Sustainable and intelligent management of energy for smarter railway systems in Europe: an integrated optimization approach


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Start date of project: 01/10/2012
Duration: 39 months
EXECUTIVE SUMMARY

This document describes D7.3 which has been delivered in the form of a proposal of UNIFE/UIC Technical Recommendation (TecRec).

In order to response to the need to have a better and more standardized integrated energy management, MERLIN partners have planned to prepare a proposal for Technical Recommendation which will serve as an input for the standardisation work of European Standardisation bodies such as CEN/CENELEC.

This proposal of Technical Recommendation will consider and analyze the architecture of the Railway Energy Management System (REM-S), including functions/components layers and the key elements of the sub-systems of a mainline railway system. The components layer will help identify where measurement equipment (energy meters) should be placed in the grid in order to achieve an integrated energy management.

Subsequently, it will provide an accurate energy consumption situation that will enable RUs and IMs together with MERLIN developments to measure/collect data on energy flows and help them decide on what components of the infrastructure grid to intervene in order to have better usage of energy/energy savings.

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Foreword

This MERLIN document (Proposal of TecRec Railway Energy Management System’s architecture and location of Energy Meters in the grid) has been prepared by a Working Group involving: UNIFE, UIC, ADIF, Alstom, Ansaldo STS, CAF, D’Appolonia, FFE, RFF, RENFE, MerMec, Oltis, Ansaldo Breda, Network Rail, Trafikverket and Siemens.

The content of this document has been prepared as a result of the outcomes of the EU funded project MERLIN – Sustainable and intelligent management of energy for smarter railway systems in Europe: an integrated optimisation approach.

The project partners involved have put forward the deliverable D7.3 included in Work Package 7 to UIC and UNIFE for its submission to the UNIFE/UIC SSG as a proposal of TecRec.

TecRecs are managed by a joint UIC/UNIFE standards management group that meets on a regular basis to coordinate the process. TecRecs can be downloaded by UNIFE and UIC members from the two organisations websites: www.uic.org and www.unife.org.

Introduction

This document is a deliverable (D7.3) of the EU founded project MERLIN and represents a draft proposal for TecRec.

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1 SCOPE

In order to response to the need to have a better and more standardized integrated energy management, MERLIN partners have planned to prepare a proposal for Technical Recommendation which will serve as an input for the standardisation work of European Standardisation bodies such as CEN/CENELEC.

This proposal of Technical Recommendation will consider and analyse the architecture of the Railway Energy Management System (REM-S), including functions/components layers and the key elements of the sub-systems of a mainline railway system. The components layer will help identify where measurement equipment (energy meters) should be placed in the grid in order to achieve an integrated energy management.

Subsequently, it will provide an accurate energy consumption situation that will enable RUs and IMs together with MERLIN developments to measure/collect data on energy flows and help them decide on what components of the infrastructure grid to intervene in order to have better usage of energy/energy savings.

2 NORMATIVE REFERENCES

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ENs are developed by CEN\(^1\) or CENELEC\(^2\) and are made available for their members.

NOTE 1: www.cen.eu

NOTE 2: www.cenelec.eu

EN 50125-1, Railway applications — Environmental conditions for equipment — Part 1: Equipment on board rolling stock

EN 50155:2007, Railway applications — Electronic equipment used on rolling stock

EN 50163:2004, Railway applications — Supply voltages of traction systems

EN 50388:2005, Railway applications — Power supply and rolling stock — Technical criteria for the coordination between power supply (substation) and rolling stock to achieve interoperability

EN 50463-1:2012, Railway applications — Energy measurement on board trains — Part 1: General


EN 50463-3:2012, Railway applications — Energy measurement on board trains — Part 3: Data Handling

EN 50463-4:2012, Railway applications — Energy measurement on board trains — Part 4:
Communication

EN 50463-5:2012, Railway applications — Energy measurement on board trains — Part 5: Conformity assessment


3 TERMS, DEFINITIONS AND ABBREVIATIONS

For the purposes of this document, the following terms and definitions apply.

3.1 CEN Comité Européen de Normalisation

3.2 CSP Concentrator photovoltaics

3.3 DAO Day-Ahead Optimisation

3.4 DER Distributed Energy Resources

3.5 DMS Distribution Management Systems

3.6 DOEM Dynamic Onboard Energy Manager

3.7 DSO Distribution System Operator

3.8 EBDM Energy Buyer Decision Maker

3.9 EM Electricity Market

3.10 EMO Electricity Market Operator
3.11
EMS
Energy Management Systems

3.12
EPP
Electricity Procurement Planner

3.13
ESO
Electrical System Operator

3.14
ESS
Energy Storage System

3.15
ETSI
European Telecommunications Standards Institute

3.16
EV
Electric Vehicle

3.17
GOS
Global Optimisation System

3.18
HMI
Human Machine Interface

3.19
IM
Infrastructure Manager

3.20
LOS
Local Optimisation System

3.21
LT
Long-Term (Contracts)

3.22
MAO
Minutes Ahead Optimisation

3.23
MAS
Multi-Agent System

3.24
MIP
Mixed Integer Programming
3.25
PCC
Point of common coupling

3.26
P.D.F.
Probability Density Function

3.27
PV
Photovoltaic

3.28
REM-S
Railway Energy Management System

3.29
RTO
Real Time Operation

3.30
RTU
Remote Terminal Unit

3.31
RU
Railway Undertaking

3.32
SGAM
Smart Grid Architecture Model

3.33
SO
System Operator

3.34
TSO
Transmission System Operator

3.35
VPP
Virtual Power Plant
4 GENERAL OPERATIONAL REM-S REFERENCE ARCHITECTURE

4.1 CONCEPT DESCRIPTION

This section describes the general concept behind the architecture of the Railway Energy Management System (REM-S), providing an overview of how the system has been built and the reference models followed. The detailed architecture of the system is also described.

The Railway Energy Management System is an integrated solution aiming at achieving a more sustainable and optimised energy usage in European electric mainline railway systems. This can be obtained through a system monitoring the energy consumptions of the different subsystems of the railway network and their components and suggesting a “smart” solution for the optimisation of use of energy in the different parts of the system.

Because of the distributed nature of the railway system, the system size, complexity and uncertainties, as well as the dynamic and moving nature of the loads, the energy management system can be based on dividing the railway system into different local areas (zones). At least one intelligent substation should be present in each zone, acting as interface for the zone entities. Hence, it should be able to communicate to the other local entities, to the intelligent substations of neighbouring zones and to the Control Centre, and through it to electricity market.

4.1.1 The Smart Grid Architecture Model (SGAM)

The architecture of the system has been developed according to the Smart Grid Architecture Model (SGAM), i.e. a reference model of smart grid architectures for different sectors of application issued by the CEN - CENELEC - ETSI Smart Grid Coordination Group and consists in the optimisation of the energy flow through the railway system at different levels.

The Smart Grid Architecture Model (SGAM) is a three dimensional model, merging the dimension of five interoperability layers with two dimensions of the Smart Grid Plane, as shown in Figure 1.
The Smart Grid Plane is made up of “Zones” - representing the hierarchical levels of power system management (Process, Field, Station, Operation, Enterprise and Market) and “Domains” covering the complete electrical energy conversion chain: Bulk Generation, Transmission, Distribution, Distributed Energy Resources and Customers Premises. The five interoperability layers (Business, Function, Information, Communication and Component) cover the whole Plane representing the third dimension of the Smart Grid model.

