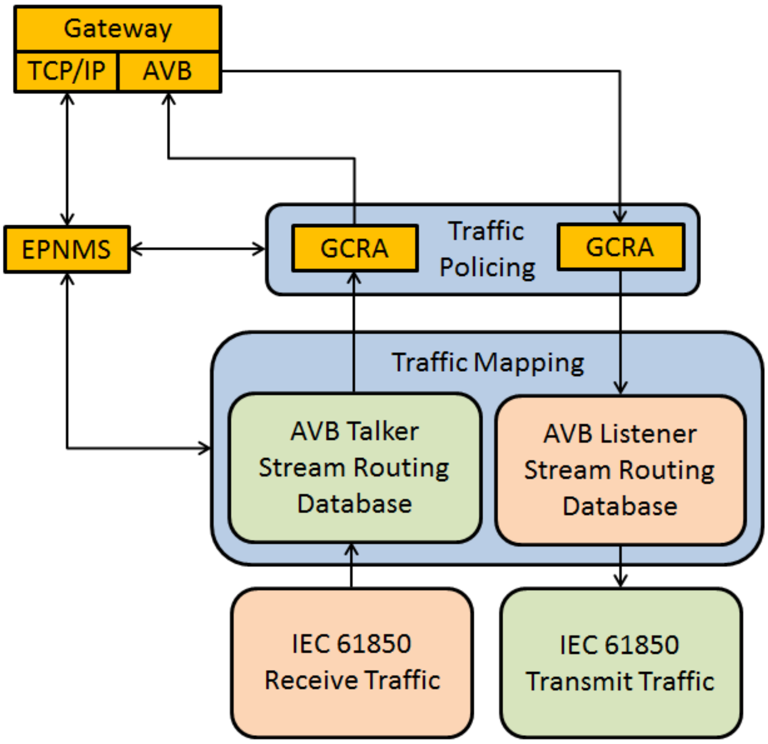


Figure 15: Suggested AVB / IEC 61850 Gateway

4 OPTIMIZATION AND DECISION SUPPORT SYSTEM SPECIFICATIONS

4.1 Generic optimization and decision support architecture for EPNs

Recall from section 2.2 that that one of the key goals of the EPN service provider is to (i) increase profitability within an EPN such that further investment in renewable technologies may be enabled and (ii) co-ordinated and optimised demand side management (DSM) and supply side management (SSM) will be used to help achieve this. The generic approach shown in figure 16 below shows how the real-word data and predictions will be used for optimisation and decision support. In the IDEAS experimentation, it is not planned to handle direct automation with the home prosumer appliances and other related equipment, but this concept could easily be considered as a part of future projects within this general framework.

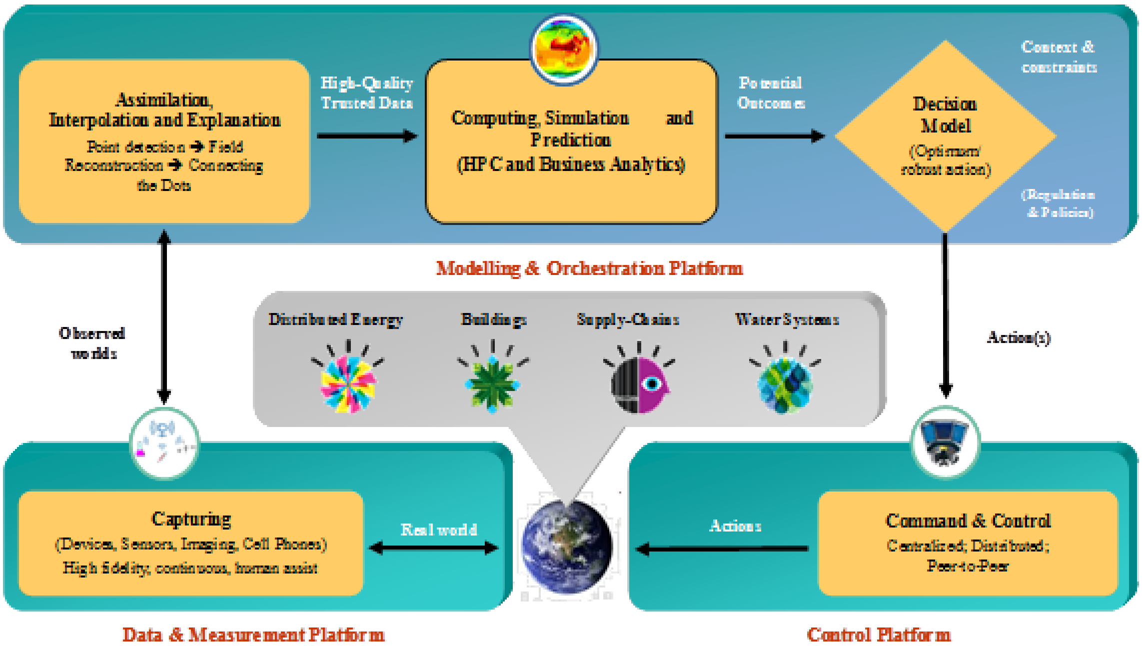


Figure 16: Generic Optimization and decision support architecture for EPNs

Next, consider that in the context of IDEAS, (i) a diverse array of resources and persons reside within an EPN and hence consumption, production and external energy pricing patterns vary considerably over time and that (ii) to effectively operate in wholesale energy trading markets, one needs to plan ahead and schedule sales and purchases as accurately as possible at least 24 hours before the time of physical delivery. As such, in IDEAS the concepts of adaptive control (to track and adapt to changing conditions and supply/demand trends within an EPN) and receding-horizon predictive control (to predict - at regular intervals - the future evolution of the EPN energy balance and re-calculate optimal corrective strategies) will be employed. For general information on the topics of adaptive and predictive control in industrial settings, the reader is referred to the definitive texts of Camacho & Bordons (2004) and Astrom & Wittenmark (1995). Based upon these concepts, the generic structure of the optimization and decision support system operating upon the ICT infrastructure within the EPN control centre is as shown in figure 17 below:

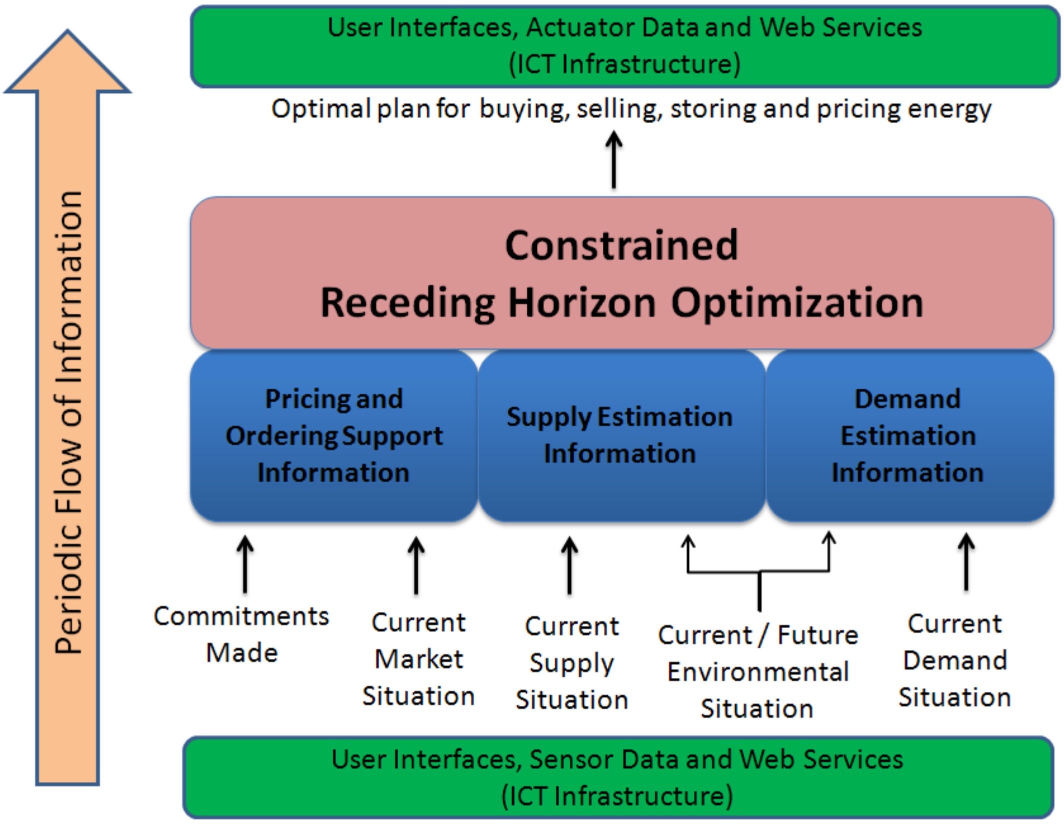


Figure 17: Optimization and decision support architecture for EPNs

As can be seen in the above figure, the data flow is periodic; note that it presents a 'special case' of the generic concept presented in figure 16. The operations highlighted in figure 17 may be split in to five distinct phases: (i) the data acquisition (DAQ) phase, (ii) the prediction (PRE) phase, (iii) the optimization and decision support (OPT) phase and (iv) the post processing (POS) phase and (v) the data distribution (DIS) phase. In the DAQ phase, the ICT platform is employed to acquire measurements of the current state of the EPN. During the PRE phase, these current and historical state measurements are employed to predict the future energy supply and demand evolution in the EPN, along with any other variables of interest such as future spot market prices. During the OPT phase, the optimal corrective strategy to balance supply and demand using the available options for storing, buying or selling energy is determined. During the POS phase, data post-processing, decision support information and KPI calculations are performed. The solution and post-processed data is then distributed or made available during the DIS phase. Housekeeping actions may be performed before or during any of the stages. Note that the optimal solution information may be *automatic* in nature (in that the ICT platform is used to automatically send machine to machine commands directly to DERs, or it may be *manual* in nature (in that information is presented to the relevant persons to help support their manual decisions). It is the latter manual aspects of decision support that will be the subject of the two main demonstrations in France and Finland.

Notations for the timings of the five stages are as shown in figure 18; the color employed in each the five stages in the figure loosely corresponds to the color of the relevant part of the periodic flow shown in figure 17. T_{Loop} represents the fixed time interval between the start times of successive cycles; T_{Off} represents a fixed offset (+ve or –ve phase shift) of the first cycle start time from the UTC 00:00 reference hour on the first day of operation. T_{DAQ}, T_{PRE},

T_{OPT}, T_{POS} and T_{DIS} represent the worst-case length of time the system should dwell in each of the corresponding cycle phases in order to ensure synchronized deliver of data at the end of the DIS phase.

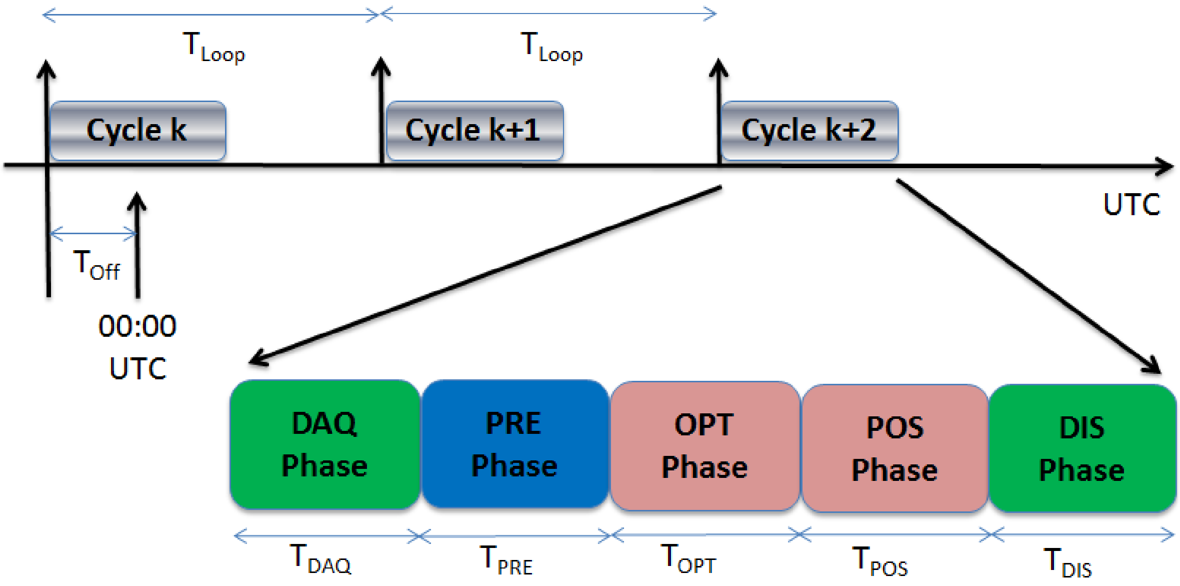


Figure 18: Phases and timings of the optimization loop

4.2 Implementation for the IDEAS Project

In this section, configuration and implementation specifications for the main optimization and decision support reference architecture are given for both of the demonstration sites. It is assumed that a central database that is capable of storing, indexing and querying discrete time-series data at a varying level of granularity (hourly, daily, weekly and monthly) is available. As such, an overloaded variable notation is employed in the following descriptions. A time-series is indicated by employing a time index '()' after the variable in question to give reference to a particular column. If the current cycle corresponds to hour *h* on day *d* of week *w* and month *m*, then the following notation is employed for this index:

$V(h)$ refers to the value of the variable V during the current hour, $V(h\text{-}1)$ the value of the variable V during the previous hour, and $V(h+1)$ the value of the variable V during the next hour.

