Ref. Ares(2019)5996716 - 26/09/2019

INTERPLAN
INTEgrated opeRation PLAnning tool towards the Pan-European Network

Work Package 4

Grid equivalenting

Deliverable D4.2

Approach for generating grid equivalents for different use cases (first version)

Grant Agreement No:	**773708**
Funding Instrument:	**Research and Innovation Action (RIA)**
Funded under:	**H2020 LCE-05-2017: Tools and technologies for coordination and integration of the European energy system**
Starting date of project:	**01.11.2017**
Project Duration:	**36 months**

Contractual delivery date:	**31.08.2019**
Actual delivery date:	**26.09.2019**
Lead beneficiary:	**2 AIT Austrian Institute of Technology GmbH**
Deliverable Type:	**Report (R)**
Dissemination level:	**Public (PU)**
Revision / Status:	**RELEASED**

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 773708

Document Information

Document Version:	5
Revision / Status:	RELEASED

All Authors/Partners

Alena Palkhouskaya / AIT
Adolfo Anta / AIT
Mihai Calin / AIT
Ata Khavari / DERlab
Marialaura Di Somma / ENEA
Roberto Ciavarella / ENEA
Giorgio Graditi / ENEA
Maria Valenti / ENEA
Helfried Brunner / AIT
Jan Ringelstein / IEE
Melios Hadjikypris / FOSS
Sawsan Henein / AIT
Sohail Khan /AIT
Venizelos Efthymiou / FOSS

Distribution List INTERPLAN consortium

Keywords: Grid Equivalents, Network models, TSO level, DSO level, Distribution Grids, Transmission Grids, Planning, Modelling.

Document History

Revision	Content / Changes	Resp. Partner	Date
1	Draft table of contents was prepared	AIT	01.06.2019
2	Most of the contents were included	AIT	01.09.2019
3	Document was finalised for internal review	AIT	22.09.2019
4	Editorial changes	AIT	23.09.2019
5	Document was reviewed	AIT	25.09.2019
6	Document was finalised for release	AIT/ENEA	26.09.2019

Document Approval

Final Approval	Name	Resp. Partner	Date
Review Task Level	Ata Khavari	DERlab	23.09.2019
Review WP Level	Marialaura Di Somma	ENEA	24.09.2019
Review Management Level	Helfried Brunner / Giorgio Graditi	AIT/ENEA	25.09.2019

Disclaimer

This document contains material, which is copyrighted by certain INTERPLAN consortium parties and may not be reproduced or copied without permission. The information contained in this document is the proprietary confidential information of certain INTERPLAN consortium parties and may not be disclosed except in accordance with the consortium agreement.

The commercial use of any information in this document may require a licence from the proprietor of that information.

Neither the INTERPLAN consortium as a whole, nor any single party within the INTERPLAN consortium warrant that the information contained in this document is capable of use, nor that the use of such information is free from risk. Neither the INTERPLAN consortium as a whole, nor any single party within the INTERPLAN consortium accepts any liability for loss or damage suffered by any person using the information.

This document does not represent the opinion of the European Community, and the European Community is not responsible for any use that might be made of its content.

Copyright Notice

Table of contents

Abbreviations

AC	Alternate Current
BSC	Base Showcase
CIM	Common Information Model
DC	Direct Current
DER	Distributed Energy Resource
DG	Distributed Generation
DPI	Dynamic Power Injectors
DSO	Distribution System Operator
EU	European Union
KPI	Key Performance Indicator
LV	Low Voltage
MV	Medium Voltage
P	Active Power
Q	Reactive Power
REI	Radial, Equivalent and Independent
RES	Renewable Energy Source
SC	Showcase
TSO	Transmission System Operator
UC	Use Case
V	Voltage

Executive Summary

Modern technological trends for massive RES integration into the electrical grid together with the evolution of energy storage systems and the increasing penetration of electric vehicles contribute greatly to decarbonization of the energy systems and energy efficiency improvement. This initiates, however, significant challenges for the future operation of EU electricity system characterized by the wide diversity of electrical networks among EU members.

Ideally, all system operators should have full models of all grids to carry out the network analysis in a digital simulation environment. However, at the present time, no network operator has models of the entire physical grid, in particular covering different voltage levels and all neighbouring network operators. The detailed modelling of the whole power system requires a huge input data and complex structure, and this clearly contributes to the problem. Therefore, the grid equivalents adequately representing the parts of European electricity systems are needed.