In order to allow a clear presentation of the architecture model, different interoperability layers are specified, as shown in Table 1.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Business</td>
<td>Represents the business view on the information exchange related to smart grids. SGAM can be used to map regulatory and economic (market) structures and policies, business models, business portfolios (products &amp; services) of market parties involved. Also business capabilities and business processes can be represented in this layer.</td>
</tr>
<tr>
<td>Function</td>
<td>Describes functions and services including their relationships from an architectural viewpoint. The functions are represented independent from actors and physical implementations in applications, systems and components. The functions are derived by extracting the use case functionality which is independent from actors.</td>
</tr>
<tr>
<td>Component</td>
<td>The physical distribution of all participating components in the smart grid context. This includes system actors, applications, power system equipment (typically located at process and field level), protection and telecontrol devices, network infrastructure (wired / wireless communication connections, routers, switches, servers) and any kind of computers.</td>
</tr>
<tr>
<td>Information</td>
<td>Describes the information that is being used and exchanged between functions, services and components. It contains information objects and the underlying canonical data models. These information objects and canonical data models represent the common semantics for functions and services in order to allow an interoperable information exchange via communication means.</td>
</tr>
<tr>
<td>Communication</td>
<td>To describe protocols and mechanisms for the interoperable exchange of information between components in the context of the underlying use case, function or service and related information objects or data models.</td>
</tr>
</tbody>
</table>

Table 1: SGAM Interoperability Layers

The power system can be represented by physical domains of the electrical energy conversion chain and hierarchical zones for the management of the electrical process; this is represented through the SGAM plane, as shown in Figure 2.
The Smart Grid Plane covers the complete electrical energy conversion chain. Table 2 lists and describes the SGAM domains.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Generation</td>
<td>Representing generation of electrical energy in bulk quantities, such as by fossil, nuclear and hydro power plants, off-shore wind farms, large scale solar power plant (i.e. PV, CSP)—typically connected to the transmission system</td>
</tr>
<tr>
<td>Transmission</td>
<td>Representing the infrastructure and organisation which transports electricity over long distances</td>
</tr>
<tr>
<td>Distribution</td>
<td>Representing the infrastructure and organisation which distributes electricity to customers</td>
</tr>
<tr>
<td>DER</td>
<td>Representing distributed electrical resources directly connected to the public distribution grid, applying mall-scale power generation technologies (typically in the range of 3kW to 10,000kW). These distributed electrical resources may be directly controlled by DSO</td>
</tr>
<tr>
<td>Customer Premises</td>
<td>Hosting both- end users of electricity, also producers of electricity. The premises include industrial, commercial and home facilities (e.g. chemical plants, airports, harbours, shopping centres, homes). Also generation in form of e.g. photovoltaic generation, electric vehicles storage, batteries, micro turbines…are hosted</td>
</tr>
</tbody>
</table>

Table 2: SGAM Domains

In Table 3 the definition of zones is provided. The zones reflect a hierarchical model considering the concept of aggregation and functional separation in power system management.
Including the physical, chemical or spatial transformations of energy (electricity, solar, heat, water, wind …) and the physical equipment directly involved (e.g. generators, transformers, circuit breakers, overhead lines, cables, electrical loads any kind of sensors and actuators which are part or directly connected to the process,…).

Including equipment to protect, control and monitor the process of the power system, e.g. protection relays, bay controller, any kind of intelligent electronic devices which acquire and use process data from the power system.

Representing the areal aggregation level for field level, e.g. for data concentration, functional aggregation, substation automation, local SCADA systems, plant supervision…

Hosting power system control operation in the respective domain, e.g. Distribution Management Systems (DMS), Energy Management Systems (EMS) in generation and transmission systems, microgrid management systems, virtual power plant management systems (aggregating several DER), Electric Vehicle (EV) fleet charging management systems.

Includes commercial and organisational processes, services and infrastructures for enterprises (utilities, service providers, energy traders …), e.g. asset management, logistics, work force management, staff training, customer relation management, billing and procurement…

Reflecting the market operations possible along the energy conversion chain, e.g. energy trading, mass market, retail market.

### Table 3: SGAM Zones

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>Including the physical, chemical or spatial transformations of energy (electricity, solar, heat, water, wind …) and the physical equipment directly involved (e.g. generators, transformers, circuit breakers, overhead lines, cables, electrical loads any kind of sensors and actuators which are part or directly connected to the process,…).</td>
</tr>
<tr>
<td>Field</td>
<td>Including equipment to protect, control and monitor the process of the power system, e.g. protection relays, bay controller, any kind of intelligent electronic devices which acquire and use process data from the power system.</td>
</tr>
<tr>
<td>Station</td>
<td>Representing the areal aggregation level for field level, e.g. for data concentration, functional aggregation, substation automation, local SCADA systems, plant supervision…</td>
</tr>
<tr>
<td>Operation</td>
<td>Hosting power system control operation in the respective domain, e.g. Distribution Management Systems (DMS), Energy Management Systems (EMS) in generation and transmission systems, microgrid management systems, virtual power plant management systems (aggregating several DER), Electric Vehicle (EV) fleet charging management systems.</td>
</tr>
<tr>
<td>Enterprise</td>
<td>Includes commercial and organisational processes, services and infrastructures for enterprises (utilities, service providers, energy traders …), e.g. asset management, logistics, work force management, staff training, customer relation management, billing and procurement…</td>
</tr>
<tr>
<td>Market</td>
<td>Reflecting the market operations possible along the energy conversion chain, e.g. energy trading, mass market, retail market.</td>
</tr>
</tbody>
</table>

### 4.1.2 SGAM and REM-S Architecture

The five layers defined in the SGAM have been identified in the REM-S architecture. Specifically, Function Layer and Component Layer are considered in the scope of this proposal for TecRec: Function Layer should consist in the definition of the functionalities of the REM-S, while Component Layer should consist in the definition and specification of components involved in Operational REM-S.

Business Layer consists in the definition of the REM-S missions. Those missions represent the operational objectives of the MERLIN project, i.e. what the Railway Energy Management system needs to achieve and realise. The REM-S missions are listed here in the following.

- To optimise the energy consumption needed for operating the railway system ensuring the fulfilment of the applicable performance requirements.
- To optimise the power demand needed for operating the railway system ensuring the fulfilment of the applicable performance requirements.
- To optimise the costs relevant to energy consumption needed for operating the railway system ensuring the fulfilment of the applicable performance requirements.
Figure 3 represents the general architecture of the REM-S and highlights the different levels of optimisation, i.e. the three corresponding “operational modes”: Day Ahead Optimisation (DAO), Minute Ahead Optimisation (MAO) and Real Time Operation (RTO).

On top of the diagram, the link to the electricity market is represented. This is performed by the EBDM, i.e. a module of the REM-S that determines the best way to purchase/sell the energy consumed/generated by the railway system managed by the REM-S.

The Energy Buyer Decision Maker helps determining the best way of combining the available contracts with the participation in the spot markets to optimize the price of the energy. The EBDM module uses as an input a list of constraints supplied by an external Electricity Procurement Planner (EPP) (bidding strategy, long term constrains for the bidding…). The Electrical Market Forecast Provider sends to the EBDM information regarding market prices previsions, behaviour of future sessions of the electricity market….

The zones (i.e. the intelligent substation) receive the day-ahead global optimisation plan from the Control Centre and implement it in their own area, locally accommodating unanticipated mismatches. As neighbouring zones are in contact, they can coordinate and resolve border issues about energy and power optimisation, like providing mutual support in case of variation of power demands and coordinating transition of trains. Multi-Agent System (MAS) technology may be applied for implementing energy management system in the zones.