$V(d)$ refers to the value of the variable V during the current day, $V(d\text{-}1)$ the value of the variable V during the previous day, and $V(h+1)$ the value of the variable V during the next day.

$V(w)$ refers to the value of the variable V at the current week, $V(w\text{-}1)$ the value of the variable V during the previous week, and $V(w+1)$ the value of the variable V during the next week.

$V(m)$ refers to the value of the variable V during the current month, $V(m\text{-}1)$ the value of the variable V during the previous month, and $V(m+1)$ the value of the variable V during the next month.

Noting that at the current time, measured data is not explicitly available for future timeslots, and this data shall be interpreted as *predicted* data with the method of prediction stated. It should be understood that, if a variable is stored and indexed at multiple levels of granularity, then the type of index (*h*, *d*, *w* or *m*) that is used in the textual reference implicitly indicates the intended level of granularity; when defined, the principal data stream is indicated in bold and underscored. Where appropriate, if there are specific relationships between different levels of granularity (e.g. daily averages formed from hourly time-series data), then the calculation method between the principal data stream and the others will be stated. Where a variable has multiple rows, the row index will be enclosed in square brackets '[]'. Row indices are assumed to start from 1. Where time-series data storage is not needed (e.g. for live data requiring no historical storage), the time index '()' will be omitted.

4.2.1 Generic Specifications for all Demo sites

Please refer to Appendix D for details of the virtual resources that will be implemented and used for both demonstration sites. Note that it is expected that these simulation models will be updated periodically, with a cycle period of 15 minutes. For details of the EMS user interfaces for the French demonstration, please refer to IDEAS deliverable D3.3, and for the EMS user interfaces for the Finnish demonstration, please refer to Appendix E.

4.2.2 Specific requirements for the French demo site

Please refer to Appendix B for the specific details of how the prediction, optimization, data management and housekeeping are to be carried out.

4.2.3 Specific requirements for the Finnish demo site

Please refer to Appendix C for the specific details of how the prediction, optimization, data management and housekeeping are to be carried out.

5 CONCLUSIONS

5.1 Contribution to overall picture

This report has presented specifications for a neighbourhood EMS. Specifically, it has included details of requirements and specifications for:

- An Internet-based ICT infrastructure;
- An energy-related optimization and decision support tool.

The report is mainly aimed at project partners involved in the prototyping (WP4) and demonstration (WP5) of the EMS to help facilitate its implementation.

5.2 Impact on other WPs and Tasks

This specifications document should provide the main point of reference for the technical development effort of the EMS and ICT infrastructure elements of this project during prototyping and implementation (WP4) and demonstration and validation (WP5). Therefore the details described in this document are the base for many of the coming activities in the IDEAS project, specifically tasks T4.1 (prototyping the neighbourhood energy management tool), T4.3 (prototyping the user interfaces), T5.2 (pre-production tests: validating and debugging the tools and system for the Finnish Pilot) and T5.3 (pre-production tests: validating and debugging the tools and system for the French Pilot).

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7 Appendices

7.1 Appendix A: A simple EPN Message Specification for the exchange of simple database objects in the IDEAS project

7.1.1 Message ID / Filename Encoding

All messages are encoded into simple XML files containing a specific unique message identifier, which also appears in the filename. Identifiers are encoded with (i) a unique ID associated with the originating client, (ii) a stamp of the day (01-31), month (01-12) and year (00-99) which the file was created, (iii) an integer sequence count for that particular day and (iv) a code appended by the server indicating if the message was generated in response to a client request or error detected. The sequence counter in each client is reset to 1 at the start of each new day, and is incremented following every file that is created at that particular site on the day in question. With this encoding, message IDs should be unique and provide some traceability.

The following filenames are employed (where dd = day, mm = month, yy = year, ss = sequence count):

For data generated by the ASEMO/PO client system: PO_ddmmyyss
For data generated by the PE client system: PE_ddmmyyss
For data generated by the NOBATEC client system: NB_ddmmyyss
For data generated by the UoT client system: UT_ddmmyyss
For data generated by the IOC server system: IC_ddmmyyss

For example, the 25th data file sent from the ASEMO/PO system on 15th June 2013 is encoded as an XML file with the filename "PO_15061325.xml". Simple security and authentication can be added if needed, such as basic encryption and/or authentication with HTTPS.
Note that, in most situations the IOC server system will be generating responses to client requests and will not generate its own identifier; however it may generate messages (e.g. status transfers) asynchronously and hence may use its own ID as given above.

7.1.2 Encoding of data within files

The message protocol is based upon clients requesting to read or write data to/from a database hosted by the server. Each message first specifies the number of read/write requests contained within the message. For each request, the message also specifies the following information: (i) demo site with which the request pertains to, (ii) whether the request is of a read or write type, (iii) the database element name that is to read from or written to, (iv) the timeslot base index, (v) the number of successive timeslots to read/write and (vi) the data if a write request (or a data placeholder if a read request).
Upon receipt of a valid message from a client, the contents of the file are parsed and appropriate writes made to the appropriate database; in case of read requests, the corresponding data is first read and then written back into the original file in the corresponding value placeholder. In the case of write requests, the written data is replaced by the string "NULL". The file is then returned to the sending client with the letter 'R' appended to the end of the filename to acknowledge receipt and processing of the data.

Each file shall have the following general structure:

```
<SOM>
<ID><Message Identifier</ID>

<DATABASE>
<DID><Database ID></DID>
<RW><Read/Write></RW>
<EN><Element Name></EN>
<BT><Base Timeslot></BT>
<NT><Number of Timeslots></NT>
<V><Data><V>
</DATABASE>

<DATABASE>
...
</DATABASE>
...
</SOM>
```

The data is contained in XML tags. An explanation of each tag field and the data requirements are follows. The colon character ':' is employed as a delimiter for fields in data tags.

`<SOM> </SOM>` = each message object should be contained within these tags. The principal use is to help message framing should raw TCP/IP sockets be used to transfer the XML file.

Each database object has the following format:

`<Message Identifier>` = the unique message identifier that appears in the filename, e.g. PO_15061325. This is again useful for helping message framing should raw TCP/IP sockets be used to transfer the XML file, and also to help with sanity checking and message form and consistency checking at the server. NB: read request responses always have an 'R' appended to the end of the original identifier.

Following the identifier, there should be a number of complete data objects. At present, the object of type `DATABASE` is supported. Each such database object has the following format:

`<DATABASE> </DATABASE>` = Each database object should be contained within these tags.

`<Database ID>` = a variable length ASCII code identifying the database for the site that the data pertains to. Acceptable values for characters are the ASCII numerical values 0-9 and uppercase letters A-Z. The current acceptable site codes have 3 characters and are as follows:

"TST" = Reserved ID code for testing purposes. Do not use unless instructed.

“COP” = City of Porvoo demo site in Finland

“IUT” = IUT Campus demo site in Bordeaux, France

All other valid character combinations are reserved for future expansion purposes and should not be used.

`<Read/Write>` = a single ASCII character indicating if the object is a read or write request, indicated by “R” for read and “W” for write.

`<Element Name>` = a variable length ASCII code identifying the element within the database indicated by <Site ID> that the read/write request pertain to. Valid elements names for the databased related to the Finnish and French demo sites are as given in chapter 4.

`<Base Timeslot>` = a fixed length ASCII code identifying the base timeslot index of the element within the database that the read/write request pertain to. Timeslot format is hh_dd_mm_yy, where hh pertains to the hour (00-23), dd the day (01-31), mm the month (01-12) and yy the year (00-99). The hour in this timeslot refers to the start of the hour that the data pertains to. Only an hourly resolution is needed since this is the resolution of the main loop for both sites.

`<Number of Timeslots>` = a numeric, non-negative integer representing the number of consecutive timeslots the data pertains to. Acceptable values are the ASCII numerical values 0-9.

`<Data>` = if the object is a write request or a read response, this field contains an ASCII string encoding the data values of the element corresponding to each timeslot, delimited by a colon ‘:’. The number of data values should be exactly the same as the number encoded by the <Number of Timeslots> field. The precision of the data should be as specified in tables I or II. If no data is available due to an instrumentation fault, then the string “FAULT” should be used instead of passing a value of zero (which implies that a reading WAS taken). If the object is a read request, then the contents of this field may be left empty or preferably replaced with the string “NULL”.

If the server receives a message that has an incorrect format or otherwise contains an error, then the following response shall instead be given in an XML file:

```
<SOM>
<ID><Message Identifier</ID>
<EM><Error Message></EM>
</SOM>
```

`<Message Identifier>` = the unique message identifier that appears in the original filename with the character ‘E’ appended to the end.

`<Error Message>` = a textual description of the error, e.g. “Bad format in object #3”.

To maintain data integrity, the server shall take no action to respond to any write or read requests contained in a message if only a sub-portion (e.g. a single object) of the message is corrupted or incorrect. As TCP/IP is employed, the serialization ordering of messages from a single client is preserved upon receipt by the server; the server shall process messages in the order of delivery. However the client has the responsibility to check for error messages in case the transmission ordering of multiple messages is important. The client also has the responsibility to correct for any errors and re-transmit messages as appropriate.

7.2 Appendix B: Optimization and Decision Support Specifications for the French Demo Site

The main actors for this use case are as discussed in Section 2.2. The main flow for this use case is as described in chapter 4. Below are listed the main data structures and constants and the specific details of each stage of the optimization cycle. Notation for time-series data and array indexing is a described in chapter 4.

7.2.1 General Configuration

1) The day is principally split into 24 hourly timeslots. The duration of the main optimization routine T_{Loop} = 1 hour. The optimization horizon H = 48 hours.
2) Timings with respect to figure 18 will be selected and fine-tuned during prototyping.
3) There are a number of virtual resources consisting of PV panels and windturbines, each having a local storage element and switchgear. The models for these resources are as specified in section 4.2.3. Exact numbers and the intended physical locations of these resources will be determined during prototyping.
4) There is a virtual energy storage facility, distributed across a number of these virtual resources, which is capable of sinking or storing energy at each hourly time-step. The model is as specified in section 4.2.3. Characteristics and constants related to this storage facility will be determined during prototyping.

7.2.2 Main data structures and constants

All variables are assumed to be real-valued (double-precision IEEE standard floating point) unless otherwise specified. Indices (*h*, *d*, *w* or *m*) are as stated above. It should be assumed that at the start of the demonstration, data structures are initialized to zero unless otherwise stated.

The following data structures / variables are defined:

1) A vector of IUT energy demands $D()$, representing the time-series of energy demands for the IUT buildings. Units will be in kWh, with temporal resolutions (***h***, *d*, *w*, *m*). At hour *h*, $D(h\text{-}1)$ is known data but $D(h)$ is not.
2) A vector of IUT building energy demands $D_x()$, representing the time-series of energy demands for IUT building *x*, for x = 1, 2, …, *Number of Buildings*. Units will be in kWh, with temporal resolutions (***h***, *d*, *w*, *m*). At hour *h*, $D_x(h\text{-}1)$ is known data but $D_x(h)$ is not.
3) A vector of IUT renewable energy supply capacities $S()$, representing the time-series of energy supplied by the IUT renewable resources. Units will be in kWh, with temporal resolutions (***h***, *d*, *w*, *m*). At hour *h*, $S(h\text{-}1)$ is known data but $S(h)$ is not.
4) A vector of IUT building energy renewable supply capacities $S_x()$, representing the time-series of energy supplied by IUT building *x*, for x = 1, 2, …, *Number of Buildings*. Units will be in kWh, with temporal resolutions (***h***, *d*, *w*, *m*). At hour *h*, $S_x(h\text{-}1)$ is known data but $S_x(h)$ is not.
5) A matrix of fundamental variables F_D[X]() representing the time-series of fundamental variables employed to obtain the predictions of future IUT demands. Temporal resolution will be (***h***). At present, it is not possible to specify the size of the constant X, and this – along with appropriate units – will be determined during prototyping.
6) A matrix of fundamental variables F_S[Y]() representing the time-series of fundamental variables employed to obtain the predictions of future IUT supplies. Temporal resolution will be (***h***). At present, it is not possible to specify the size of the constant Y, and this – along with appropriate units – will be determined during prototyping.

7) A vector of prices $P_S()$, representing the time-series of the grid energy purchase price. Units will be in Eur/kWh and temporal resolution will be (***h***).
8) A vector of prices $P_D()$, representing the time-series of grid energy sale price. Units will be in Eur/kWh and temporal resolution will be (***h***).
9) A vector of CO_2 costs $E()$, representing the time-series of the emissions cost for grid energy. Units will be in g/kWh and temporal resolution will be (***h***).
10) An energy storage vector $C()$, representing the amount of energy contained within an energy store. Units will be in kWh and temporal resolution will be (***h***). Note that at hour h, $C(h)$ is known data but $C(h+1)$ is not.
11) A vector of decision variables $X_C()$, representing the time-series of the optimal decisions taken related to the storage and retrieval of energy into/from the storage facility. Units will be in kWh and temporal resolution will be (***h***). Note that $X_C(h) < 0$ indicates storage (with efficiency C_α) at hour h, and $X_C(h) > 0$ indicates retrieval at hour h.
12) A vector of slack variables $X_{GS}()$ representing the time-series of the optimal decisions which are used to denote how much energy is to be purchased from the grid. Units will be in kWh and temporal resolution will be (***h***). Note that at hour h, the actual value of $X_{GS}(h\text{-}1)$ can be calculated from known data, but the optimal $X_{GS}(h)$ must be calculated from predicted data.
13) A vector of slack variables $X_{GD}()$ representing the time-series of the optimal decisions which are used to denote how much energy is to be sold to the grid. Units will be in kWh and temporal resolution will be (***h***). Note that at hour h, the actual value of $X_{GD}(h\text{-}1)$ can be calculated from known data, but the optimal $X_{GD}(h)$ must be calculated from predicted data.
14) A scalar R to denote the rolling sum of profit/loss since switch-on. Units will be in Eur. Note that this is live data.
15) Integer counter variables h, d, w, and m to denote the number of elapsed hours, days, weeks and months (28 days) since power-on. All variables should be initialized to -1. Note that this is live data.