During the equivalenting process, a large, branched part of the network can be substituted by a relevant simplified counterpart while keeping network characteristics at an appropriate level of accuracy. This will reduce large amount of calculations and increase the model simulation speed greatly. Generating grid equivalents instead of the detailed model has thereby a great practical significance and the grid equivalents can be convenient for different power system applications.

In deliverable D4.2, a general concept of generating grid equivalents is being introduced alongside of a classification of the generated grid equivalents. The proposed methodology is needed to generate grid equivalents that will allow an accurate analysis of the complex network, by considering local active elements in the grid. Based on the developed INTERPLAN use cases, showcases and requirements for network models and interfaces, the project will provide and deliver grid equivalents covering all voltage levels to be incorporated in the integrated operation planning tool and semi-dynamic simulations environment. In a further step, the developed grid equivalents will be validated during the project runtime. Hence, a validated set of grid equivalents will be provided on the public on the website and presented to the scientific community during international conferences and through relevant publications. Using appropriate grid equivalents for the distribution grid, the complexity of such investigations can be reduced significantly and can help distribution system operators (DSOs) to identify the optimal standard parametrization of small-scale distributed energy resources (DER).

The “grid equivalenting”, is the process to generate a grid equivalent model encompassing a large part of network substituted by a smaller counterpart having the same relevant properties. To this aim, the network models of use cases will be designed in numerical power system simulation environment. Then, a clustering methodology for transmission and distribution systems up to the end user level will be applied, and a detailed approach for generating grid equivalents will be used for different use cases. To realize the transition from feeder to the network level, new grid elements have to be considered, for example transformers, generators or synchronous machines. Depending on the available data, variables dealing with these grid elements are to be examined to complete the grid representation.

The consortium intends to provide an integrated operation planning tool to the prospective users (mainly transmission system operators (TSOs) and DSOs) with the following features and advantages. It will include a library of grid equivalents responding to all known needs of operators and system analysts and covering all voltage levels and their active components and it will provide easy to use grid clustering techniques that are adaptive and responsive to the dynamic growth of the evolving grid thus refreshing and valid as new technologies emerge and adapted in the grid.

1 Introduction

During the early days of power system network analysis by digital computers, the need for network equivalents arose in order to allow the analysis of large-scale power systems to be practically possible given the limited computational speed and storage and at that time. However, due to the huge developments in computer technology, this constraint is no longer applicable and very large power systems can nowadays be analysed quickly and cost effectively on personal computers. However, power system equivalents are still required in industry. Practical examples include a distribution network company that owns and operates a distribution network and obtains its bulk power needs from a transmission company from one or several substations. The transmission network may be very large and an equivalent at one or more boundary nodes that are judiciously selected is usually sufficient for the short-circuit analysis needs of the distribution company. Similarly, the transmission company itself would not need to represent the distribution network in its entirety and an appropriate equivalent at one or more boundary nodes is usually sufficient.

Network reduction is a mathematical process that combines and eliminates network nodes and branches, so that the reduced equivalent contains smaller number of nodes and branches than the original network. The equivalent must be capable of reproducing the electrical behaviour of the original network at the boundary interface or nodes with sufficient accuracy. There are several types of power system equivalents the characteristics of which depend on the type of power system analysis being carried out. Equivalents may generally be classed as static or dynamic equivalents. The former may be used in DC (direct current) and AC (alternate current) loadflow analysis, AC short-circuit analysis and harmonic analysis etc. The latter are used in power system stability and control analysis.

At the present time no network operator has models of the entire physical grid covering different voltage levels and all neighbouring network operators. The detailed modelling of the whole power system requires a huge input data and complex structure, and this clearly contributes to the problem. So, the grid equivalents adequately representing the parts of European electricity systems are needed.

1.1 Purpose of the Document

The aim of this deliverable D4.2 is to introduce a general concept of generating grid equivalents alongside of a classification of the generated grid equivalents. The proposed methodology is needed to generate grid equivalents that will allow an accurate analysis of the complex network, by considering local active elements in the grid. Based on the developed INTERPLAN use cases, showcases and requirements for network models and interfaces, the project will provide and deliver grid-equivalents covering all voltage levels to be incorporated in the integrated operation planning tool and semi-dynamic simulations environment. In a further step, the developed grid equivalents will be validated during the project runtime. Hence, a validated set of grid equivalents will be provided accessible by public on the website and presented to the scientific community during international conferences and publications. Using appropriate grid equivalents for the distribution grid, the complexity of such investigations can be reduced significantly and can help DSOs to identify the optimal standard parametrization of small-scale DER. Several internal reports will be drafted regularly to illustrate the different iterations and improvement of the concept and will be summarized in the final version of this deliverable due at the end of the project.