Given that the generic load “railway system” interacts with the larger power system (public grid) and its market (electricity market), it makes sense to adopt a similar time structure for the energy optimisation, yielding three operational modes:
The main aim of the Day Ahead Optimisation (DAO) is to calculate the optimum behaviour of the network for the next 24/48 hours horizon; it is usually done once a day or when the MAO asks for a recalculation (due to a big deviation not solved in the Minutes Ahead Optimisation) but the periodicity of the calculation is configurable. DAO is performed by the component “Global Optimisation System” (GOS); the GOS is an intelligent module responsible for making a plan for the next 24/48 depending to the forecasted energy profiles, in order to optimise energy consumption, power demand and cost in the whole system. The main output of this application, i.e. the optimised day ahead power profile per subnetwork is sent to the component “Local Optimisation Application” (LOS).

MAO is a minutes ahead optimisation process, performed by the LOS; the main aim of this process is to follow the optimised 24 hours ahead power profile per sub-network coming from the DAO throughout the next minutes. The time interval considered in MERLIN for the Minutes Ahead Optimisation is 15 minutes, but this periodicity can be configured differently. The optimisation process is usually done every 15 minutes or when there is a deviation between the forecasted and the real behaviour of the system during the 15 minutes process that cannot be solved by the RTO control. Local Optimisation System is responsible for making the plan for the next 15 minutes depending to the real time measuring results and forecasted energy profiles, in order to follow the global energy consumption plan of the system and optimise energy consumption and power demand at its own local area.

The main aim of the Real Time Operation is to fulfil the calculated MAO profiles for the sub-network (optimised sub-network 15 minutes or the remaining of 15 minutes power profile), taking into account the real time status and behaviour of all the components of the sub-network, as well as the surpluses and needs of the adjacent sub-networks.

Figure 4 below represents the functions of the different operational modes above described and their implementation along the timeline.
Figure 5 depicts the energy management concept with the three modes of operation in time and location. In this architecture DAO runs a Global EMS (Energy Management System) for the whole railway network yielding energy, power or cost optimisation with a top-bottom approach based on train timetables and power estimation profiles, railway distribution network characteristics, Distributed Energy Resources estimated generation and External Consumers power estimated demand. In Minutes Ahead time slices, Local EMSs executed in each zone optimizes power profiles locally with the target of following Global EMS plan. The Local EMS is done by coordinating resources to address fast, unanticipated occurrences, such as use of regenerated energy from trains, surplus energy stored in Energy Storage Systems (ESSs) or request of more energy for a train which is delayed. This level of optimisation is the link between centralized EMS and the Real Time Operation in all zone agents. Solving one centralized optimisation problem for the short term flexibilities in the massive railway system is unfeasible, while applying the MAS approach with Local EMS, the short term (Minutes Ahead) optimisation is achievable.
4.1.3 The Business Case Overview

The Business case depicted in Figure 6 presents a general overview of the Business Actors of the system, their assigned Business Goals (represented with green rectangles) and the Business Cases (represented with yellow eclipses) performed by the Business Actors in order to reach the individual Business Goals. Each of the Business Cases is further detailed through the High Level Use Cases (represented with blue eclipses), which represents the high level functions of the REM-S.
4.2 REM-S ACTORS

The business model proposed for the REM-S includes some main business actors, contributing to implement the overall optimisation of energy flows in the railway system. The actors part of the system are presented in this section. The different actors have relationships among themselves through the business use cases above described. The operational Railway Energy Management System should collaborate with internal and external partners, and carry out the optimization measures. REM-S includes wayside and onboard parts. Specifically, on wayside, the global and local optimisation should be carried out and interfaces with the energy market are implemented; on-board, the indications received from on ground optimisation are applied.

The main business actors of the REM-S are described in the following.

The Electricity Market Operator represents any company in charge of all the operations required for the electricity market operation (receiving the purchasing/selling bids, matching process, billing….).
The **Electrical System Operator** role in a wholesale electricity market is to manage the security of the power system in real time and co-ordinate the supply of and demand for electricity, in a manner that avoids fluctuations in frequency or interruptions of supply.

The **Grid Owner** acts as Transmission System Operator (TSO) and Distribution System Operator (DSO). TSO is an entity entrusted with transporting energy in the form of electrical power on a national or regional level, using fixed infrastructure. DSO is responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution system in a given area and, where applicable, its interconnections with other systems and for ensuring the long term ability of the system to meet reasonable demands for the distribution of electricity.

**Infrastructure Manager (IM)** means any body or firm responsible in particular for establishing, managing and maintaining railway infrastructure, including traffic management and control-command and signalling; the functions of the Infrastructure Manager on a network or part of a network may be allocated to different bodies or firms.

**Railway Operator** means any public or private undertaking licensed according to the "Directive 2012/34/EU of the European Parliament and of the Council," Official Journal of the European Union, European Union, 2012., whose principal business is to provide services for the transport of goods and/or passengers by rail with a requirement that the undertaking ensure traction; this also includes undertakings which provide traction only. It may possess the rolling stocks and it is authorized with the access to the railway infrastructure.

An **Energy Supplier** refers to a party that supplies the customers or the market with electricity, and receives profits from the energy trading activities.

Beside SGAM business actors, linking business use cases and REM-S missions, SGAM actors (named "SGAM elements" the diagram below) have been identified. These represent the entities directly connected to the components, which will implement all system functionalities.

The SGAM Actors are described here below.

The **Forecast Provider** is an external entity which is in charge of forecasting the behaviour of future sessions of the electricity market (prices, energy purchased/sold…).

The **Global Optimisation System (GOS)** is responsible for making a plan for the next 24/48 depending to the forecasted energy profiles, in order to optimise energy consumption, power demand and cost in the whole system.

**Energy Buyer Decision Making (EBDM)** determines the best way to purchase/sell the energy consumed/generated by the railway system managed by the REM-S.

**Local Optimisation System (LOS)** is the main responsible for minutes ahead optimisation process; this consists in following the optimised 24 hours ahead power profile per sub-network coming from the DAO throughout the next minutes.

**Distribution Management System (DMS)** supports all operation activities at each subnetwork to dispatch energy internally or to the neighbour subnetwork.
4.2.1 Actors and Components

Component Layer consists in the definition and specification of components involved in Operational REM-S. SGAM Actors of the REM-S are in relationship with the components as shown in Figure 7.

Each component is responsible for the implementation of a function, as shown in the following table; for each function, the name of the relevant component is highlighted, as well as a description of how it can support the REM-S functions.