The following constants will be defined during prototyping:

1) The efficiency of the energy store is given as a fixed and known constant denoted as C_α. This is a dimensionless constant.
2) There are fixed and known constraints on the absolute minimum and maximum capacity of the energy store which are denoted as C^{Min} and C^{Max}. Units are in kWh.
3) There are fixed and known constraints on the minimum and maximum amount of energy that may be sunk/sourced by the energy store - ΔC^{Min} and ΔC^{Max} - during any particular hour. Units are in kWh/h.

7.2.3 Start-of-cycle

The following housekeeping calculation shall be performed at the start of every new cycle:

1) The counter variable h is updated as $h = h + 1$.

2) If mod(h, 24) == 0, then the counter variable d is updated as $d = d + 1$.

3) If mod(d, 7) == 0, then the counter variable w is updated as $w = w + 1$.

4) If mod(w, 4) == 0, then the counter variable m is updated as $m = m + 1$.

7.2.4 Data Acquisition Phase

Steps taken during the data acquisition phase may be summarized as follows:

1) Consumption data for the last hour is forwarded from the Nobatec measurement system and processed to obtain the latest measured energy demand for each building in the IUT campus in the last hour $D_x(h\text{-}1)$, x = 1, 2, …, *Number of Buildings*. The exact specification of this data transfer is currently unknown, but shall be based upon the EPNMS and developed during prototyping.
2) Renewable availability data is calculated using the simulation models as specified in Appendix D and processed to obtain the latest measured energy supply of the IUT campus resources in the last hour $S_x(h\text{-}1)$, x = 1, 2, …, *Number of Buildings*.
3) The current weather conditions at the IUT site are obtained, and any updates of the future building occupancy data is forwarded by the Nobatec measurement system.
4) Weather forecast information is retrieved from the yr.no (http://api.yr.no) website for every hour over the prediction horizon $h+k$, k = 0, 1, 2, …, H-1, and combined with the data from steps 2 and 3 to form the fundamental variable matrices $F_D[](h+k)$ and $F_S[](h+k)$, k = 0, 1, 2, …, H-1.
5) The latest information regarding the CO_2 expenditure for grid energy in France is retrieved from the website http://www.rte-france.com/fr/developpement-durable/eco2mix/emission-de-co2-par-kwh-d-electricite-produite-en-france.
6) Stored energy availability data is calculated using the simulation models as specified in section 4.2.3 and processed to obtain the latest measured availability of the neighbourhood storage resources $C(h)$.

7.2.5 Pre-processing / Prediction Phase

Steps taken during the pre-processing / prediction phase may be summarized as follows:

1) Current consumption data $D_x(h\text{-}1)$, x = 1, 2, …, *Number of Buildings* is summed for each building in the IUT campus to obtain the site energy demand for the last hour $D(h\text{-}1)$.
2) Current renewable energy supplies $S_x(h\text{-}1)$, x = 1, 2, …, *Number of Buildings* is summed for each building in the IUT campus to site energy supply for the last hour $S(h)$.
3) The site demand $D(h+k)$, k = 0, 1, 2, …, H-1 shall be predicted over the horizon using the technique described in section 7.2.5.1.
4) The site supply $S(h+k)$, k = 0, 1, 2, …, H-1 shall be predicted over the horizon using the technique described in 7.2.5.2.
5) Grid CO_2 emissions $E(h+k)$, k = 0, 1, 2, … , H-1 shall be predicted for each step over the prediction horizon, using the technique described in 7.2.5.3.
6) Knowledge of the pricing and tariff structure (on-peak prices P_{sp} and P_{dp} / off-peak prices P_{sb} and P_{db}) shall be employed, along with knowledge the current hour, day and month and the peak#1 and peak #2 start/stop times, to set the grid price vectors $P_s(h+k)$ and $P_d(h+k)$, k = 0, 1, 2, …, H-1.

7.2.5.1 Energy demand prediction

Let the variable $D(h)$ represent the demand for electricity (in kW) for the group of buildings during hour h. Assume that the demand has the auto-regressive integrated white-noise 'dynamics' given by:

$$D(h) = A(z)D(h) + B(z)F_D(h) + \frac{e(h)}{\Delta}$$

In which $e(h)$ is a zero-mean white noise sequence, z^{-1} is the backshift (delay) operator, $\Delta = 1\text{-}z^{-1}$ and $A(z)$ is a monic polynomial with unknown coefficients. $F_D(h)$ is a vector of fundamental variables whose values are known (or predicted) for hour h, and $B(z)$ is a vector of polynomials with unknown coefficients. The integrated white sequence means that the process is effectively experiencing unknown disturbances that are akin to Brownian motion or a random walk. In particular, this provides resilience against non-constant means (which demand data seems to exhibit).

Let the temperature during hour h be denoted as $T(h)$, and setting $\Delta T(h) = T(h) - T(h\text{-}1)$ gives the first difference in the temperature. Let $O(h)$ represent the mean occupancy (in %age format) of the buildings during hour h, and $\Delta O(h) = O(h) - O(h\text{-}1)$ the change in mean occupancy. The two signals ΔT and ΔO become the vector of fundamentals $F_D(h)$. Incorporating the B polynomials and setting $\Delta D(h) = D(h) - D(h\text{-}1)$ gives the suggested model structure:

$$D(h) = D(h-1) + a_1 \Delta D(h-1) + a_2 \Delta D(h-24) + a_3 \Delta D(h-168) + b_1 \Delta T(h) + b_2 \Delta O(h)$$

The one-step head prediction equation for the above model, using all information available up to and including time t, becomes:

$$\hat{D}(h \mid h-1) = D(h-1) + a_1 \Delta D(h-1) + a_2 \Delta D(h-24) + a_3 \Delta D(h-168) + b_1 \Delta \hat{T}(h) + b_2 \Delta \hat{O}(h)$$

k-step ahead predictions are obtained by recursion upon the above equation.

The parameters a_1, a_2, a_3 and b_1, b_2 are first updated on-line to minimize the following objective function J (the final weighted quadratic prediction error):

$$J = \sum_{i=0}^{h-1} \lambda^{(t-i)} \left(D(i) - \hat{D}(i) \right)^2$$

With $0 < \lambda \leq 1$. This parameter estimation should be carried out using recursive least squares (RLS) before the predictions are carried out. It is suggested to initially set $\lambda \approx 0.9932$ to optimally fit the parameters over a period of about a month (the weight of data 671 time steps ago is reduced to $\approx$ 1%). This can be fine-tuned during prototyping.

7.2.5.2 Energy supply prediction

We employ a similar strategy to the above: Let the supply $S(h)$ represent the supply of electricity (in kWh) by a specific resource during hour h. Assume that the supply has the auto-regressive integrated white-noise 'dynamics' given by:

$$S(h) = A(z)S(h) + B(z)F_S(h) + \frac{e(h)}{\Delta}$$

In which $e(h)$ is a zero-mean white sequence, z^{-1} is the backshift (delay) operator, $\Delta = 1\text{-}z^{-1}$ and $A(z)$ is a monic polynomial with unknown coefficients. $F_S(h)$ is a vector of fundamental variables whose values are known (or predicted) during hour h, and $B(z)$ is again a vector of polynomials with unknown coefficients. The structure of the A and B polynomials will be identified during prototyping, along with the variables that must be used in the $F_S(h)$ vector of fundamentals. It is likely that these will include components related to temperature, insolation levels and cloud cover. Weighted recursive least squares will be employed to adaptively track the unknown parameters as described above.

7.2.5.3 Grid CO2 Emission Prediction

For the solution of the linear programs specified above it is required to predict the future CO_2 emissions of grid-drawn energy. Current and past estimates of the levels of CO_2 / kWh are available from the website as detailed in the above section. For the purposes of optimization, the future prediction of CO_2 emissions will be taken as the arithmetic mean of the measured data in the corresponding time slot one hour ago, the corresponding time slot one day ago and the corresponding time slot one week ago.

7.2.6 Optimization Phase

The following assumption is made:

1) Assumption: The initial state of the storage facility $C(h)$ satisfies $C^{Min} \leq C(h) \leq C^{Max}$. If this is not the case, the optimization will be immediately deemed infeasible.

The optimization problem to be solved is defined as follows:

Define the expected financial profit for hour k ($k \geq h$) as the difference between the energy sold to the grid and the energy bought from the grid:

$$\mathrm{Profit}(k) = X_{GS}(k) \cdot P_S(k) - X_{GD}(k) \cdot P_D(k)$$

Then the total expected profit (loss) made across the horizon H at hour h can be formed from the available data as:

$$\mathrm{Profit}_{\mathrm{H}}(h) = \sum_{i=0}^{H-1} \mathrm{Profit}(h+i)$$

Define the inverse of the expected CO_2 emission costs for hour k ($k \geq h$):

$$\mathrm{CO}_2(k) = -X_{GD}(k) \cdot E(k)$$

Then the total expected CO_2 emission costs incurred across the horizon H at hour h can be formed from the available data as:

$$\mathrm{CO}_{2\mathrm{H}}(h) = \sum_{i=0}^{H-1} \mathrm{CO}_2(h+i)$$

So the weighted objective function may be expressed as:

$$\mathrm{OBJ}_{\mathrm{H}}(h) = (1-\gamma)\mathrm{Profit}_{\mathrm{H}}(h) + \gamma CO_{2H}(h)$$

With $\gamma \in [0, 1]$ representing the relative importance (weighting) between financial and CO_2 emissions costs.

Noting that maximizing the inverse of the emission costs is identical to minimizing the direct emission costs, we can define the optimization problem to be solved at time step t:

Maximize$\{\mathrm{OBJ}_{\mathrm{H}}(h)\}$

With respect to:

$X_{GD}(h+k)$, $k = 0, 1, 2, 3, \ldots, H$-1;
$X_{GS}(h+k)$, $k = 0, 1, 2, 3, \ldots, H$-1;
$X_C(h+k)$, $k = 0, 1, 2, 3, \ldots, H$-1;

Subject to:

Energy balance constraints:

$$\forall i, 0 \le i \le H-1:$$
$$S(h+i) + X_{GS}(h+i) + X_C(h+i) = D(h+i) + X_{GS}(h+i)$$

Non-negative supply/demands:

$$\forall i, 0 \le i \le H-1:$$
$$X_{GS}(h+i) \ge 0$$
$$X_{GD}(h+i) \ge 0$$

Energy storage constraints:

$$\forall i, 1 \le i \le H-1:$$
$$C(h+i) = C(h+i-1) - \max\{C_\alpha \cdot X_C(h+i-1), X_C(h+i-1)\}$$

Energy storage/retrieval rate and capacity constraints:

$$\forall i, 1 \le i \le H-1:$$
$$C^{Min} \le C(h+i) \le C^{Max}$$
$$\forall i, 0 \le i \le H-1:$$
$$\Delta C^{Min} \le X_C(h+i) \le \Delta C^{Max}$$

The above linear program is to be solved twice to explore various trade-offs between costs and emissions by varying γ. In particular for $\gamma = 0$ (Solution Sol 1) emissions are not taken into account, and for $\gamma = 1$ (Solution Sol 2) financial costs are not taken into account.

7.2.7 Post-processing phase

7.2.7.1 Housekeeping

The following housekeeping calculations shall be performed during the POS stage every hour:

1) Rolling averages of the electricity demand and supply on a daily, weekly and monthly timescale will be recursively calculated.

2) The energy quantity solution variables will be rounded to the nearest whole Watt.

3) The true energy stored/retrieved from the storage facility during the last hour $X_C(h\text{-}1)$ is calculated from $X_C(h\text{-}1) = C(h) - C(h\text{-}1)$.

4) The total profit or loss R will be calculated using the measured (known) values of $D(h\text{-}1)$, $S(h\text{-}1)$ and $X_C(h\text{-}1)$ using knowledge of the prices of the previous hour $P_{GS}(h\text{-}1)$ and $P_{GD}(h\text{-}1)$. The calculation will be:

$$\Delta = S(h-1) + X_C(h-1) - D(h-1);$$
$$R = R + \begin{cases} \Delta \cdot P_{GD}(h-1) & \text{if } \Delta \geq 0 \\ \Delta \cdot P_{GS}(h-1) & \text{if } \Delta < 0 \end{cases}$$

5) The grid variables $X_{GD}(h\text{-}1)$ and $X_{GS}(h\text{-}1)$ shall be updated as:

$$X_{GD} = \begin{cases} \Delta : \text{if } \Delta \geq 0 \\ 0 : \text{if } \Delta < 0 \end{cases}; \quad X_{GS} = \begin{cases} 0 : \text{if } \Delta \geq 0 \\ \Delta : \text{if } \Delta < 0 \end{cases}$$

7.2.7.2 KPI Calculations

The following KPIs shall be calculated during the POS stage every hour:

1) The filtered absolute percentage prediction error for hourly electricity demands (E_E) shall be recursively calculated at every hour h with a first-order filter having time-constant of 8 hours using the relationship:

$$E_E = 0.882 \cdot E_E + 0.118 \cdot 100 \cdot \left| \frac{D(h-1) - \hat{D}(h-1)}{D(h-1)} \right|$$

If the value of E_E is below a pre-determined threshold value (say 5%), the KPI status will be considered to be True (1), otherwise it will be considered to be False (0). The threshold value will be fine-tuned during prototyping.