1.2 Scope of the Document

The scope of the deliverable is to document the development of an approach to generate simplified grid equivalents representing the original networks according to the required granularity by the individual INTERPLAN use cases.

1.3 Structure of the Document

The report introduces the approach for generating grid equivalent models for complex electricity grids considering clustering methods, by analysing the requirements in respect to INTERPLAN project use cases and showcases in Chapter 2. Chapter 3 describes the methodology for generating the grid equivalents considered for the usage in INTERPLAN project. Chapter 4 presents the different grid equivalent models types, which are derived by the requirements analysis done in Chapter 2. Chapter 5 shows the conclusions of the work and presents the next steps for generating and refining the grid equivalents in different iterations and through a high interaction with the other developments in the project.

2 Grid equivalents requirements in the view of INTERPLAN project

The “grid equivalenting” is the process to generate a grid equivalent model encompassing a large part of network substituted by a smaller counterpart having the same relevant properties. To this aim, the network models of use cases and showcases will be designed in numerical power system simulation environment.

As previously mentioned, the scope of the work is the development of an approach to generate simplified grid equivalents representing the original networks according to the required granularity by the individual use cases. These equivalents for instance may be two-bus grid equivalent or representative grid equivalents (with a few more nodes). If a use case or showcase does not allow such a two-bus simplification (due to result accuracy) accurate grid models will be designed.

The reduction of grids to grid equivalents requires to assign load/generation data of the replaced grid to suitable locations in the grid equivalent. Based on the experiences and results within the project duration, the grid equivalents are going to be iteratively improved and enhanced if required. In order to define the grid equivalents, a mapping of the requirements for grid equivalents to the developed use cases and showcases was done by the project partners.

In the project, the concepts of “base showcase (SC)” and “showcase” were defined [1] :

The base showcase was defined as “*Presentation of base use case(s) with no planning criteria and no controllers for emerging technologies, such as Renewable Energy Resources (RES), Distributed Generation (DG), demand response or storages in the frame of chosen scenario, simulation type, test model, and time-series data. The base showcase allows to analyze the operation challenges of the related use case(s) and improvements achieved through the application of planning criteria with related implementation of controllers in the associated showcase”,* while the showcase was defined as *“Presentation of use case(s) in the frame of chosen scenario, simulation type, test model, time-series data and planning criteria”.*

Based on those definitions and use cases developed in the project, five base showcases and five showcases have been developed:

- Low inertia systems
- Effective DER operation planning through active and reactive power control
- TSO-DSO power flow optimization
- Active and reactive power flow optimization at transmission and distribution networks
- Optimal energy interruption management

These showcases are aiming to achieve the following planning criteria:

- Minimize losses
- Minimize costs
- Maximize share of RES
- Assure voltage stability
- Assure transient stability
- Optimize TSO/DSO interaction
- Maximize DG/RES contribution to ancillary services
- Assure frequency stability
- Minimize energy interruptions

As already mentioned, the consortium intends to provide in the integrated operation planning tool, which will be presented in INTERPLAN deliverable D5.2 [1], the following features and advantages in regards to the clustering and grid equivalenting. It will include a library of grid responding to the needs of INTERPLAN project and covering all voltage levels and their active components and it will provide easy to use grid clustering techniques that are adaptive and responsive to the dynamic growth of the evolving grid thus refreshing and valid as new technologies emerge and adapted in the grid. The following flowchart shows how grid equivalenting is going to be integrated into the INTERPLAN tool set. The related description of the tool set is provided in deliverable D5.2.