Components can include system actors, applications, power system equipment, protection and tele-control devices, network infrastructure (wired/wireless communication connections, routers, switches, servers) and any kind of computers.
<table>
<thead>
<tr>
<th>Function</th>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy trading Estimation</td>
<td>Energy trading Application</td>
<td>Calculating the next day energy price forecast by estimation algorithms</td>
</tr>
<tr>
<td></td>
<td>Marketplace system</td>
<td>Getting information about sellers and buyers in order to be able to apply estimation algorithms</td>
</tr>
<tr>
<td>Creation of forecast EC power demand (day ahead)</td>
<td>IM server</td>
<td>Gathering historic data about ECs, check weather forecast and apply forecasting algorithm</td>
</tr>
<tr>
<td>Creation of forecast DER power generation (day ahead)</td>
<td>DER EMS and VPP system</td>
<td>Gathering historic data about DERs energy generation, check weather forecast and apply forecasting algorithm</td>
</tr>
<tr>
<td>Creation of forecast RU power profile (day ahead)</td>
<td>RU server</td>
<td>Gathering historic data about train timetables, fleet characteristics, weather forecast</td>
</tr>
<tr>
<td>Global optimisation</td>
<td>HMI</td>
<td>The interface which is considered in order to prepare a display for the whole system and make the possibility to control the system manually at the Control Centre.</td>
</tr>
<tr>
<td></td>
<td>Router</td>
<td>To communicate Global Optimisation internally to the Subnetworks, Energy trading application and Marketplace system and to Public Network infrastructure.</td>
</tr>
<tr>
<td></td>
<td>RTU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EMS/SCADA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EMS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Global optimisation Application</td>
<td>Supports the intelligent part of Global Optimisation function which contains optimisation algorithm in order to prepare day ahead energy profile proposal for the whole system (Subnetworks, Energy trading, …)</td>
</tr>
<tr>
<td>Audit</td>
<td>Global optimisation Application</td>
<td>Check optimisation results with IM and RU constraints</td>
</tr>
<tr>
<td>Energy trading</td>
<td>Router</td>
<td>To communicate Energy trading internally to Global Optimisation and Marketplace system and externally to Electricity Market</td>
</tr>
<tr>
<td>Function</td>
<td>Component</td>
<td>Description</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>----------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Energy trading Application</td>
<td></td>
<td>To calculate best price for buying and selling energy according to received</td>
</tr>
<tr>
<td></td>
<td></td>
<td>information and to calculate the deviation between the estimated price and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the real price at the closure of the market to decide whether Global</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Optimisation function is needed or not.</td>
</tr>
<tr>
<td>Marketplace system</td>
<td></td>
<td>Prepare information for this function about the buyers and sellers and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>negotiate with them</td>
</tr>
<tr>
<td>Mapping scheduling to subnetworks consumption</td>
<td>Global optimisation Application</td>
<td>Distribute the next optimal power profile to all subnetworks</td>
</tr>
<tr>
<td>Deviation Alert MAO</td>
<td>Global optimisation Application</td>
<td>Re-launch the optimisation algorithm based on the triggers received from MAO</td>
</tr>
<tr>
<td>Reporting</td>
<td>Meter Data Management System</td>
<td>Do necessary analysis to develop useful information from gathered data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>which would be useful for managerial report</td>
</tr>
<tr>
<td></td>
<td>Data Storage</td>
<td>Store information and reports</td>
</tr>
<tr>
<td>Billing</td>
<td>Data Storage</td>
<td>Send required information to Billing and store the calculated bills</td>
</tr>
<tr>
<td></td>
<td>Router</td>
<td>To communicate Billing internally to Data Storage, RU IM and externally to</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grid owner and Energy Suppliers</td>
</tr>
<tr>
<td></td>
<td>RTU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Billing Application</td>
<td>Calculate the energy bill based on received measured information</td>
</tr>
</tbody>
</table>

Table 4: REM-S Functions and Components
4.3 SGAM LAYERS (FUNCTION AND COMPONENTS)

4.3.1 Introduction

Based on SGAM Model defined in section 4.1.1 Function and Components interoperability layers are chosen to best describe Railway Energy Management System’s architecture. While functions are categorised into operational modes (Day Ahead Optimisation (DAO), Minutes Ahead Optimisation (MAO) and Real time operation (RTO), components are defined individually matching high level function defined in previous chapters with requirements to fulfil tasks.

4.3.2 Function layer

4.3.2.1 Day Ahead Optimisation (DAO)

The Day Ahead Optimisation should perform the two basic functions to optimise the power/energy consumption and energy costs of the whole network.

This should be performed for the next 24/48 hours (or during the remaining of the 24 hours if optimisation is re-launched after major deviations), trying to reduce the peaks of power and the total amount of consumed energy.

The optimisation should be based on information coming from Infrastructure Manager and Railway Undertaking, such as status of the network, timetable, current consumption restrictions, prediction of generation and consumptions received from Distributed Energy Resources and External Consumers and real time status of each equipment from the RTO Real time data acquisition function.

The energy required at each PCC divided in blocks of given likelihood, for each hour should be sent to the DAO Energy trading function.

When the price is fixed (railways not buying energy one day in advance), there is no cost optimisation. Optimisation of energy and power is only performed; this optimisation affects costs, but cost in this case is not a variable for optimisation.

Following typical DAO functionalities are attributed to the SGAM zones applicable in the function layer of the SGAM plane.
In the following the basic functions, which can cover all or several SGAM domains, are described in relation of the applicable SGAM zones.

**Market Zone.** At the Market zone the energy trading estimation function forecasts the price of the energy in order to calculate the global optimisation and, once the optimisation is calculated, the Energy trading function will buy the necessary energy at the best price possible.

**Enterprise Zone.** At the Enterprise zone, the billing function should calculate the real cost of the consumed energy and send this data to the Energy Suppliers, Grid Owner, IM and RU. The main aim of this function is to calculate the real cost of the consumed energy. In order to do that, this function will receive the real consumption per PCC, the real consumption per train and the real consumption per external consumer and take into account the contractual arrangements with IM, RU, Grid Owner and Energy Suppliers.

**Operation Zone.** At the Operation zone, the creation of forecast EC power demand function should forecast the power consumption of the ECs, the creation of forecasted power generation function should forecast the power generation of the DERs and the creation of forecasted power profile by RU function should forecast the power profile of the different trains. What is more, the Global Optimisation function should optimise the power and energy consumption of the whole network and the Audit function should check if the result of the Global Optimisation function fulfils the constraints received from IM and RU.

Once the optimisation has been checked, the Mapping scheduling to subnetwork consumption function should divide the optimised profile per subnetworks.

Once the DAO period is over, the Reporting function should check the performance of the optimisation, by comparing the expected consumption with the real one and this data should be stored in order to improve further optimisations.
Last but not least, the Deviation Alert_MAO function should check if it receives a notification from the MAO, indicating that there is a deviation between the MAO and the real status of the subnetwork that cannot be solved without recalculating the DAO.

Figure 9 and Figure 10 depict the high level use case models of the DAO Optimisation of energy/power and DAO Optimisation of price functions.

**Figure 9: High Level Use Case Model: DAO Optimisation of energy and power**
4.3.2.2 Minutes Ahead Optimisation (MAO)

MAO (Minutes Ahead Optimisation) is a periodic function whose main aim is to follow the optimised 24 hours ahead power profile coming from the DAO function throughout the next minutes, per sub-network. The time interval (validity period between executions) should be configurable and may depend on the application. Nevertheless, the MAO function should also take place if there is a deviation between the forecasted and the real behaviour of the system during such validity period which cannot be solved by the RTO control (see 4.3.2.3).

The MAO function should be executed by each of the LOS - Local Optimisation Systems (see 4.3.3.3) in a synchronised way.

According to the SGAM function layer (see Figure 11) the MAO function is placed at Operation covering areas from Customer Premises to Distribution, excluding both Transmission and Generation.
Figure 11: MAO in the SGAM function layer

The MAO function consists of several sub-functions:

- Local optimisation
- Day ahead power profile slicing
- Supervision
- Power mismatch calculation
- Negotiation
- Deviation alert and RTO triggering

Figure 12: MAO high level use case model
Day Ahead Profile Slicing

To execute the MAO function the LOS should receive the optimised day ahead consumption profile generated by the GOS component through the DAO function (see 4.3.2.1). This means all the LOS components and the GOS should be connected through the infrastructure manager’s intranet. The exact mechanism used to perform this transmission (GOS to LOS) is out of the scope of this document and it is not relevant to interoperability.

The consumption profile should then be sliced in a number of timeslots whose duration corresponds to the validity period (e.g. if the period is 15 minutes, 96 timeslots will be created). The granularity of the data is application dependant and may be affected by the billing procedure. For each timeslot the mean value of power should be obtained, if not provided directly by the GOS through the DAO function.