2) The filtered absolute percentage prediction error for hourly electricity supplies (E_S) shall be recursively calculated every hour h with a first-order filter having time-constant of 8 hours using the relationship:

$$E_E = 0.882 \cdot E_E + 0.118 \cdot 100 \cdot \left| \frac{S(h-1) - \hat{S}(h-1)}{S(h-1)} \right|$$

If the value of E_S is below a pre-determined threshold value (say 5%), the KPI status will be considered to be True (1), otherwise it will be considered to be False (0). The threshold value will be fine-tuned during prototyping.

3) The filtered optimizer percentage error indicator (E_O) shall be recursively calculated every hour h with a first-order filter having time-constant of 8 hours using the relationship:

$$E_O = 0.882 \cdot E_O + 0.118 \cdot \begin{cases} 0 : & \text{Optimization was sucessful at hour } h \\ 100 : & \text{Optimization was not sucessful at hour } h \end{cases}$$

If the value of E_O is below a pre-determined threshold value (say 10%), the KPI status will be considered to be True (1), otherwise is will be considered to be False (0). The threshold value will be fine-tuned during prototyping.

4) The filtered EPN Energy Positivity Indicator EPI shall be recursively calculated as a percentage every hour h with a first-order filter having time-constant of 224 hours (one month) using the relationship:

$$EPI = 0.996 \cdot EPI + 0.004 \cdot 100 \cdot \frac{\Delta}{D(h-1)}$$

If the value of E_O is above a pre-determined threshold value (0%), the KPI status will be considered to be True (1), otherwise is will be considered to be False (0). The threshold value will be fine-tuned during prototyping.

Please note that other KPIs (e.g. related to CO_2 emissions) may be developed as-needed

during the prototyping stages of the project.

7.2.7.3 Decision Support

For the French demonstration, no specific decision support logic needs to be implemented. A facility for occasional status update messages to be sent to residents will be left open; the specific format and triggering logic for this (if used) will be specified during prototyping.

7.2.8 Data distribution phase

The solution data is made available for ancillary displays, user interfaces and simulated equipment by updating the appropriate records in the database. Exact timings for the data availability for partner sites will be determined during prototyping. Solution data is also refreshed and embedded into a specific webpage hosted by the IOC: refer to D3.3 for further details.

7.2.9 Summary of Global Data Structures

In order to appropriately size the databases for the French demonstration site, the following table provides a summary of the global data structures. It is suggested that space be provisioned to allow at least 12 months of data for each variable to be retained.

Name	Type	Ref	Units	Element	Size (r)	Size (c)	Resolution
Building xx Energy Demand	real	Dx	kWh	BxxEDz	16	H,D,W,M	3 d.p.
Building xx Energy Supply	real	Sx	kWh	BxxESz	16	H,D,W,M	3 d.p.
Area Energy Demand	real	D	kWh	AEDz	1	H,D,W,M	3 d.p.
Area Energy Supply	real	S	kWh	AESz	1	H,D,W,M	3 d.p.
Area Energy Storage	real	C	kWh	AECz	1	H,D,W,M	3 d.p.
Grid CO_2 Emission Cost	real	E	g/kWh	CO2C	1	H	1 d.p.
Weather (Temp)	real	Fd/Fs	°C	WFT	1	H	3 d.p.
Weather (Insolation)	real	Fd/Fs	J/mm^2	WFI	1	H	3 d.p.
Weather (Cloud Cover)	real	Fd/Fs	% age	WFC	1	H	3 d.p.
Weather (Wind Speed)	real	Fd/Fs	KpH	WFWS	1	H	3 d.p.
Weather (Wind Direction)	real	Fd/Fs	°	WFWD	1	H	3 d.p.
Building xx Occupation	real	Fd/Fs	% age	BxxO	16	H	3 d.p.
Grid Energy Price (buy, peak)	real	Psp	Eur/kWh	GEPB	1	L	2 d.p.
Grid Energy Price (sell, peak)	real	Pdp	Eur/kWh	GEPS	1	L	2 d.p.
Grid Energy Price (buy, off	real	Psb	Eur/kW	GEPB	1	L	2 d.p.

p)			h				
Grid Energy Price (sell, off p)	real	Pdb	Eur/kW h	GEPS	1	L	2 d.p.
Peak time #1 (start, stop)	int	N/A	Hour	PTS1y	2	L	0 d.p.
Peak time #2 (start, stop)	int	N/A	Hour	PTS2y	2	L	0 d.p.
Storage Variables Sol y	real	Xc	kWh	SVSy	2	H	3 d.p.
Grid Slack Variables Sol y	real	Xg	kWh	GVSy	2	H	3 d.p.
EPN Cycle Status	int	N/A	N/A	EPNSTAT	1	L	0 d.p.
EPN Elapsed Hours Count	int	h	Hours	EPNEHC	1	L	0 d.p.
EPN KPIs	int	KPI	N/A	EPNKPI	1	L	0 d.p.
EPI (Short Term)	real	EPI	% age	EPIST	1	H	2 d.p.
EPI (Long Term)	int	EPI	% age	EPILT	1	L	0 d.p.
EPN Global Message	strin g	N/A	N/A	EPNMS G	1	L	N/A
EPN Profit/Loss	real	R	Eur	EPNPL	1	L	2 d.p.

NB1: 'xx' is integer in the range 01 – 16, 'y' is integer in the range 01-02, 'z' is a single char mnemonic from the list of letters 'H', 'D', 'W', 'M' or 'L', see below.

NB2: NB2: Size(r) = number of rows (vertical size of array), size(c) = number of columns (horizontal size of array). The following codes are used to enumerate the column index sizes (and control access formats):

'H' = hourly (8760 entries/variable/year)

'D' = daily (365 entries/variable/year)

'W' = weekly (52 entries/variable/year)

'M' = monthly (12 entries/variable/year)

'L' = live data, continuously updated, no history kept

NB3: EPNSTAT is an enumerated representation of the cycle state (see figure 18).

The enumeration is:

0x00 = EPN is Idle

0x01 = EPN is in DAQ phase

0x02 = EPN is in PRE phase

0x03 = EPN is in OPT phase

0x04 = EPN is in POS phase

0x05 = EPN is in DIS phase

<u>It is assumed that the status indicator is updated by the EMS automatically.</u>

NB4: EPNKPI is a bit-wise enumeration of the EPN KPIs (section 7.2.7.2).

The enumeration is:

Bit 0: Demand Model Convergence (1 = OK, 0 = NOT OK)

Bit 1: Supply Model Convergence (1 = OK, 0 = NOT OK)

Bit 3: Optimization Healthy (1 = OK, 0 = NOT OK)

Bit 4: Area is Energy Positive (1 = OK, 0 = NOT OK)

NB5: EPNMSG is a formatted string containing the text of the last global message made available to the EPN (section 7.2.7.3).

NOTE: the data above is subject to changes during the prototyping phases of the IDEAS project. Specific read/write permissions will be set for the demonstration stage of the project.

7.3 Appendix C: Optimization and Decision Support Specifications for the Finnish Demo Site

The main actors for this use case are as discussed in Section 2.2. The main flow for this use case is as described in chapter 4. Below are listed the main data structures and constants and the specific details of each stage of the optimization cycle. Notation for time-series data and array indexing is a described in chapter 4.

7.3.1 General Configuration

1) The day is principally split into 24 hourly timeslots. The duration of the main optimization routine for electrical energy T_{Loop} = 1 hour. The optimization horizon H = 48 hours. The current timeslot is indexed by the variable t.
2) The resolution of the prediction routine for district heating is 1 day, and the prediction horizon H_{DH} = 10 days; the predictions are made with updated information at the same rate as the main loop (T_{Loop} = 1 hour).
3) Timings with respect to figure 18 will be selected and fine-tuned during prototyping.
4) There are a number of virtual resources consisting of PV panels and windturbines, each having a local storage element and switchgear. Some of the resources are owned by the EPN, and some by the residents. Exact numbers and the intended physical locations of these resources will be determined during prototyping. The models for these resources are as specified in section 4.2.3.
5) There is a virtual energy storage facility, distributed across a number of these virtual resources, which is capable of sinking or storing energy at each hourly time-step. The model is as specified in section 4.2.3. Characteristics and constants related to this storage facility will be determined during prototyping.
6) The total number of electrical energy sources for supply and/or demand transactions is set to n = 10. This is made up from 9 possible independent energy traders (IETs), and a single trader representing a supplier offering spot market prices (NordPool).

7.3.2 Main data structures and constants

All variables are assumed to be real-valued (double-precision IEEE standard floating point unless otherwise specified). Indices (h, d, w or m) are as stated above. It should be assumed that at the start of the demonstration, data structures are initialized to zero unless otherwise stated.

The following data structures are defined:

1) A vector of total area electrical energy demand $D()$, representing the time-series of electrical energy demands for the total area. Units will be in kWh, with temporal resolutions ($\underline{\boldsymbol{h}}$, d, w, m). At hour h, $D(h\text{-}1)$ is known data but $D(h)$ is not.
2) A vector of total area district heating energy demands $D_{DH}()$,representing the time-series of electrical energy demands for the total area. Units will be in kWh, with temporal resolutions ($\underline{\boldsymbol{d}}$, w, m). At day d, $D_{DH}(d\text{-}1)$ is known data but $D_{DH}(d)$ is not.
3) A vector of total area electrical energy supplies $S()$, representing the time-series of electrical energy supply for the total area. Units will be in kWh, with temporal resolutions ($\underline{\boldsymbol{h}}$, d, w, m). At hour h, $S(h\text{-}1)$ is known data but $S(h)$ is not.
4) Vectors $S_R()$ and $S_{EPN}()$, representing the time-series of electrical energy supply of resident-owned and EPN-owned resources respectively. Units will be in kWh, with temporal resolution ($\underline{\boldsymbol{h}}$). At hour h, $S_R(h\text{-}1)$ and $S_{EPN}(h\text{-}1)$ are known data but $S_R(h)$ and $S_{EPN}(h)$ are not. Note that for all h, $S_R(h) + S_{EPN}(h) = S(h)$.
5) A vector of EPN committed energy sales $D_C()$, representing the time-series of

commitments (if any) that the EPN has *already* made with respect to the sale of energy. Units will be in kWh, with temporal resolution (***h***).

6) A vector of EPN committed energy purchases $S_C()$, k = 0, 1, 2, … , H-1, representing the time-series of commitments (if any) that the EPN LM has *already* made with respect to the purchase of energy. Units will be in kWh, with temporal resolution (***h***).
7) A vector of CO_2 costs $E()$, representing the time-series of the emissions cost for grid energy. Units will be in g/kWh and temporal resolution will be (***h***).
8) For each of the n IETs, a vector of purchase prices $P_S[j]()$, representing the time-series of prices to buy energy from IET j for j = 1, 2, … , n. Units will be in Eur/kWh, with temporal resolution (***h***).
9) For each of the n IETs, a vector of purchase constraints $P_S^{Max}[j]()$, representing the time-series of maximum energy availability for each IET j, for j = 1, 2, … , n. Units are in kWh, with temporal resolution (***h***).
10) For each of the n IETs, a vector of sale prices $P_D[j]()$, representing the time-series of prices to sell energy to IET j for j = 1, 2, … , n. Units will be in Eur/kWh, with temporal resolution (***h***).
11) For each of the n IETs, a vector of sale constraints $P_D^{Max}[j]()$, representing the time-series of maximum energy requirement for each IET j, for j = 1, 2, … , n. Units are in kWh, with temporal resolution (***h***).
12) A matrix of fundamental variables $F_D[X]()$ representing the time-series of fundamental variables employed to obtain the predictions of future area electricity and heat demands. Temporal resolution will be (***h***). At present, it is not possible to specify the size of the constant X, and this – along with appropriate units – will be determined during prototyping.
13) A matrix of fundamental variables $F_S[Y]()$ representing the time-series of fundamental variables employed to obtain the predictions of future area electricity supplies (EPN owned and resident owned). Temporal resolution will be (***h***). At present, it is not possible to specify the size of the constant Y, and this – along with appropriate units – will be determined during prototyping.
14) A matrix of fundamental variables $F_P[Z]()$ representing the time-series of fundamental variables employed to obtain the predictions of future electricity prices. Temporal resolution will be (***h***). At present, it is not possible to specify the size of the constant Z, and this – along with appropriate units – will be determined during prototyping.
15) An energy storage vector $C()$, representing the amount of energy contained within an energy store. Units will be in kWh and temporal resolution will be (***h***). Note that at hour h, $C(h)$ is known data but $C(h+1)$ is not.
16) A vector of decision variables $X_C()$, representing the time-series of the optimal decisions taken related to the storage and retrieval of energy into/from the storage facility. Units will be in kWh and temporal resolution will be (***h***). Note that $X_C(h) < 0$ indicates storage (with efficiency C_α) at hour h, and $X_C(h) > 0$ indicates retrieval at hour h.
17) For each of the n IETs, a vector of decision variables $X_S[j]()$, representing the time-series of energy purchases from each IET j, for j = 1, 2, … , n. Units are in kWh, with temporal resolution (***h***).
18) For each of the n IETs, a vector of decision variables $X_D[j]()$, representing the time-series of energy sales to each IET j, for j = 1, 2, … , n. Units are in kWh, with temporal resolution (***h***).
19) A vector of EPN differential pricing signals $\beta()$, representing the time-series of electricity prices offered to the area. Units will be Eur/kWh, with temporal resolution (***h***).
20) For each of the n IETs, a scalar purchase constraint P_S^T, representing the maximum

energy availability for the combined purchases of each IET j over the planning horizon, for j = 1, 2, … , n. Units are in kWh. Note that this is live data.