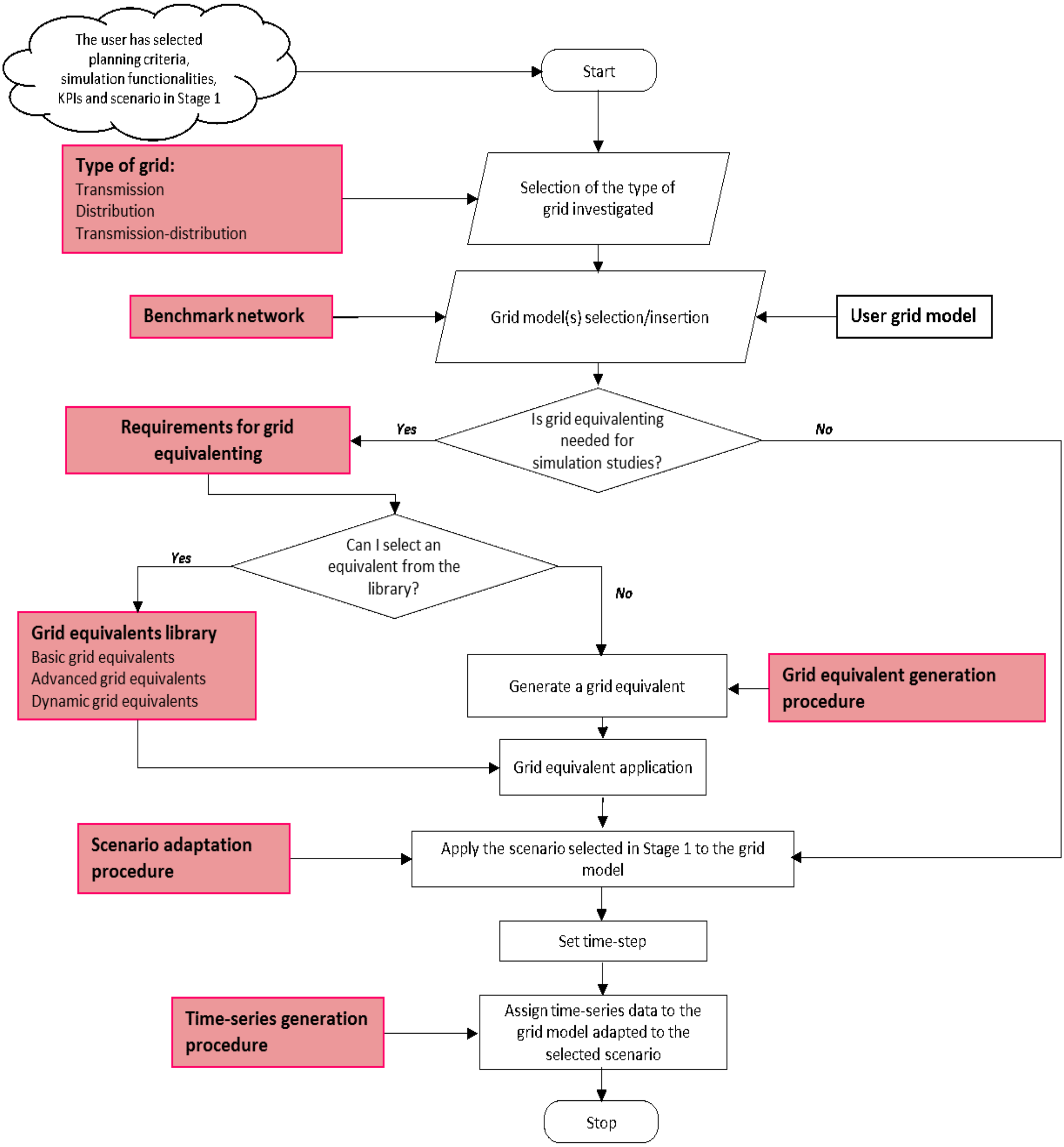


Figure 1 Section of the INTERPLAN tool flowchart that reflects the application of grid equivalenting

2.1 General Considerations

Considering the INTERPLAN use cases and showcases the following table defines the requirements of the grid equivalents.