![Day ahead profile slicing](image)

Figure 13: Day ahead profile slicing

Supervision

The MAO function requires supervising activities in order to carry out the minutes ahead optimisation. Indeed, the function should collect data about the electrical status of the network including cost related data, to have a complete overview of available reservoir of energy and system constraints to optimise the following timeslot. In particular it needs information about:

- Actual power consumption at the substations of the LOS’ controlled zone
- Status of the electric network and power supply within the LOS’ controlled zone to assess its real and actual capacity
- Actual charge of any energy storage system located within the controlled zone
- Actual consumption of the infrastructure auxiliary loads (e.g. stations, buildings…) that are connected to the grid
- Available renewable energy sources connected to the grid and their actual performance
- Optionally, depending on the optimisation algorithms, real time information about the energy market (i.e. actual energy cost) could be considered.
Power mismatch calculation

This sub-function is in charge of comparing the forecasted power consumption with the actual measured values at substation level.

Local optimisation

Optimising the power and energy consumption is the ultimate goal of the MAO function. The objective is to minimise or even avoid any deviation between the actual consumption profile and the optimised profile obtained from the DAO function, balancing shortages and surpluses. This local optimisation process is limited to the next timeslot and takes into account the following inputs:

- Concerned DAO’s ahead profile slice
- Supervised data coming from the supervision process
- Power consumption/production forecast calculated by the grid agents (e.g. trains, substations, renewable energy sources, loads…)
- Recalculation trigger from the RTO function

The outputs of the process are:

- Power or energy consumption constraints for the consumers, if needed
- Power or energy injection orders for the producers or storages, if needed
- DAO trigger, if needed

![Diagram](image)

**Figure 14: MAO’s local optimisation inputs & outputs**

The local optimisation algorithms are application dependant and therefore out of the scope of this document. However, it may be the case that the algorithms rely on multi-train simulations constrained to the controlled zone and within the concerned timeslot. As these simulations may take time, the optimisation process should be started well in advance before the targeted timeslot.
As a result of the process three cases may occur (from lowest to highest severity):

1. No deviations are present (the DAO profile is fulfilled) and no additional actions are needed.
2. Slight deviations are identified. The RTO function can cope with them.
3. Noticeable deviations are expected. Power and/or energy constraints are allocated to consumers and/or power and/or energy orders are allocated to the producers. This starts an iterative process, called negotiation, where consumers and producers inform about their new power profile (consumed or produced) to start a new local optimisation process.
4. If the deviation is so big that the optimisation cannot be performed, the DAO function should be re-launched (DAO is triggered).

Thresholds to delimit each case are application dependant.

The MAO function (i.e. optimisation algorithms) should define the length (i.e. timeslot period) and accuracy (i.e. number of points per timeslot) of the forecast. The agents should then provide the information to the LOS for aggregation. The format is defined in the case of the DOEM as it is subject to interoperability.

![Figure 15: Forecasted power profile](image)

**Negotiation**

As a result of the local optimisation a negotiation amongst the agents may be required in order to fulfil the existing operational envelop (e.g. DAO related energy procurements, network degraded conditions…).

When the aggregated consumption forecasts sent by the agents upon LOS request significantly do not follow the expected DAO’s profile (i.e. deviation not absorbable by RTO), MAO should request agents to modify their expected behaviour in the following timeslot and provide a new forecast to start a new iteration in the optimisation process.

Involved agents should have a communication link with the LOS and be able to calculate through simulation or specific algorithms an estimation of their consumption and/or production in the following timeslot. There are mobile agents (i.e. DOEM) and trackside agents, amongst them, LOS in the neighbourhoods are included.
In that sense, to solve the power mismatch it should be also possible to take power from or give power to the neighbour zones.

![Diagram of Negotiation sequence]

**Figure 16: Negotiation sequence diagram**

**Deviation alert RTO**

The main aim of this sub-function is to re-launch the MAO function when a deviation that cannot be solved in RTO is detected (see [Error! Reference source not found.]).

In order to detect it, this function will receive a deviation warning from the Control function of the RTO Operational Mode.

### 4.3.2.3 Real Time Operation (RTO)

**Objective**

RTO (Real Time Operation) is a periodic function whose main aim is to follow 24 hours ahead power profile coming from the DAO function through MAO suggestions, per sub-network.

The time interval (validity period between executions) should be configurable and may depend on the application. Moreover, RTO functions should provide necessary real time status data, MAO behaviour estimations per actor and accurate indications to controllable actors.

The RTO function should be executed by each component belonging LOS - Local Optimisation Systems in an integrated way.

According to the SGAM function layer (see Figure 17) the RTO is defined by four high level functions.
- Real Time Data acquisition function is placed at Field covering areas from Customer Premises to Distribution, excluding both Transmission and Generation. This function consists of the following functions:
  - Real Time Data acquisition for MAO
  - Real Time Data acquisition for RTO
  - Consumption Measuring

- Estimation for MAO function is placed at Station covering areas from Customer Premises to Distribution, excluding both Transmission and Generation. This function consists of the following functions:
  - Estimation for MAO
  - 15 min forecast aggregation

- Operation control function is placed at Operation covering areas from Customer Premises to Distribution, excluding both Transmission and Generation.

- Actions Implementation and optimisation, placed at Stations covering areas from Customer Premises to Distribution function is excluding both Transmission and Generation.

![](image)

**Figure 17: RTO Function Layer in the SGAM Plane**

**Consumption Measuring**

The main aim of this function is to measure power/energy consumption/generation from each Point of Common Coupling (PCC) and actor of the network. Every “t” seconds, measurement devices should read from each actor measured mean power and store it. The accuracy and frequency of stored data is application dependant.

**Real Time Data acquisition for MAO and RTO**
The main aim of this function is to obtain the real time status of each agent of the current subnetwork from consumption measuring. If current status of any of the trains, DERs or External Consumers is not stored, the information should be obtained from 15 min forecast aggregation function.

Real Time Data acquisition function should provide actual power/energy consumption data related to each actor when requested by the LOS.

Involved actors (DERs, ESSs, RSSTs, SSTs, ECs and LOS) should have a communication link with Real Time Data acquisition function. However, this is out of scope of this document.

**Estimation for MAO**

The main aim of this function is to estimate the behaviour of the DOEMs, DERs and external consumers for the next MAO Slot. This estimation should be calculated prior MAO Optimisation.

- DOEM should generate MAO Estimation power profile based real time information
- DER should predict the power generation (kW related to time) for the next MAO Slot based on the weather forecast
- External Consumers should estimate the power consumption (kW related to time) for the next MAO Slot.

**15 min forecast aggregation**

The main aim of this function is to aggregate the MAO Estimations calculated by the previous function.

If the estimation is not received from a train, DERs or External Consumers, this function should calculate a default forecast taking into account internal characteristics of train, External Consumer or DER. This should be also done with grey trains. Internal simulator to forecast consumption when information is not provided should be necessary.

When requested by the Real Time Data acquisition function, this function should sends the aggregated forecast.

**Operation control**

Suggestions generation for DERs, ESSs, RSSTs, SSTs and ECs is the main aim of RTO functions. The objective is to minimise the deviation between MAO outputs (see 4.3.3.2) and the real time behaviour of each agent. The suggestion generation algorithm is application dependant and therefore out of the scope of this document.

When the deviation between the real time status and the MAO optimum profile is so big that it cannot be solved by any real time suggestion, Operation control function should request MAO relaunching (see 4.3.3.3).

Involved actors (DERs, ESSs, RSSTs, SSTs and ECs) should have a communication link with the LOS. However, this is out of scope of this document.

**Actions Implementation and optimisation**
The main aim of this function is to calculate the optimum way to fulfil the suggestions from the Control function. It should be executed within each component.

- External Consumers should fulfil P/E limitations
- ESS should follow the charge/discharge orders related to time
- DER should generate energy or not
- SST/RSST should follow suggestions

4.3.3 Components layer

4.3.3.1 Global Optimisation System (GOS)

The Global Optimisation System is responsible for the Day Ahead Optimisation, i.e. to optimise the power, energy consumption and costs of the whole network. It is an intelligent module responsible for making a plan for the next day depending to the forecasted energy profiles, in order to optimise energy consumption, power demand and cost in the whole system. The main output of this application, i.e. the optimised day ahead power profile per subnetwork can then be sent to Local Optimisation Application.