21) For each of the n IETs, a scalar sales constraint $P_D{}^T$, representing the maximum energy requirement for the combined sales of each IET j over the planning horizon, for j = 1, 2, … , n. Units are in kWh. Note that this is live data.
22) A scalar R to denote the rolling sum of profit/loss since switch-on. Units will be in Eur. Note that this is live data.
23) A scalar P to denote the current area electricity price. Units will be in Eur. Note that this is live data.
24) A scalar T to denote the electrical energy demand target for the current hour. Units will be in kWh. Note that this is live data.
25) Integer counter variables h, d, w, and m to denote the number of elapsed hours, days, weeks and months since power-on. All variables should be initialized to -1. Note that this is live data.

The data structures accositated with IET1 which are P_S[1](), $P_S{}^{Max}$[1](), P_D[1]() and $P_D{}^{Max}$[0]() are reserved for Nordpool prices and should not be used by any other IETs.

The following constants will be defined during prototyping:

1) The efficiency of the energy store is given as a fixed and known constant denoted as C_α. This is a dimensionless constant.
2) There are fixed and known constraints on the absolute minimum and maximum capacity of the energy store which are denoted as C^{Min} and C^{Max}. Units are in kWh.
3) There are fixed and known constraints on the minimum and maximum amount of energy that may be sunk/sourced by the energy store - ΔC^{Min} and ΔC^{Max} - during any particular hour. Units are in kWh/h.
4) A fixed price P is required to be set such that the maximum dynamic price that can be offered to residents is known. Units are in Eur.
5) A fixed additive (subtractive) surcharge of O_s applied by IET1 for the purchase (sale) of small quantities of energy at wholesale (Nordpool) prices.
6) An upper energy limit DH_L to trigger a district heating warning message. Units are in kWh.
7) Upper and lower price limits β^{Max} and β^{Min} to trigger resident notification messages. Units are in Eur.

7.3.3 Start-of-cycle

The following housekeeping calculation shall be performed at the start of every new cycle:

1) The counter variable h is updated as $h = h + 1$.
2) If mod(h, 24) == 0, then the counter variable d is updated as $d = d + 1$.
3) If mod(d, 7) == 0, then the counter variable w is updated as $w = w + 1$.
4) If mod(w, 4) == 0, then the counter variable m is updated as $m = m + 1$.

7.3.4 Data Acquisition Phase

Steps taken during the data acquisition phase may be summarized as follows:

1) Consumption data for the last hour is forwarded from the POS measurement system and processed to obtain the latest available (measured) hourly demand for the EPN area in the last hour $D(h-1)$.

2) At the first available point after 12:00 every day d, consumption data for the previous day is forwarded from the PE measurement system and processed to obtain the latest available (measured) daily district heating demand $D_{DH}(d\text{-}1)$.
3) Renewable supply data is calculated using the simulation models as specified in Appendix D and processed to obtain the latest measured supply for the EPN area resources $S_R(h\text{-}1)$ and $S_{EPN}(h\text{-}1)$ in the last hour. The quantity $S(h\text{-}1) = S_R(h\text{-}1) + S_{EPN}(h\text{-}1)$ shall be calculated.
4) Hourly weather forecast information is retrieved from the yr.no (http://api.yr.no) website for every hour over the prediction horizon $h+k$, $k = 0, 1, 2, \ldots, H\text{-}1$ at the EPN site, and combined with the data from steps 2 and 3 to form the fundamental variable matrices $F_D[](h+k)$ and $F_S[](h+k)$, $k = 0, 1, 2, \ldots, H\text{-}1$.
5) Daily weather forecast information is retrieved from the yr.no (http://api.yr.no) website for every day over the heating prediction horizon $d+k$, $k = 0, 1, 2, \ldots, H_{DH}\text{-}1$ at the EPN site, and combined with the data from steps 2 and 3 to form the fundamental variable matrix $F_{DH}[](d+k)$, $k = 0, 1, 2, \ldots, H_{DH}\text{-}1$.
6) Weather forecast information is retrieved from the yr.no (http://api.yr.no) website for every hour over the prediction horizon $h+k$, $k = 0, 1, 2, \ldots, H\text{-}1$ at various sites of interest, and used to form the fundamental variable matrix $F_P[](d+1)$ for $\mathrm{mod}(h, 24) < 16$ and $F_P[](d+2)$ for $\mathrm{mod}(h, 24) \geq 16$.
7) If $\mathrm{mod}(h, 24) \geq 16$ and Elspot prices for $d+1$ are not yet known, updates to the published Elspot prices for Finland are checked for via an FTP server located at: [FTP server URL TBC].
8) The current Finnish area power deficit/surplus situation and load measurements are extracted from: http://www.fingrid.fi/en/electricity-market/power-system/Pages/default.aspx.
9) The latest information regarding the CO_2 expenditure for grid energy in Finland is retrieved from the website: (Website address TBC).
10) Stored energy availability data is calculated using the simulation models as specified in Appendix D and processed to obtain the latest measured availability of the EPN storage resources $C(h)$.

7.3.5 Pre-processing / Prediction Phase

Steps taken during the pre-processing / prediction phase may be summarized as follows:

1) The EPN site electricity demand $D(h+k)$, $k = 0, 1, 2, \ldots, H\text{-}1$ shall be predicted over the horizon using the technique described in section 7.3.5.1.
2) The EPN site heat demand $D_{DH}(d+k)$, $k = 0, 1, 2, \ldots, H_{DH}\text{-}1$ shall be predicted over the horizon using the technique described in section 7.3.5.1.
3) The EPN site renewable supplies $S_R(h+k)$ and $S_{EPN}(h+k)$, $k = 0, 1, 2, \ldots, H\text{-}1$ shall be predicted over the horizon using the technique described in 7.3.5.2, and the main area prediction vector $S(h+k)$ formed using the relationship $S(h+k) = S_R(h+k) + S_{EPN}(h+k)$.
4) Unknown NordPool spot prices across the horizon H, and the current regulation price are predicted using the technique described in section 7.3.5.3.
5) Once unknown prices have been predicted, they shall be transferred - along with the *known* spot prices - in to IET[0]'s data structures which are reserved for supplier transactions. $P_S[0](h+k)$ and $P_D[0](h+k)$ are reserved for these known and predicted prices; the supplier overhead (see section 2.2) of O_s Eur/kWh should be added / subtracted from the spot price respectively.

7.3.5.1 Energy demand prediction

Let the variable $D(h)$ represent the demand for electricity (in kWh) for the EPN area during hour h. Assume that the demand has the auto-regressive integrated white-noise 'dynamics' given by:

$$D(h) = A(z)D(h) + B(z)F_D(h) + \frac{e(h)}{\Delta}$$

In which $e(h)$ is a zero-mean white sequence, z^{-1} is the backshift (delay) operator, $\Delta = 1-z^{-1}$ and $A(z)$ is a monic polynomial with unknown coefficients. $F_D(h)$ is a vector of fundamental variables whose values are known (or predicted) for hour h, and $B(z)$ is a vector of polynomials with unknown coefficients. The integrated white sequence means that the process is effectively experiencing unknown disturbances that are akin to Brownian motion or a random walk. In particular, this provides resilience against non-constant means (which demand data seems to exhibit).

Let the temperature during hour h be denoted as $T(h)$, and setting $\Delta T(h) = T(h) - T(h\text{-}1)$ gives the first difference in the temperature. Let $\beta'(h)$ represent the electricity price signal during hour h, and $\Delta\beta'(h) = \beta'(h) - \beta'(h\text{-}1)$ the change in price signal. The two signals ΔT and $\Delta\beta'$ become the vector of fundamentals $F_D(h)$. Incorporating the B polynomials and setting $\Delta D(h) = D(h) - D(h\text{-}1)$ gives the suggested model structure:

$$D(h) = D(h-1) + a_1\Delta D(h-1) + a_2\Delta D(h-24) + a_3\Delta D(h-168) + b_1\Delta T(h) + b_2\Delta\beta'(h)$$

The one-step head prediction equation for the above model, using all information available up to and including time t, becomes:

$$\hat{D}(h\,|\,h-1) = D(h-1) + a_1\Delta D(h-1) + a_2\Delta D(h-24) + a_3\Delta D(h-168) + b_1\Delta\hat{T}(h) + b_2\Delta\beta'(h)$$

k-step ahead predictions are obtained by recursion upon the above equation.

The parameters a_1, a_2, a_3 and b_1, b_2 are first updated on-line to minimize the following objective function J (the final weighted quadratic prediction error):

$$J = \sum_{i=0}^{h-1} \lambda^{(t-i)} \left(D(i) - \hat{D}(i)\right)^2$$

With $0 < \lambda \leq 1$. This parameter estimation should be carried out using recursive least squares (RLS) before the predictions are carried out. It is suggested to initially set $\lambda \approx 0.9932$ to optimally fit the parameters over a period of about a month (the weight of data 671 time steps ago is reduced to $\approx$ 1%). This can be fine-tuned during prototyping.

In a similar fashion, let the demand for district heating $D_{DH}(d)$ represent the demand for district heating energy (in kWh) during day d. Assume that the heat demand has the auto-regressive integrated white-noise 'dynamics' given by:

$$D_{DH}(d) = A(z)D_{DH}(d) + B(z)F_{DH}(d) + \frac{e(d)}{\Delta}$$

In which $e(d)$ is a zero-mean white sequence, z^{-1} is the backshift (delay) operator, $\Delta = 1-z^{-1}$

and $A(z)$ is a monic polynomial with unknown coefficients. $F_{DH}(d)$ is a vector of fundamental variables whose values are known (or predicted) for day d, and $B(z)$ is a vector of polynomials with unknown coefficients. The structure of the A and B polynomials will be identified during prototyping, along with the variables that must be used in the $F_{DH}(d)$ vector of fundamentals. It is likely that this will principally include a temperature forecast. Weighted recursive least squares will be employed to adaptively track the unknown parameters as described above.

7.3.5.2 Energy supply prediction

We employ a similar strategy to the above: Let the supply $S(h)$ represent the supply of electricity (in kWh) by a specific resource during hour h. Assume that the supply has the auto-regressive integrated white-noise 'dynamics' given by:

$$S(h) = A(z)S(h) + B(z)F_S(h) + \frac{e(h)}{\Delta}$$

In which $e(h)$ is a zero-mean white sequence, z^{-1} is the backshift (delay) operator, $\Delta = 1\text{-}z^{-1}$ and $A(z)$ is a monic polynomial with unknown coefficients. $F_S(h)$ is a vector of fundamental variables whose values are known (or predicted) during hour h, and $B(z)$ is again a vector of polynomials with unknown coefficients. The structure of the A and B polynomials will be identified during prototyping, along with the variables that must be used in the $F_S(h)$ vector of fundamentals. It is likely that these will include components related to temperature, insolation levels and cloud cover. Weighted recursive least squares will be employed to adaptively track the unknown parameters as described above.

7.3.5.3 NordPool and Regulation Price Prediction

The ARMAX model structure as suggested by Kristiansen (2012) will be used to give predictions of the Elspot day-ahead prices using the vector of fundamentals $F_P[](d+1)$ for mod(h, 24) < 16 and $F_P[](d+2)$ for mod(h, 24) ≥ 16. Unknown and time-varying parameters in the model shall be estimated using RLS as detailed above, when new pricing information becomes available.

7.3.6 Optimization Phase

The following assumption is made:

1) Assumption: The initial state of the storage facility $C(h)$ satisfies $C^{Min} \leq C(h) \leq C^{Max}$. If this is not the case, the optimization will be immediately deemed infeasible.

The optimization problem to be solved is defined as follows:

Assume that residents will shift their demands $D(h+k)$ for ($k \geq 0$) by some small fraction $b_2\beta'(h+k)$ in response to a price signal $-1 \leq \beta'(h+k) \leq 1$. The value of b_2 may be identified (in a statistical sense) as part of the demand modelling process (see section 4.2.2.4.1). In all likelihood b_2 will have a small (negative) value. Note that the actual $\beta(h+k)$ value sent to the residents must be normalized from the raw $\beta'(k)$ values considered here according to $\beta(h+k) = (\beta'(h+k)+1)/2$ after the optimization has taken place.

Note that both the price and the demand may be shifted by the price signal $\beta'[k-1]$: thus the profit obtained at step k for ($k \geq h$) from sales to EPN residents only - $p(k)$ - is given by:

$p(k)$ = Demand at k x Price at k = $(D(k)+ b_2\beta'(k))$ x $((\beta'(k)+1)/2)$

Since the term $\beta'(k)^2$ appears after the expansion of the above expression, we have a quadratic term in the objective function; it is hence convex in the decision parameters.