Table 1 Requirements of the grid equivalent in the view of INTERPLAN project

Use Case / Showcase	Grid(s) investigated	Requirements for grid equivalent model
UC_1: Coordinated voltage/reactive power control	Transmission-distribution grid	Sub Use Case (UC) needs two grid equivalents one modelling TSO and the other modelling DSO. It means while studying TSO, DSO should be placed as an equivalent grid and vice versa. The grid equivalent can involve just the overall information of each connection point including voltage, active and reactive power.
UC_2: Grid Congestion Management	Transmission-distribution grid	The grid equivalent should keep the following: • number of busbars; • several sensitivities parameters (dP/dP, dV/dP, dP/dQ, etc.); • lines characteristics
UC_3: Frequency tertiary control based on optimal	Transmission-distribution grid	Sub UC needs two grid equivalents, one modelling TSO and the other modelling DSO. It means while studying TSO, DSO should be placed as an equivalent grid and vice versa. The grid equivalent can involve just the overall information of each connection point including voltage, active and reactive power.
UC_4: Fast Frequency Restoration Control	Transmission-distribution grid	The grid equivalent should keep following requirements: • Total grid freq. droop contribution per each control area; • Tie-line active power flow among control areas;
UC_5: Power balancing at DSO level	Transmission-distribution grid	Simple grid equivalent model for transmission network has to be considered
UC_6: Inertia management	Transmission-distribution grid	Dynamic grid equivalent models need to be developed for both transmission and distribution grids
UC_7: Optimal generation scheduling and sizing of DER for-energy interruption management	Transmission-distribution grid	The equivalent for the low voltage (LV) feeder and medium voltage (MV) feeder is required for the network preparation. The grid equivalent model should represent with the minimum size the properties of the original network with certain accuracy.
SC_1: Low inertia systems	Transmission-distribution grid	Dynamic grid equivalent models need to be developed for both transmission and distribution grids. Grid topology can be ignored.
SC_2: Effective DER	Transmission-	For the show case, the detailed equivalent model as

Use Case / Showcase	Grid(s) investigated	Requirements for grid equivalent model
operation planning through active and reactive power control	distribution grid	result of clustering approach is not needed, rather a simplified representation should be sufficient. The sensitivity of only the critical node with respect to point of connection can be incorporated in the grid equivalent.
SC_3: TSO-DSO power flow optimization	Transmission-distribution grid	SC needs two grid equivalents one modelling TSO and the other modelling DSO. It means while studying TSO, DSO should be placed as an equivalent grid and vice versa. The grid equivalent can involve just the overall information of each connection point including voltage, active and reactive power.
SC_4: Active and reactive power flow optimisation at transmission and distribution networks	Transmission-distribution grid	SC needs two grid equivalents one modelling TSO and the other modelling DSO. It means while studying TSO, DSO should be placed as an equivalent grid and vice versa. The grid equivalent can involve just the overall information of each connection point including voltage, active and reactive power. Grid equivalenting should be possible by providing simplified network models with aggregated values for voltage (V), active Power (P) and reactive power (Q)
SC_5: Optimal energy interruption management	Transmission-distribution grid	The equivalent for the LV feeder and MV feeder is required for the network preparation. The grid equivalent model should represent with the minimum size the properties of the original network with certain accuracy.

2.2 Requirements analysis

After analysing the gathered information from Table 1, several conclusions can be considered:

- There is the need to have different types of grid equivalents depending on the voltage levels and model granularity.
- Models should be developed for both transmission and distribution networks.
- Basic models (simplified network models) should be simple enough to lower simulation time and maintain key characteristics of the “original” grid (e.g. voltage at connection point, active and reactive power etc.)
- A set of grid equivalent models should consider also the grid topology and reflect different voltage levels
- For some of the use cases / showcases dynamic grid equivalents should be developed

3 General Concept of Generating Grid Equivalents

To support the EU power system planning and operation, a more fruitful interaction between DSOs and TSOs is expected, for which grid equivalents representing different parts of electrical networks are required. A fundamental step for this is feeder/ grid clustering, which allows to identify unique grid/ feeder clusters depending on specific network properties. Clustered electrical networks will provide the basis for the creation of a standardized reference grid model, permitting a wide range of simulations while requiring limited data input.

The networks used to determine grid clusters should be representative of the network of interest, for which a grid equivalent is to be computed, not only in terms of their electrical characteristics or topological structure, but also regarding many other aspects, such as for example, type of customers and their loads, supply areas (industrial/ urban or rural). This will allow to establish the equivalent model of electrical grids more accurately.

A general approach proposed for generating grid equivalents is schematically presented in Figure 2.