The components configuring the GOS can consist of:

- **HMI**, which is the interface considered to view for the whole system and allow for manual control at the Control Centre;
- **Router and RTU**, which enable communication between Global Optimisation internally and to the sub networks, energy trading application and marketplace system and to public network infrastructure;
- **EMS/SCADA and EMS**, which performs the operational role of the Global Optimisation function (both in transmission and distribution level); their task is to control and monitor the grid, managing power quality and security of the system and in other words support all operational activities;
- **Global optimisation Application**, which supports the intelligent part of Global Optimisation function which contains optimisation algorithm in order to prepare day ahead energy profile proposal for the whole system (Subnetworks, Energy trading, …).

4.3.3.2 Energy Buyer Decision Maker (EBDM)

The EBDM is a module of the REM-S that determines the best way to purchase/sell the energy consumed/generated by the railway system managed by the REM-S. It performs the following tasks:

**A) Optimization of the energy procurement in the 24/48h horizon, determining:**

- For each hour, determines which amount of energy is purchased by means of the long term agreements, satisfying the constraints derived from them (minimum and maximum amount of energy, indivisible or not, etc.).
For each of the hours: calculates which amount of the energy has to be offered in each session of the spot market. For each hour covered by each session, splits the energy into blocks and assigns them a price, according to the bidding strategy and to the contractual agreements available (for example the maximum price of the blocks may come from a contract). The result is the purchase/sale bid for each markets session, which would be sent to the EMO.

Calculation of the estimated price of the energy, to provide it to the REM-S, as the weighted mean of the price of the energy bought/sold by means of contracts and the price of the energy bought/sold in each session of the electricity markets.

EMO/ESO/TSO supply additional costs to obtain the final price of the energy. This price is given for each PCC.

This optimization can be used to perform two main functions:

- Energy Trading Estimation: determines an initial guess of the prices of the energy based on:
  - an initial estimation of the energy to be consumed/generated (based on historic data) coming from the global optimization.
  - the forecasted behaviour of the electricity markets coming from a forecast provider.
  - the 24/48h ahead restrictions based on the contractual arrangements and the bidding strategy, coming from the EPP.
  - an estimation of the additional costs charged by the ESO/TSO/DSO.

- Energy Trading: provides the data required to perform the energy and the optimization of the operation performed by the REM-S. It incorporates:
  - results of every available electricity market session, provided by EMO/ESO.
  - an updated version of the energy to be consumed/generated after the last execution of the Global Optimization.
  - the estimated price of the energy updated after the latest session.

B) Update of the energy procurement in shorter horizon, when necessary

EBDM can take the following decisions when, in the planned operation, a major variation occurs in the planned operation:

- Determines which sessions of the spot markets can be used to sell/buy the electricity.
- Determines which contracts can still be used for buying/selling the energy.
- Repeat the same process, but restricted to the actual time horizon.

C) Informing of unexpected market sessions

In case of the EMO/ESO opens an additional session, EBDM communicates it to the REM-S.

The figures below represent the main functions, the outputs and inputs of the EBDM are included:

1. Energy Trading Estimation, which determines an initial guess of the prices of the energy (see Figure 18) based on: (i) an initial estimation of the energy to be consumed/generated (based on historic data), (ii) the forecasted behaviour of the electricity markets, (iii) the 24/28h day ahead restrictions based on the contractual arrangements, (iv) the bidding strategy and (v) an estimation of the additional costs charged by the ESO/TSO/DSO.
2. Energy Trading, which, in addition incorporates: (i) the results of every available electricity market session, (ii) an updated version of the energy to be consumed/generated after the last execution of the Global Optimization and (iii) the estimated price of the energy updated after the latest session. This function provides the data required to perform the energy trading (see Figure 19) and the optimization of the operation performed by the REM-S.

The EBDM has the following main components:

1. Generator of the stochastic scenarios.
2. Simulator the spot market participation.
3. Optimizer of the average energy price.
4. Calculator of the expected average energy price.

1. **Generator of Energy Demand and Price stochastic scenarios**

This module builds all the operational stochastic scenarios that will be taken into account by the optimization procedure. An operational stochastic scenario is defined by a combination of the conditions of each market where energy is purchased/sold and the actual energy demand.

The energy demand of railways and the energy prices in the spot markets are independent and not correlated. But strong correlations may exist between the energy price scenarios in subsequent markets.

To take into account their volatility, electricity market prices are represented by means of their Probability Density Function (p.d.f.), one for each market session, which are supplied by an Energy Price Forecast Provider (a third party entity which sell this forecast, obtained based on all kind of relevant information and advanced mathematical models) and updated continuously, so that the most updated version can be used at any moment to improve the next energy purchases. For generating the different stochastic scenarios, this p.d.f is discretised into NM intervals, where M refers to the specific market (day-ahead, intraday, etc.).

Similarly, the actual demand of the railways managed by Merlin can be represented by another p.d.f. which would be updated continuously, so that the most updated version can be used at any moment to improve the next energy purchases.

Historic data may be used for its determination, taking into account the two different types of factors originating the dispersion of the p.d.f:

- **Endogenous factors**, related to railways operation issues (delays, congestions, temporal outages, etc.) of the energy demand.
- **Exogenous factor**, due to the distributed generation sources, especially to the inherent randomness of some renewable technologies.

As far as their functionalities are concerned, these modules the railway electrical demand and the electricity market forecasts build up the corresponding operation stochastic scenarios.

2. **Simulator of the spot markets**

The purpose of the spot market simulation is to determine, for each stochastic scenario and given a bidding strategy provided by the EPP, the amount on energy that would be purchased/sold in the market (with a probability pssc), which is used in the optimization of the energy procurement.

In the simulation process, the energy blocks are calculated based on the remaining energy according to: (i) the energy partitioning criteria specified in the bidding strategy, (ii) the demand p.d.f. and (iii) the result of previous market sessions. The price for each energy block is assigned as specified in the bidding strategy. Complex conditions (ramps, minimum income, etc.) are not considered.
Once the energy blocks have been built, based on the final price of the session (which is known with a given probability) the accepted energy blocks, i.e. the purchase blocks whose offered price is higher or the sale blocks whose price is lower than the session final price, are determined. The final price of the energy will be the price determined in the market session.

Based on operational stochastic scenarios and the bidding strategy, this module determines how much energy would be purchased/sold in each session of the electricity spot markets.

3. Optimizer of the average energy price

This component formulates and solves of a mixed integer programing (MIP) optimization problem to determine best possible usage of the available contracts in order to hedge the risk due to the volatility of the prices and the deviations in the demand/generation from the planned values.

The formulation of the optimization problem forces the real energy to be acquired for each hour ($h$) using any of the mechanisms available (spot market, contracts and deviations market).

Based on the available contracts and the expected results of the electricity spot markets, this module determines how much energy should be purchased/sold using each contract.

For each operational stochastic scenario, this component determines the expected deviations and its cost.

4. Calculation of average prices

This component calculates the average price of the energy ($P_{E_{avg}}$) based on the amount and price of the energy purchased/sold by means of the spot market, the contracts and the deviations market.

The functionality of this component is to calculate the expected energy average price.