Define the expected profit for step k as the difference between the (i) energy sold to residents and IETs and (ii) the energy purchased from IETs or residents (neglecting the commitments already made):

$$\begin{aligned}\text{Profit}(k) = &\sum_{j=0}^{n-1} X_D[j](k)\cdot P_D[j](k) + 0.5\cdot P\cdot D(k) + 0.5\cdot P\cdot\beta'(k)\cdot D(k) + 0.5\cdot P\cdot b_2\beta'(k)^2 + 0.5\cdot P\cdot b_2\cdot\beta'(k)\\ &-\sum_{j=0}^{n-1} X_S[j](k)\cdot P_S[j](k) - 0.5\cdot P\cdot S_R(k) - 0.5\cdot P\cdot\beta'(k)\cdot S_R(k)\end{aligned}$$

Then the total expected profit made across the horizon H at hour h can be formed from the available data as:

$$\text{Profit}_{\text{H}}(h) = \sum_{i=0}^{H-1}\text{Profit}(h+i)$$

Define the optimization problem to be solved at hour h:

Maximize{$\text{Profit}_{\text{H}}(h)$}

With respect to:

$X_S[i](h+j)$, $i = 1, 2, 3, \ldots, n$: $j = 0, 1, 2, 3, \ldots, H$-1;
$X_D[i](h+j)$, $i = 1, 2, 3, \ldots, n$: $j = 0, 1, 2, 3, \ldots, H$-1;
$X_C(h+i)$, $i = 0, 1, 2, 3, \ldots, H$-1;
$\beta'(h+i)$, $i = 0, 1, 2, 3, \ldots, H$-1;

Subject to:

Energy balance constraints:

$$\forall i, 0 \le i \le H-1:$$
$$S(h+i) + S_C(h+i) + \sum_{j=1}^{n} X_S[j](h+i) + X_C(h+i) = D(h+i) + b_2\beta'(h+i) + D_C(h+i) + \sum_{j=1}^{n} X_D[j](h+i)$$

Resident Pricing Constraints:

$$\forall i, 0 \le i \le H-1:$$
$$-1 \le \beta'(h+i) \le 1$$

Energy storage constraints:

$$\forall i, 1 \le i \le H:$$
$$C(h+i) = C(h+i-1) - \max\{C_\alpha \cdot X_C(h+i-1), X_C(h+i-1)\}$$

Energy storage/retrieval rate and capacity constraints:

$\forall i, 1 \leq i \leq H:$
$C^{Min} \leq C(h+i) \leq C^{Max}$
$\forall i, 0 \leq i \leq H-1:$
$\Delta C^{Min} \leq X_C(h+i) \leq \Delta C^{Max}$

Buying capacity constraints:

$\forall i, 1 \leq i \leq n: \sum_{k=0}^{H-1} X_S[i](h+k) \leq P_S^{Max}[i]$
$\forall i, 1 \leq i \leq n:$
$\forall j, 0 \leq j \leq H-1:$
$0 \leq X_S[i](h+j) \leq P_S^{Max}[i](h+j)$

Selling/supply capacity constraints:

$\forall i, 1 \leq i \leq n: \sum_{k=0}^{H-1} X_D[i](h+k) \leq P_D^{Max}[i]$
$\forall i, 1 \leq i \leq n:$
$\forall j, 0 \leq j \leq H-1:$
$0 \leq X_D[i][h+j] \leq P_D^{Max}(i)(h+j)$

7.3.7 Post-processing Phase

7.3.7.1 Housekeeping

The following housekeeping calculations shall be performed during the POS stage every hour:

1) Rolling averages of the electricity and heating demand and supply on a daily, weekly and monthly timescale will be recursively calculated as appropriate.

2) The energy quantity solution variables will be rounded to the nearest whole Watt.

3) The true energy stored/retrieved from the storage facility during the last hour $X_C(h\text{-}1)$ is calculated from $X_C(h\text{-}1) = C(h) - C(h\text{-}1)$.

3) All non-zero IET solution variables (X_S, X_D) for IED2 though to IED*n* across the horizon will be immediately processed as follows to schedule the transactions. (Purchases): For any non-zero $X_S[i](h+k)$, the corresponding value of $S_c(h+k)$ shall be incremented by $X_S[i](h+k)$ and R decremented by $X_S[i](h+k)$ x $P_S[i](h+k)$. (Sales): For any non-zero $X_D[i](h+k)$, the corresponding value of $D_c(h+k)$ shall be incremented by $X_D[i](h+k)$ and R incremented by $X_D[i](h+k)$ x $P_D[i](h+k)$. Note: IED1 is not processed as above.

3) The total profit or loss will be further updated using the measured (known) values of supply and demand from the last hour as follows. (Transactions with residents): R shall first be recomputed as $R = R + \{\beta(h\text{-}1)\text{x}(D(h\text{-}1)\text{-}S_R(h\text{-}1))\}$. (Failure to deliver upon commitments): R shall next be recomputed as:

$$\Delta = S(h-1) + S_C(h-1) + X_C(h-1) - D(h-1) - D_C(h-1)$$
$$R(h) = R(h) + \begin{cases} \Delta \cdot P_D[1](h-1) & \text{if } \Delta \geq 0 \\ \Delta \cdot P_S[1](h-1) & \text{if } \Delta < 0 \end{cases}$$

4) The value of T corresponding to the target electricity usage at the end of the current hour

is computed by iterating the electricity demand prediction equation once:

5) The current live hour price P^* is made directly available from $\beta(t)$ for convenience.

7.3.7.2 KPI Calculations

The following KPIs shall be calculated during the POS stage every hour:

1) The filtered absolute percentage prediction error for hourly electricity demands (E_E) shall be recursively calculated every hour h with a first-order filter having time-constant of 8 hours using the relationship:

$$E_E = 0.882 \cdot E_E + 0.118 \cdot 100 \cdot \left| \frac{D(h-1) - \hat{D}(h-1)}{D(h-1)} \right|$$

If the value of E_E is below a pre-determined threshold value (say 5%), the KPI status will be considered to be True (1), otherwise it will be considered to be False (0). The threshold value will be fine-tuned during prototyping.

2) The filtered absolute percentage prediction error for hourly electricity supplies (E_S) shall be recursively calculated every hour h with a first-order filter having time-constant of 8 hours using the relationship:

$$E_E = 0.882 \cdot E_E + 0.118 \cdot 100 \cdot \left| \frac{S(h-1) - \hat{S}(h-1)}{S(h-1)} \right|$$

If the value of E_S is below a pre-determined threshold value (say 5%), the KPI status will be considered to be True (1), otherwise it will be considered to be False (0). The threshold value will be fine-tuned during prototyping.

3) At the first available time after 16:00 every day d, the filtered absolute prediction error for EPN daily heating demands (E_H) shall be recursively calculated with a first-order filter having time-constant of 8 days using the relationship:

$$E_H = 0.882 \cdot E_H + 0.118 \cdot \left| \frac{D_{DH}(d-1) - \hat{D}_{DH}(d-1)}{D_{DH}(d-1)} \right|$$

If the value of E_H is below a pre-determined threshold value (say 5%), the KPI status will be considered to be True (1), otherwise is will be considered to be False (0). The threshold value will be fine-tuned during prototyping.

4) At 00:00 every day d, the filtered absolute prediction errors for Nordpool price predictions (E_P) shall be recursively calculated with a first-order filter having time-constant of 8 days using the relationship:

$$E_P = 0.882 \cdot E_P + \frac{0.118}{24} \cdot \sum_{i=0}^{23} \left| \frac{P_S[1](h+i) - \hat{P}_S[1](h+i)}{P_S[1](h+i)} \right|$$

If the value of E_P is below a pre-determined threshold value (say 5%), the KPI status will be considered to be True (1), otherwise is will be considered to be False (0). The threshold value will be fine-tuned during prototyping.

5) The filtered optimizer percentage error indicator (E_O) shall be recursively calculated every hour h with a first-order filter having time-constant of 8 hours using the relationship:

$$E_O = 0.882 \cdot E_O + 0.118 \cdot \begin{cases} 0: & \text{Optimization was sucessful at step } h \\ 100: & \text{Optimization was not sucessful at step } h \end{cases}$$

If the value of E_O is below a pre-determined threshold value (say 10%), the KPI status will be considered to be True (1), otherwise is will be considered to be False (0). The threshold value will be fine-tuned during prototyping.

6) The filtered EPN Energy Positivity Indicator EPI shall be recursively calculated as a percentage every hour *h* with a first-order filter having time-constant of 224 hours (one month) using the relationship:

$$EPI = 0.996 \cdot EPI + 0.004 \cdot 100 \cdot \frac{\Delta}{D(h-1) + D_C(h-1)}$$

If the value of E_O is above a pre-determined threshold value (0%), the KPI status will be considered to be True (1), otherwise is will be considered to be False (0). The threshold value will be fine-tuned during prototyping.

Please note that other KPIs (e.g. related to CO_2 emissions) may be developed as-needed during the prototyping stages of the project.

7.3.7.3 Decision Support

The following two rules shall be implemented to control the creation of global message strings contained in the structure EPNMSG every hour *h*:

Rule 1 Message (high prices):
IF ((KPI1 == TRUE) AND (KPI2 == TRUE) AND (KPI5 == TRUE)) THEN:
IF (($\beta(h) > \beta^{Max}$) AND (No Rule 1 messages in last 4 hours)) THEN:
EPNMSG = "The price has been increased this hour to try to reduce energy consumption in the EPN!"
END IF
END IF

Rule 2 Message (low prices):
IF ((KPI1 == TRUE) AND (KPI2 == TRUE) AND (KPI5 == TRUE)) THEN:
IF (($\beta(h) < \beta^{Min}$) AND (No Rule 2 messages in last 4 hours)) THEN:
EPNMSG = "The price has been reduced in this hour to try to increase energy consumption in the EPN!"
END IF
END IF

The following rule shall also be implemented to control the creation of global message strings contained in the structure EPNMSG at 16:00 every day *d*:

Rule 3 Message (low temperatures / district heating):
IF (KPI3 == TRUE) THEN:
IF (($\max_{1 \le i \le 4}\{D_{DH}(d+i)\} > DH_L$) AND (No Rule 3 messages in last 3 days)) THEN:
EPNMSG = "We predict the low temperatures will place excessive demands upon the district heating system in the coming days. Please consider to lower your central heating setting by 2° if you have not already done so!"

END IF

END IF

The threshold values, structure of the rules and message contents may be fine-tuned during prototyping. It should be understood that local decision support for the residents will also be performed using the home user energy application: refer to D3.3 for details.

7.3.8 Data distribution phase

The solution data is made available for ancillary displays, user interfaces and simulated equipment by updating the appropriate record in the database. Exact timings for the data availability for partner sites will be determined during prototyping. Solution data is also refreshed and embedded into a specific webpage hosted by the IOC: refer to IDEAS deliverable D3.3 or further details.

7.3.9 Summary of Database Structure

In order to appropriately size the databases for the Finnish demonstration site, the following table provides a summary of the global data structures. It is suggested that space be provisioned to allow at least 12 months of data for each variable to be retained.

Name	Type	Spec Ref	Units	Element	Size(r)	Size(c)	Resol.
Area Energy Demand (Elec)	real	D	kWh	AEDEz	1	H, D, W, M	3 d.p.
Area Energy Demand (Heat)	real	D_{Dh}	kWh	AEDHz	1	D, W, M	3 d.p.
Area Energy Supply (Elec)	real	S	kWh	AESEz	1	H, D, W, M	3 d.p.
Area Energy Demand (Ave)	real	N/A	kWh	AEDAz	1	H, D, W, M	3 d.p.
Control Area Demand (Elec)	real	N/A	kWh	CAEDEz	1	H, D, W, M	3 d.p.
Control Area Demand (Heat)	real	N/A	kWh	CAEDHz	1	D, W, M	3 d.p.
Control Energy Demand (Ave)	real	N/A	kWh	CAEDAz	1	H, D, W, M	3 d.p.
Area Committed Demand (Elec)	real	Dc	kWh	ACDE	1	H	3 d.p.
Area Committed Supply (Elec)	real	Sc	kWh	ACSE	1	H	3 d.p.
Area Agg Level (Elec)	int	N/A	Houses	AALE	1	L	0 d.p.
Area Agg Level (Heat)	int	N/A	Houses	AALH	1	L	0 d.p.
Control Area Agg Level (Elec)	int	N/A	Houses	CAALE	1	L	0 d.p.
Control Area Agg Level (Heat)	int	N/A	Houses	CAALH	1	L	0 d.p.
Area Energy Storage (Elec)	real	C	kWh	AECE	1	H	3 d.p.
Grid CO_2 Emission Cost	real	E	g/kWh	CO2C	1	H	1 d.p.
Weather (Temp #1)	real	Fd/Fs	°C	WFT1	1	H	3 d.p.
Weather (Insolation #1)	real	Fd/Fs	J/mm^2	WFI1	1	H	3 d.p.
Weather (Cloud Cover #1)	real	Fd/Fs	% age	WFC1	1	H	3 d.p.
Weather (Wind Speed #1)	real	Fd/Fs/Fp	KpH	WFWS1	1	H	3 d.p.
Weather (Wind Direction #1)	real	Fd/Fs/Fp	°	WFWD1	1	H	3 d.p.
Weather (Wind Speed #2)	real	Fd/Fs/Fp	KpH	WFWP2	1	H	3 d.p.
Weather (Wind Direction #2)	real	Fd/Fs/Fp	°	WFWD2	1	H	3 d.p.
Weather (Precipitation)	real	Fd/Fs/Fp	mm/h	WFP	1	H	3 d.p.
IET xx Energy Price (buy)	real	Ps	Eur/kWh	IETxxPB	10	H	2 d.p.
IET xx Energy Price (sell)	real	Pd	Eur/kWh	IETxxPS	10	H	2 d.p.
IET xx Energy Limit (buy)	real	Ps	kWh	IETxxLB	10	H	3 d.p.
IET xx Energy Limit (sell)	real	Pd	Eur/kWh	IETxxLS	10	H	3 d.p.

IET xx Total Energy Limit (buy)	real	PsT	kWh	IETxxTB	10	L	3 d.p.
IET xx Energy Limit (sell)	real	PdT	kWh	IETxxTS	10	L	3 d.p.
IET xx Solution (buy)	real	Xs	kWh	IETxxSB	10	H	3 d.p.
IET xx Solution (sell)	real	Xd	kWh	IETxxSS	10	H	3 d.p.
Resident Energy Price (Elec)	real	β	Eur/kWh	REPE	1	H	3 d.p.
Storage Variables Sol (Elec)	real	Xc	kWh	SVSE	1	H	3 d.p.
Current Hour End Target (Elec)	real	T	kWh	CHETE	1	L	3 d.p.
Current Hour Price (Elec)	real	P*	Eur/kWh	CHPE	1	L	3 d.p.
EPN Cycle Status	int	N/A	N/A	EPNSTAT	1	L	0 d.p.
EPN Cycle Count	int	k	Cycles	EPNCNT	1	L	0 d.p.
EPN KPIs	int	KPI	N/A	EPNKPI	1	L	0 d.p.
EPI (Short Term)	real	EPI	% age	EPIST	1	H	2 d.p.
EPI (Long Term)	int	EPI	% age	EPILT	1	L	0 d.p.
EPN Global Message	string	N/A	N/A	EPNMSG	1	L	N/A
EPN Profit/Loss	real	R	Eur	EPNPL	1	L	2 d.p.

NB1: ‘xx’ is integer in the range 01 – 10, ‘z’ is a single char mnemonic from the list of letters ‘H’, ‘D’, ‘W’, ‘M’ or ‘L’, see below.

NB2: Size(r) = number of rows (vertical size of array), size(c) = number of columns (horizontal size of array). The following codes are used to enumerate the column index sizes (and control access formats):

‘H’ = hourly (8760 entries/variable/year)

‘D’ = daily (365 entries/variable/year)

‘W’ = weekly (52 entries/variable/year)

‘M’ = monthly (12 entries/variable/year)

‘L’ = live data, continuously updated, no history kept

NB43 wind speed and wind direction are likely to be needed for two sites: 1 refers to the demo site and 2 refers to Denmark (for prediction of Elspot prices).

NB4: EPNSTAT is an enumerated representation of the cycle state (see figure 18).

The enumeration is:

0x00 = EPN Is Idle

0x01 = EPN is in DAQ phase

0x02 = EPN is in PRE phase

0x03 = EPN is in OPT phase

0x04 = EPN is in POS phase

0x05 = EPN is in DIS phase

It is assumed that the status indicator is updated by the EMS automatically.

NB5: EPNKPI is a bitwise enumeration of the current EPN KPIs (see section 7.3.7.2).

The enumeration is:

Bit 0: Demand Model (Elec) Convergence (1 = OK, 0 = NOT OK)

Bit 1: Supply Model Convergence (1 = OK, 0 = NOT OK)

Bit 2: Demand Model (Heat) Convergence (1 = OK, 0 = NOT OK)

Bit 3: Price Model Convergence (1 = OK, 0 = NOT OK)

Bit 4: Optimization Healthy (1 = OK, 0 = NOT OK)

Bit 5: Area is Energy Positive (1 = OK, 0 = NOT OK)

NB6: EPN Global Message is a formatted string containing the text of the last global message made available to the EPN (section 7.3.7.3).

NB7: It is unsure at this stage how the area averages (AEDA and CAEDA) will be calculated: it is likely this will be done in the POS server and the information sent directly.

NOTE: the data above is subject to changes during the prototyping phases of the IDEAS project. Specific read/write permissions may be set for the demonstration stage of the project.

7.4 Appendix D: Simulation Models for Virtual Resources

7.4.1 Solar PV generation model

A mathematical model is used to calculate the solar panel power generation output. This model is proposed by Richardson and Thomson (2011). This model is composed of various validated sub-models. This model gives the power generated by the solar panel(s) at any instant. This is capable of short time step (high resolution) simulation depending on the resolution of input data.

According to this model, the maximum power will be generated by the solar panel at solar noon. The power generated by the solar panel depends on the atmospheric and weather conditions. Also, according to this model, the power output of the solar panel is dependent on the intensity of the solar irradiance falling on the solar panel. In this model, a method is proposed to synthetically calculate the intensity of the solar irradiance. The model is able to generate synthetic irradiance data for any geographical location. According to this model, in clear sky conditions, the irradiance is maximum at the middle of the day. The irradiance value is decreased due to overhead clouds and due to changing weather conditions. This model is able to synthetically calculate the irradiance at the surface, when the sky is clear. It can also simulate the attenuation in irradiance due to changing weather conditions (overhead clouds).

7.4.1.1 Modelling the clear sky outdoor irradiance

According to this model, the clear sky irradiance at any given location (specified by longitude and latitude) can be approximated through the calculation of the position of the sun. This model also takes into account the day of year and the local time of the day. This model takes into account clock variation such as Daylight Saving Time (DST). This irradiance model uses the approach presented by Dusabe, Munda and Jimoh (2009), and Masters (2004). According to this model, the clear sky solar irradiance at the surface is equal to the sum of these components:

1. Direct irradiance
2. Diffuse irradiance
3. Reflected irradiance

All these components are a function of the direct solar beam radiation from the sun at the surface. The direct beam irradiance depends on the solar irradiance outside the earth atmosphere as well as the variation in solar irradiance, when the beam passes through earth's atmosphere. In this model, the effect on solar irradiance when passing through earths atmosphere is described the coefficient "optical depth" of the atmosphere. This coefficient takes into account the distance travelled through atmosphere, beam scattering and absorption. For the clear sky case, the optical depth represents atmospheric conditions without cloud. According to Goswami et al. (2000), the extra-terrestrial solar irradiation intensity at a point outside the atmosphere depends on the variation of the distance of the earth from the sun during the year

In Australian government (2010), The Equation of Time provides the relationship between the time of solar noon and the actual local time at the given latitude. This takes into account the Earth's rotation angle and the eccentricity of the orbit. The clear sky irradiance model output is the clear sky beam irradiance at the horizontal surface, solar altitude and azimuth. A limitation of the clear sky irradiance model is that it does not take into account the attenuation in solar irradiation due to passing clouds. This limitation is addressed by defining a clearness index as given next.

7.4.1.2 Modelling attenuation in solar irradiation due to clouds

The attenuation in solar irradiation due to passing clouds is a complex and random phenomenon. A simple method to model solar irradiation attenuation due to clouds is given in Skartveit and Olseth (1992). They have defined a simple coefficient called "clearness index". A clearness index of 1.0 means clear sky conditions, clearness index of 0.5 means that the cloud conditions is allowing only half of the clear sky solar irradiation to reach the surface. Mathematically, it is written as:

$$\begin{aligned} &Irradiance\ at\ surface\ due\ to\ clouds \\ &\qquad = clear\ sky\ surface\ irradiance \times Clearness\ Index \end{aligned}$$

The clearness index is variable as the cloud cover and atmospheric conditions change. A time series of synthetic or real world clearness index for a particular region can be generated. For this model to calculate the solar irradiance and solar power generated, the table of input parameters and their units is given below:

Inputs		
Value	**Unit**	**Source**
Latitude	Degrees	User defined
Longitude	Degrees	User defined
Day of the year n	Integer (1-365)	User defined
Local time hours	0-23	User defined
Local time minutes	0-59	User defined
Day of the year summer starts	Integer (1-365)	User defined
Day of the year summer ends	Integer (1-365)	User defined
Local standard time (LSTh) hours	0-23	Calculation (summer time offset)
Local standard time (LSTm)(minutes)	0-59	Calculation (summer time offset)
Local standard time meridian (LSTM)	Degrees	User defined
Slope of panel	Input (degrees)	User defined
Azimuth of panel	Input (degrees)	User defined
Ground reflectance ρ	Input (for example 0.2)	User defined
Solar Panel area A	Input	User defined
System efficiency η	Input (0.0-1.0)	User defined
Sky clearness Index SCI	0.0(full cloud) -1.0 (clear sky)	Weather station

B is given by:

$$B^{\circ} = (n - 81) \times \left(\frac{360}{364}\right)$$

The Equation of time, which describes the difference between a 24 hour day and a solar day, is given by:

$$E^{\circ} = 9.87 sin2B - 7.53 cosB - 1.5 sinB$$

Time correction factor is given by:

$$TCF = \left(4 \times (Longitude^{\circ} - LSTm^{\circ})\right) + E^{\circ}$$

Hours before solar noon is given by:

$$HBSN = 12 - \left(LSTh + \frac{LSTm}{60} + \frac{TCF}{60}\right)$$

Extra-terrestrial radiation G_0 is given by:

$$G_0 = 1367 \times \left(1 + \left(0.034 \times cos\left(\frac{360 \times n}{365.25}\right)\right)\right)$$

The optical depth k is given by:

$$k = 0.174 + 0.035sin\left(\frac{360(n-100)}{365}\right)$$

The hour angle H is the angle in degrees that the earth must rotate such that the sun will be directly over the local meridian (line of longitude). As the earth rotates 360 degrees in 24 hours, or 15 degrees in 1 hour, the hour angle can be written as:

$$H = \left(\frac{15°}{hour}\right) \times HBSN$$

Declination δ is the angle between the plane of the equator and a line drawn from the centre of the earth. It is given by:

$$\delta = 23.45sin\left(\frac{360(284+n)cos\delta sinH}{365.25}\right)$$

Solar altitude angle β is given by:

$$\beta = sin^{-1}(cosLcos\delta cosH + sinLsin\delta)$$

The azimuth and altitude angles of the sun depend on the latitude, day number, and the time of day.

The azimuth of sun $\emptyset_S$ is given by:

$$\emptyset_S = sin^{-1}\left(\frac{cos\delta sinH}{cos\beta}\right)$$

A test must be done to determine whether the azimuth angel of the sun is greater or less than 90° away from south. This test is given as:

$$IF\ cosH \geq \frac{tan\delta}{tanL}, THEN\ abs(\emptyset_S) \leq 90°\ ; \text{OTHERWISE}\ abs(\emptyset_S) > 90°$$

Solar incident angle on panel θ will be a function of the collector orientation and the altitude and azimuth angles of the sun at any particular time:

$$\theta = cos^{-1}(cos\beta\cos(\emptyset_S - \emptyset_C)sin\Sigma + \ sin\beta cos\Sigma)$$

Clear sky beam radiation at surface (horizontal) G_B is given by:

$$IF\ \beta > 0 \quad THEN\ \ G_B = G_0 \times exp\left(\frac{-k}{sin\beta}\right), \qquad ELSE\ \ G_B = 0$$

Direct beam radiation on panel I_{BC} is given by:

$$IF\ abs(\theta) > 90 \quad THEN\ \ I_{BC} = 0\ , \qquad ELSE\ \ I_{BC} = I_B cos\theta$$

The approximation of sky diffuse factor C is given by:

$$C = 0.095 + 0.04\ sin\left(\frac{360}{365} \times (n - 100)\right)$$

The diffuse radiation on panel I_{DC} is given by:

$$I_{DC} = CI_B\left(\frac{1 + cos\Sigma}{2}\right)$$

The reflected radiation on the solar panel I_{RC} is given by:

$$I_{RC} = \rho I_B(sin\beta + C)\left(\frac{1 - cos\Sigma}{2}\right)$$

Total radiation on the panel (clear sky) I_{TOTAL} (W/m^2) is given by:

$$I_{TOTAL} = I_{BC} + I_{DC} + I_{RC}$$

Global outdoor irradiance (horizontal) I_{GLOBAL} is given by:

$$I_{GLOBAL} = I_{BC} + I_{DC} + I_{RC}$$

Net radiation on panel (cloud cover) I_{NET} (W/m2) is given by:

$$I_{NET} = SCI \times I_{TOTAL}$$

Power generated P_{PV} (W) by the solar panel is given by Paatero and Lund (2007):

$$P_{PV} = SCI \times I_{NET} \times A \times \eta$$

Where A is the area of panel (m2) and η is the efficiency of the solar panel.

7.4.2 Wind turbine generation model

The Wind turbine power generation model is proposed in (Hongxing, Wei and Chengzhi, 2009). The power output of the wind turbine depends on the wind speed. According to this model, the power output characteristics of a typical wind turbine can be approximated in the following way:

1. At cut-in wind speed v_C the wind turbine starts generating power.
2. As the wind speed is increased from v_C to rated wind speed v_R, the power output of the wind turbine increases linearly.
3. From v_R to cut-out wind speed, v_F, the power generated is equal to the rated power P_R.

The above can be written in the equation form as:

$$P_{WT} = \begin{cases} P_R \times \frac{v - v_C}{v_R - v_C} \ldots (v_C \le v \le v_R) \\ P_R \ldots (v_R \le v \le v_F) \\ 0 \ldots (v < v_C \; or \; v > v_F) \end{cases}$$

Where P_{WT} is the output power of the wind turbine at any instant. To calculate the instantaneous wind velocity at each sample interval, as this is essentially a random variable some knowledge of its distribution is needed. It is known that wind velocity can be closely approximated by a Weibull or Rayleigh distribution (Bradbury, 2013). Using the latter as it is easier to compute, the shape parameter of the distribution σ can be computed from knowledge of the average (mean) expected velocity μ according to the following relationship:

$$\sigma = \mu \cdot \sqrt{\frac{2}{\pi}}$$

As such, if U is uniformly distributed in the interval (0, 1), the wind velocity may then be calculated using the simple formula:

$$v = \sigma\sqrt{-2\ln(U)} = \mu\sqrt{\frac{-4\ln(U)}{\pi}}$$

7.4.3 Battery Model

Energy storage is mechanism by which energy is stored in any format for later use. Energy storage allows using energy from storage format/media when normal energy supply is in short supply or is expensive. Also, use of energy storage can reduce import and export of energy. Energy storage helps to cope with periods of excess or shortage of energy supply. There are many forms of energy storage. A suitable micro storage form is Lead-acid battery. There are many models proposed to simulate the behaviour of Lead acid battery. For real-time demand/supply matching, it is preferable to use minute resolution models. The battery model given below is proposed in Jenkins et al (2008).