4.3.3.3 Local Optimisation System (LOS)

The Local Optimisation System (LOS) locally predicts and optimises zone status in the upcoming timeslot, such as 10 or 15 minutes for instance. Following the Day Ahead Optimisation (DAO) profile, Minutes Ahead Optimisation (MAO) covers the interaction with all zone agents to fulfil power restrictions and suggestions, to accommodate surpluses and needs of the adjacent zones, and accordingly to suggest actions to zone agents, i.e. SSTs (substations), RSSTs (reversible substations), DERs (Distributed Energy Resources), ESSs (Energy Storage Systems) and trains passing through the zone.

Architecture
The MAO is performed by the LOS, which divides the railway systems in several parts, such as several electrical sections. The SGAM plane of component layer at Minutes Ahead Optimisation mode is illustrated on Figure 20.

![Figure 20: Minutes Ahead Optimisation - Component Layer in SGAM plane.](image)

**Operation Zone**

At Operation Zone DMS/SCADA and Local optimisation application are located. The DMS/SCADA is located here to support all operation activities at subnetworks and dispatch energy internally in the subnetwork or dispatch it to the neighbour subnetwork. The DMS will locate at the intelligent substation of each subnetwork. The intelligent substation is facilitated by control and automation devices and the intelligent decision maker: Local optimisation application. The Local optimisation application firstly slice daily profile to 15 minutes ahead power profile and then by comparing it with the real situation, will develop a new optimal plan for the next 15 minutes. Supervision, calculation of mismatch power and also receiving the deviation alert from RTO are done with this application too.

**Station Zone**

At Station, the supporting devices such as RTU and Router are located to prepare the possibility of communication between neighbourhood subnetworks. Data Storage is considered to save the optimisation results. It is assumed an HMI system at the intelligent substation to make an interface for manual applications.

The table below is clarified that for each function of Minute Ahead Optimisation mode which components are applied and how they can support the REM-S functions.
<table>
<thead>
<tr>
<th>Function</th>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day ahead profile slicing</td>
<td>Local optimisation Application</td>
<td>Prepare every 15 minutes power profile from optimised day ahead power profile</td>
</tr>
<tr>
<td>Supervision</td>
<td>Local optimisation Application</td>
<td>Calculate the deviation between the DAO reference power profile and the real energy consumption</td>
</tr>
<tr>
<td></td>
<td>Meter Data Management System</td>
<td>The required data for calculating deviation between reference power profile and real energy consumption is gathered here based on the measured data from field devices</td>
</tr>
<tr>
<td></td>
<td>Data Storage</td>
<td>The stored data is needed here for comparison and calculating the deviation</td>
</tr>
<tr>
<td>Supervision</td>
<td>Data Storage</td>
<td>Store the 15 minutes optimisation results</td>
</tr>
<tr>
<td>Local optimisation</td>
<td>HMI</td>
<td>The interface which is considered in order to prepare a display for the local area (subnetwork) and make the possibility to control the system manually at the intelligent substation.</td>
</tr>
<tr>
<td></td>
<td>Router</td>
<td>To communicate with Control Centre (Global Optimisation) and neighbour subnetworks</td>
</tr>
<tr>
<td></td>
<td>RTU</td>
<td>Supports the intelligent part of local Optimisation function which contains optimisation algorithm in order to prepare optimum 15 minute power profile proposal or the remaining part of it for the whole subnetwork</td>
</tr>
<tr>
<td>Power mismatch calculation per subnetwork</td>
<td>Local optimisation Application</td>
<td>Calculate the deviation between DAO optimal 15 minute power profile or the remaining part of it and MAO 15 minute optimal power profile or the remaining part</td>
</tr>
<tr>
<td>Negotiating among neighbour subnetworks</td>
<td>DMS/SCADA</td>
<td>Responsible for energy transaction operational issues between neighbourhood subnetworks</td>
</tr>
<tr>
<td></td>
<td>HMI</td>
<td>The interface which is considered in order to prepare a display for the local area (subnetwork) and make the possibility to control the system manually at the intelligent substation.</td>
</tr>
<tr>
<td></td>
<td>Router</td>
<td>To communicate with neighbour subnetworks</td>
</tr>
<tr>
<td></td>
<td>RTU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Local optimisation Application</td>
<td>Find the best way to the problem of mismatch power (surplus/shortage) by neighbour subnetworks</td>
</tr>
<tr>
<td>Deviation alert_RTO</td>
<td>Local optimisation Application</td>
<td>Re-launch the optimisation algorithm based on the triggers received from RTO</td>
</tr>
</tbody>
</table>

**Table 5 – Components related to each function of MAO**
LOS and MAO implementation and example of optimisation method

The most important parameters which are required in MAO to define characteristics of railway system in each zone are fixed in optimisation process can be categorised as below:

1. The parameters which clarify the topology of network such as:
   - Topology of line: length of line and its borders
   - Substation topology: the location of substation and its distance from other substations or start and end stations
   - Define each zone border

2. The parameters which specify the electrification specification of system like substation capacity or charging/discharging efficiency rate of storages

3. The DAO planned parameters like timetable of trains with best driving styles and power demand at each PCC

The variables defined for MAO which are not fixed and by changing them optimisation process can be done are listed below:

- Estimated power profiles of trains passing the zone at each timeslot
- Estimated power profiles of ECs at each timeslot
- Generated power of dispatchable DERs at each timeslot
- Estimated power demand at each PCC for each timeslot
- Charging level of ESSs for each timeslot

There are some electrical constraints like maximum tolerable capacity of substations or maximum capacity of storages. Some contractual constraints can effect on MAO as well. Constraints are given to the MAO as input parameters.

In MAO, the optimization is done based on the negotiation between zone agent and other agents present in the zone in order each agent try to modify its profile to follow zone agents request, for minimizing the deviation between planned power demand of each PCC and estimated power demand. The Figure 21 below shows a brief flowchart of MAO general steps.

The optimization procedure starts before starting each time slot.

At starting time, all zone agents ask agents which are attended at their zone to send their estimated power profiles for next timeslot. After receiving the power profiles, the zone agents starting analysing the power profiles of trains in order to understand which part of received profiles are belong to their zone and which part of the profiles are belong to neighbourhood zones. By
finishing the analysis, all zone agents send the part of profiles belong to neighbourhood zones to them.

For the next step, zone agent compare the estimated power demand of PCC which is located at its zone with the planned power demand and find out at which period of time in next timeslot the deviation can occur. The next step is to find at this duration which loads are present at zone and calculate their contribution in making power demand at PCC.

Based on each load share, the zone agent send some limitation file to load agents, with tendency to contribute in optimization and ask them to limit their consumption to a limit at specific period of time which deviation occurs. After sending this request to load agents, zone agent waits for substitute profiles. The load agents should start calculating new profile according to received limitation file and send it to zone agent. Zone agent based on new profiles received from load agents and new power profile of PCC received from Energy Railway Simulation Tool, again start finding deviation from DAO plan. This procedure can continue several times. At the last round of negotiation for minimizing the deviation, the zone agent checks the new PCC power profile with the hard constraints of network (e.g. maximum capacity of substation).

In case of having some peak values which exceed the limitations, the zone agents make the limitation files of load agent in order to remove the peak value. After finalizing the negotiation, if still some deviations exist, in case of having ESS in the zone, it is ESS responsibility to smoothen the PCC profile as much as it is possible according to charge level of storage. In case of having
dispatchable DER in zone, it is more beneficiary to compensate the surplus of energy by the power generated from local DERs instead of buying it from power grid.

4.3.3.4 Dynamic Onboard Energy Manager (DOEM)

The Dynamic Onboard Energy Manager (DOEM) is the mobile agent of the Railway Energy Management System (REM-S), installed onboard trains. Its main two responsibilities are:

- To participate in the MAO and RTO functions of the REM-S by calculating periodically power consumption forecasts under the existing operational and energetic constraints.
- To efficiently manage the available energy resources onboard while fulfilling the operational constraints, providing advice to the driver in order to follow the previously calculated power and speed profiles, and managing the auxiliaries efficiently.

Architecture

This component can be executed in any of the onboard end devices connected to the vehicle communication bus (e.g. MVB or ECN), but typically the Human Machine Interface (HMI), the Consist Control Unit (CCU) or the Traction Control Unit (TCU) are chosen for this purpose.

The DOEM component can be understood as a connected Driver Advisory System (DAS) with some additional features to support the REM-S.

The simplest architecture (see Figure 22) connects the DOEM with only two other onboard devices: The DAS as an interface with the driver and the MCG to provide the train-to-ground communication.

![Figure 22: Simple DOEM links](image)

Depending on the optimisation algorithms and the accuracy of the inputs for the MAO function, the DOEM could be connected to other subsystems, like the TCU and the CCU, amongst others, taking benefit of the communication bus.
Figure 23: Typical DOEM links

Trackside connection

The connection between the DOEM and the trackside components of the REM-S should be performed through the train's Mobile Communication Gateway (MCG) according to the IEC61375-2-6 standard. The wayside counterpart is the Local Optimisation System (see 4.3.3.3) and other sources of information, like the traffic control centre or the train owner.

Upon its start-up, the DOEM should look up for the active LOS where the train is located and try to establish the communication to register the DOEM in the controlled zone. It should also manage the LOS handover when leaving a controlled zone and entering a new one.

When the communication fails, the DOEM may continue working in local mode, without receiving updates and indications from the trackside components but with all the necessary information stored onboard. The agent should try to recover the connection between train and wayside systems periodically.

Basic modules

The internal implementation of the DOEM and its algorithms are not subject of this document. However, in order to achieve the objectives, the DOEM should include at least three functional modules.
Figure 25: DOEM’s minimum set of functional modules

- **Embedded Train Simulator**: It is in charge of providing optimised consumption profiles in real time taking into consideration operational constraints (e.g. timetable, track topology, speed limits…) and energy or power constraints received from the LOS during the MAO function (negotiation phase). The produced outputs should be the basis to perform the onboard energy management through optimised speed profiles (i.e. driving style) and optimised auxiliaries’ consumption. Used algorithms are not subject of this document and may be application dependent. Complexity but accuracy may be increased if available information about real weight, adhesion factor, car occupancy, traction or brake status, for example, is taken into account.

- **Database**: The DOEM should access a database or files containing the following information:
  - Train model. Content and format may be application dependant.
  - Track topology. It is subject of interoperability so RailML® should be used. This database or file should include information related to the REM-S layout (i.e. LOS addresses, locations and their controlled zones). This information is liable to be updated locally during maintenance or remotely during operation to cope with changes in the tracks or speed limits, for example.
  - Timetable. It is subject of interoperability so RailML® should be used. This information is liable to be updated locally during maintenance or remotely during operation to cope with changes in arrival or departure times, for example.

- **Communications driver interfaces** the vehicle bus (e.g. MVB or preferably ECN) to exchange information with other subsystems and with the wayside components through the MCG.

**Functions**

The DOEM should perform the following functions:

- Recalculate an optimised power consumption profile when necessary. A triggering event should be a request received from the LOS during the execution of the MAO function and the consequent negations. Other triggers, depending on the implementation, may be, for example: A deviation in the expected arrival time, receiving a new timetable, receiving new power limitations or entering a degraded mode.

- Distribute the available power and/or energy amongst auxiliary loads and traction system. In power/energy restriction zones. Remaining available power and/or energy for auxiliaries should be managed efficiently with smart algorithms (out of the scope of this document).
- Generate the driver advice. The driver should receive, according to the calculated power profile, simple instructions how to drive efficiently following such profile.

![Diagram of DOEM inputs and outputs]

**Figure 26: DOEM inputs and outputs**

For interoperability reasons, interfaces between ground and train should be standardised. The internal exchange between onboard equipment and DOEM are application dependant and may vary with the implemented optimisation algorithms.

The train should receive from trackside equipment standardised information related to the latest operational updates (dynamic operational data), such us new arrival times and new speed limitations. When the MAO function is executed the DOEM may receive power and/or energy constraints from the LOS.

The DOEM should also need to monitor the train current location, its speed and status to carry out its functions.

**Optimised profile calculation**

As said DOEM should have an embedded train simulator with capability of calculating efficient speed and traction power profiles, for both the efficient driving speed profile and the consumption forecast of the MAO function.

In order to perform such calculation, a number of inputs should be available for the optimisation algorithm.

Inputs should contain all the relevant information related to track topology, updated speed limitations and timetable. Vehicle related information should also be made available for the profile generator: Actual weight, drag values, traction characteristics, braking curve, internal component efficiency... Depending on the optimisation algorithm the extension and details of the necessary variables may vary, affecting accuracy.
The embedded train simulator should also be able to interpret and deal with power and/or energy constraints that may receive during the negotiation phase of the MAO function. Generated power and speed profiles should fulfil the target points (waypoints arrival time and timetable) accomplishing power/energy constraints, if there is any.

**Driver advice and deviation generation**

The generated power consumption profile should be translated into efficient driving profiles and simple advices (e.g. coasting) to be given to the driver through the DAS.

All the interfaces participating in this function might be defined by the manufacturer as they are not part of interoperability interfaces. However, the use of a standardised DAS interface is highly recommended.

**Available power distribution**

The DOEM should calculate the optimum power distribution amongst traction and auxiliary loads when power and/or energy constraints are received from the LOS.

The definition of the internal algorithm for determining the amount of power or energy dedicated to traction and auxiliary loads is out of this document scope, so each manufacturer could define its best option. Interfaces participating in this task might be defined by the manufacturer as they are not part of interoperability interfaces.

**Interaction with the signalling system & safety**

None of the function performed by the DOEM is safety related as the complete system, including the driver advising functionality, relies on the train’s protection system (ATP).

Modern signalling systems integrate automatic driving features, which could implement some of the DOEM’s functions easily. In case of the ETCS, the DOEM should be integrated through the ATO, using most of its interfaces towards the train and towards ground.

Information concerning track topology, timetable or speed limits are obtained from the ATO, while pure energy related aspects (interface with the LOS) keep the original way through the MCG.
5 ENERGY MEASUREMENT

Today in Europe the railway companies use different billing models of energy. A model is the billing by from the energy suppliers to the IM, and then from the IM to the railway operator, another model is the billing from the energy suppliers to the railway operator (both models may be used on a single railway).

TSI development, such as the 2008/284/EC defines the energy subsystem in the railway sector and the process of closing its open points will allow in the future having a general system to apply in all European countries. One of the open points is the communication protocol between energy meters on board and energy collector device on ground that includes all these measures for the final billing. It is possible to conclude from this TSI that each railway operator may request the infrastructure manager to include in the bill of energy the actual consumption of each train. This
implies that if the rolling stock has homologated energy meters on board, its energy consumption values shall be those included in the bill.

The IM must discern the energy dedicated to traction from the one dedicated to operations. The IM bill the railway operators the energy dedicated to traction. As far as the share for traction is concerned, some will be directly consumed by trains more the transport losses (the consumption of the railway electrical power supply system is part of the traction bill). The share for operations is dedicated to supply auxiliary systems, stations, technical buildings, etc.

Therefore, it is necessary to situate the energy meters border point between traction substation and the electric company and in the outputs for other electrical systems such as signaling, technical buildings, etc. Thus, it will be possible to register in a differentiated way those consumptions related to the operation and traction.

Data flow

![Data Flow Diagram](image)

Figure 28 – Consumption data exchange

The scheme shows the IM responsibility on consumption sharing between actors before transmission at the energy providers. Train location allows the infrastructure manager to bill exactly the train consumption on his network.