This model takes into account power generation from AC (for example wind turbines) and DC (for example solar panels) sources and power losses in inverters, power electronic equipment and efficiently losses during battery charge and discharge cycles. In this model, the domestic load is assumes to be AC. The AC output from wind turbines is assumed to be regulated and the DC output from the solar panel is converted to AC by using an inverter. The model is flexible enough to allow simulation of different battery types and sizes. The Lead-acid battery model is described in Jenkins et al (2008). as follows: The inputs to this model is given in the Table below

Required input	Suggested default
electrical demand (kW)	Minutely profile
DC onsite generation (kW)	Minutely profile
AC onsite generation (kW)	Minutely profile
Voltage across cell (V)	2.1
Maximum discharge rate	C/5
Maximum charge rate	C/10
No. of cells in series n for each battery	User defined
No. of batteries in parallel	User defined
Maximum cell capacity C_{cell}	50 A h
Lower capacity limit of battery SOC	20%
Maximum capacity limit of battery SOC	100%
Number of batteries in parallel N	User defined
Storage capacity of battery pack containing N batteries in parallel C_0 (Ah)	Sum of capacities of N batteries in parallel
Battery-to-load inverter power rating (kW)	Based on max. discharge power
DC-to-load inverter power rating (kW)	Based on max. DC generation
Efficiency of charge controller	98%

An AC, DC generation, battery, load and grid configuration is given in Figure 19. The power calculation is given below:

7.4.3.1 Power at AC bus

The total power at the AC bus P_{BUS} is given as:

$$P_{BUS} = P_{AC} + \epsilon_A P_{DC}$$

Where P_{AC} and P_{DC} are the AC and DC power generated by their sources respectively and ϵ_A is the efficiency of "inverter A" (i.e. DC to bus). This efficiency is a function of the inverter power output and the inverter power rating.

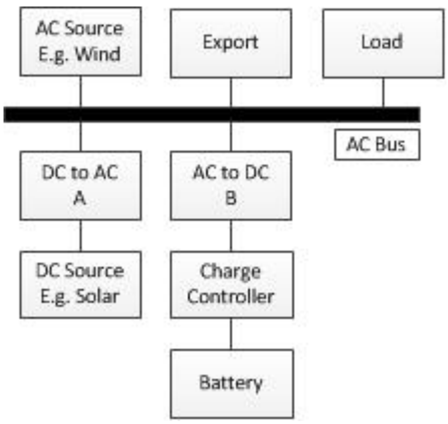

Figure 19: adapted from Jenkins et al (2008)

If the power demand of the building P_D is lower than the power available at the bus P_{BUS} at any time, then the surplus power P_+ is given by:

$$P_+ = P_{BUS} - P_D \quad , P_{BUS} > P_D$$

In a case where the power available at the bus is less than the power demand, the shortfall in power P_- is given by:

$$P_- = P_D - P_{BUS} \quad , P_D > P_{BUS}$$

According to this model, the power demand can only be satisfied if there is power surplus available at the bus. The power needed P_{RES} to satisfy the power demand is given by:

$$P_{RES} = P_{BUS} - P_+ \; , \; P_+ > 0$$

In a case where there is no power demand then $P_{RES} = 0$ and $P_+ = P_{BUS}$

7.4.3.2 Discharge and charge currents

Battery charge controller ensures protection and efficient operation. It will limit the charging and discharging current. Battery will receive charging current if it's not already fully charged and if there is power surplus available. The charge controller will limit the charging current to maximum allowed charging currentI_{Cmax}. According to this model, the value of the available charge current I_{C0} (i.e. ignoring the state of the battery) at any time is given by:

$$I_{C0} = \frac{P_+ \times \epsilon_C \times \epsilon_{B1}}{V_B}$$

Where ϵ_C is the efficiency of the charge controller (approx. 98%), ϵ_{B1} is the efficiency of the AC to DC converter and V_B is the voltage across the battery. V_B is equal to the product of the number of cells in series, n, and cell voltage VC (usually 2.1 V)). The actual charge current, I_C can have maximum value of I_{Cmax}. Similarly, the state of charge (SOC) of battery can have a maximum value of SOC_{max}.. for this model, the typical value of SOC_{max} is 100%. In case of power shortfall, the power demand will be partly or fully met by discharge of battery. The discharge current I_{D0} is given by:

$$I_{D0} = \frac{P_-}{V_B \times \epsilon_C \times \epsilon_{B2}}$$

Where ϵ_{B2} is the efficiency of the DC to AC inversion. The maximum value of discharge current is limited to I_{Dmax}. The state of charge is limited to minimum state of charge of SOC_{min}. For this model, the SOC_{min} is typically 20%.

7.4.3.3 Battery State of Charge (SOC)

The battery State of Charge (SOC) can be determined by knowing the values of charging current I_{C0} and discharging current I_{D0} at any given time. At 100% SOC, the total capacity C_0 of the battery pack (number of batteries connected in parallel) is given as:

$$C_0 = N \times C_i$$

Where N is the number of batteries in parallel and C_i is the capacity of the individual battery. When the battery is discharging, then the discharged capacity C_D (units A h) during interval Δt is given by:

$$C_D = \frac{I_D \times \Delta t}{\alpha} \quad , \quad 0 \leq \alpha \leq 1$$

Where α is the discharge efficiency given as:

$$\alpha = \frac{13.3 \times ln(C_0 \div I_D) + 59.8}{100}$$

For the previous equation the maximum value of, α will be limited to 1. This will ensure that maximum charge removed during time period Δt will be limted to $I_D \times \Delta t$. During charging, the change in battery capacity ΔC during time Δt is given by:

$$\Delta C = I_C \times \Delta t - C_D$$

$\Delta C$is negative during discharging and positive during charging. The battery capacity C_t at any time according to this model is given by:

$$C_t = C_{t-1} + \Delta C$$

Where C_{t-1} is the charge of the battery during the previous time period. This will be limited by the expression:

$$SOC_{min} \leq C_t \leq SOC_{max}$$

7.4.3.4 Power satisfying electrical demand

The local power generation will satisfy the building power demand, the battery charge demand, and export (if surplus power available.). The power demand is assumed always met and the as the power shortfall will be met by the grid. The power satisfied by the grid is given by:

$$P_{grid} = P_D - P_{BUS} - P_{batt} \qquad for\ P_D > P_{BUS}$$

Therefore:

$$P_{grid} = P_{-} - P_{batt}$$

Or:

$$P_{grid} = P_{-} - I_D \times V_B \times \varepsilon_{B2} \times \varepsilon_C$$

Where P_{batt} is the power output of the battery at any time. When no power is supplied by the battery, the power shortfall between the local power generation and the building power demand is met by the grid. Conversely, if the power shortfall is equal to the power supplied from the battery, there is no power supplied by the grid.

7.4.3.5 Exported power

It will be possible to export power if P_{+} is positive and battery is either fully charged or the charge current I_{C0} is greater than I_{Cmax}. The power exported P_{exp}, is given by:

$$P_{exp} = \left(\frac{I_{C0}}{\varepsilon_{B1} \times \varepsilon_{C}} - I_{C} \right) \times V_{B} \quad , \qquad for\ I_{C0} > I_{C}$$

The exported power is due to the difference in the available and allowed charge currents and the power electronics efficiencies.

7.5 Appendix E: Simplified EMS Interface Use Case

In this Appendix, only brief details are provided for the EMS interface. It is expected that an agile development procedure will be employed during prototyping to design the specific formats and presentation of the required data to the EPN FM.

7.5.1 Use Case Description

This use case describes the user interface for decision support for energy service companies (ESCos) for energy trading. It includes (i) the visualization of estimated future energy supply, demand and the optimal plan for buying, selling and/or storing energy and (ii) functionality for configuring the optimizer and acting upon the support information provided by the tool. The main justification for this use case is that intuitive user interfaces that display the likely future energy supply, demand and cost can help make energy service companies make informed decision regarding when to buy/sell energy and how much.

Http request are to be sent to the energy management system at a pre-defined interval (1 hour) to retrieve estimated energy supply, demand and pricing information. A UI will display this information. The system also enables sending committed sales/purchase request to the energy management system. The horizontal axis will display the time in hours. The vertical axis will display the energy supply, demand and cost of buying/selling energy. It would be possible to zoom into the graph for better visualization. The unit of energy in a time slot is kW.

7.5.2 Basic Flow of Events

1. The basic flow is triggered once an hour (at a preset clock offset from the hour).
2. At every trigger, an http request is sent from the UI to the EMS. The optimal solution for this hour and the predictions / solution data are requested.
3. The EMS returns a file with the data for estimated energy supply, energy demand (heat and electricity), prices and optimal buying/selling strategy. The granularity of information is 1 hour for electricity and is displayed for the next 48 hours, 1 day for heating for the next 10 days.
4. The energy supply, demand, and cost information for next 48 hours (electricity) and 10 days (heating) will be displayed by the user interface.
5. The user may zoom and adjust display as necessary.

7.5.3 Finnish Demonstration User Interface Flow Diagram

Please see Figure 20 overleaf.

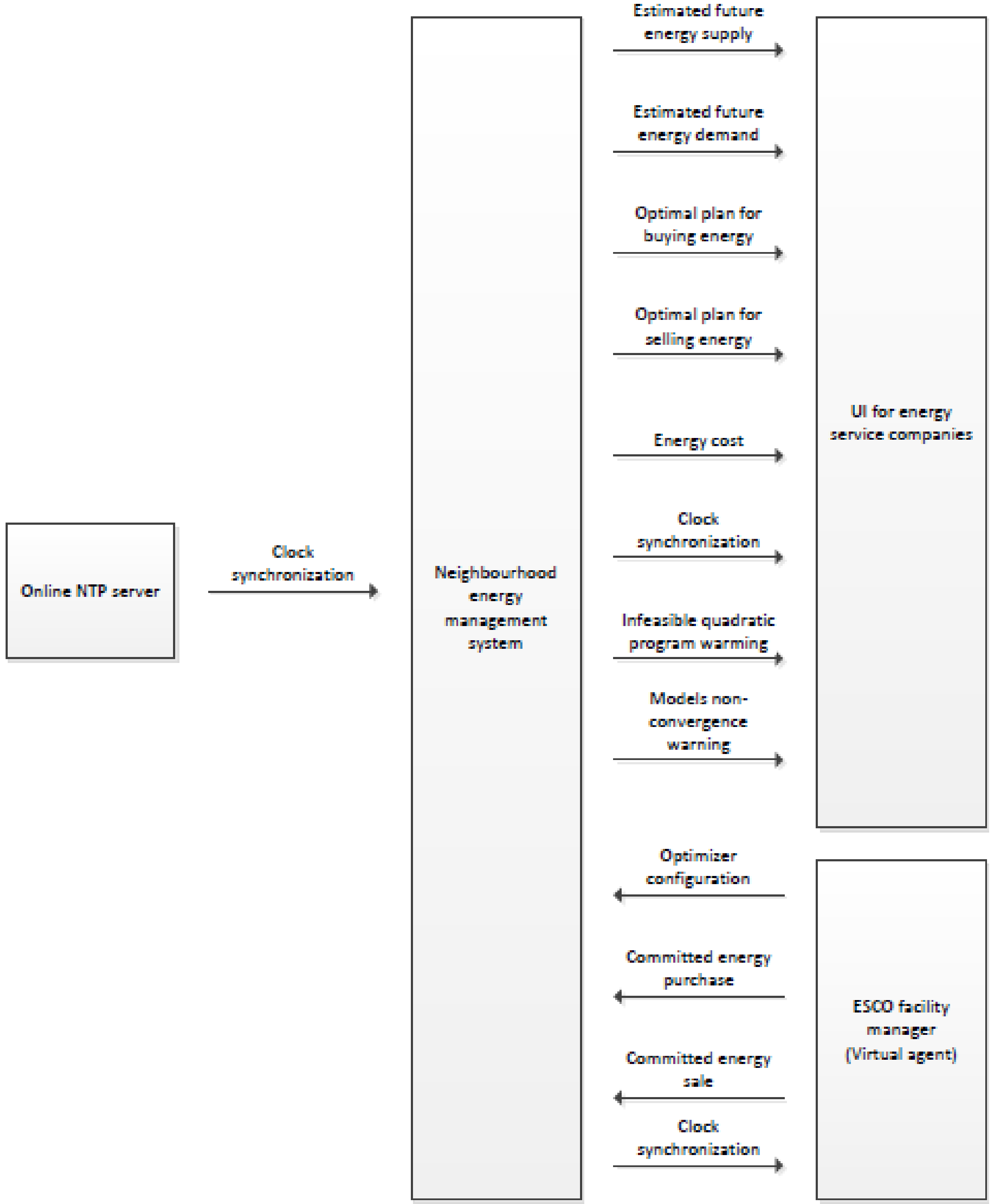

Figure 20: ESCo User Interface Flow Diagram Overview