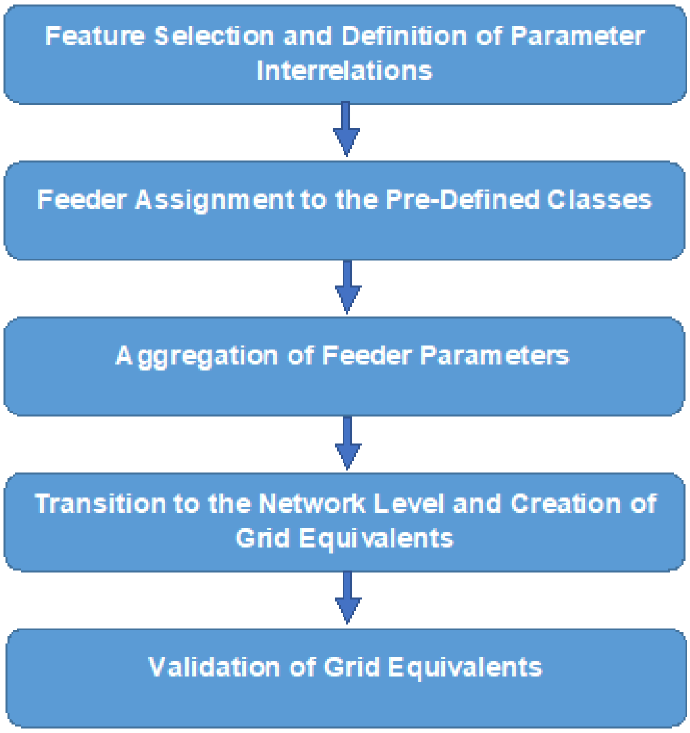


Figure 2: Basic algorithm for generating grid equivalents

3.1 Feature Selection and Definition of Parameter Interrelations

As a starting point for the computation of grid equivalents, it is considered that grid clusters have already been identified. Hence, those equivalents would be built upon predefined clusters, by identifying subsets of a network to their corresponding clusters, and merging feeders belonging to the same cluster first. As a final step, feeders corresponding to heterogeneous clusters will be combined to obtain a simple grid equivalent. In order to merge homogeneous and heterogeneous feeders, it is necessary to identify the relationship between Key Performance Indicators (KPIs) and network parameters defined in [1]. Such relationships or maps tell how the parameters of the grid equivalent would look like.

- **Feature selection**

Before starting an equivalenting process the most appropriate KPIs should be identified. In an ideal case, all characteristics related to the KPI calculation have to be already implemented into a preceding clustering procedure. If the functional relationship between the KPI-variables and common clustering parameters cannot be directly observed, it is recommended to specify the model of dependence among the characteristics by using regression analysis.

In the case of linear regression, the model, that relates the dependent variable to the given features, can be defined as follows:

$$y = Xw + \varepsilon \qquad (1)$$

where y is a vector of the dependent variable;

ε is an error term, corresponding to the random, unpredictable model error;

X is a matrix of feature observations, sized *n* rows by (*p+1*)-columns, where *n* represents the number of observations and *p* represents the number of parameters;

w is a (*p+1*)-dimensional parameter vector; its elements are often referred to as "weights".

Thus, the problem of determining the relationship between the chosen KPI-variable and feeder features used for clustering has the main task in finding the optimal weights w_i from the given data set.

For a better understanding of linear regression models the matrix form of equation (1) is visualized on Figure 3.

X
matrix of feature observations, including the fictitious column $x_0 = 1$ on the left

y

		Feature 1	Feature 2	…	Feature p	KPI-Variable
Feeder 1	1	x_{11}	x_{12}	$\cdots$	x_{1p}	y_1
Feeder 2	1	x_{21}	x_{22}	$\cdots$	x_{2p}	y_2
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
Feeder n	1	x_{n1}	x_{n2}	$\cdots$	x_{np}	y_n

Figure 3: Matrix representation of the linear regression model

- **Definition of Parameter Interrelations**

Another important issue in understanding of parameter interrelation is the definition of requirements for parameter combining. It is necessary to decide, how the equivalent variable could be represented: as a resulting sum of each variable of the given type, e.g. the sum of impedances or the sum of power losses; as an extremum value, e.g. the maximum voltage drop/ rise or maximum loading; or as any other representative parameter value.

3.2 Feeder Assignment to the Pre-Defined Classes

Figure 4 schematically illustrates an example of a distribution grid with *n* radial feeders connected to the substation terminal. The given grid is assumed to be substituted by a simplified equivalent grid model.

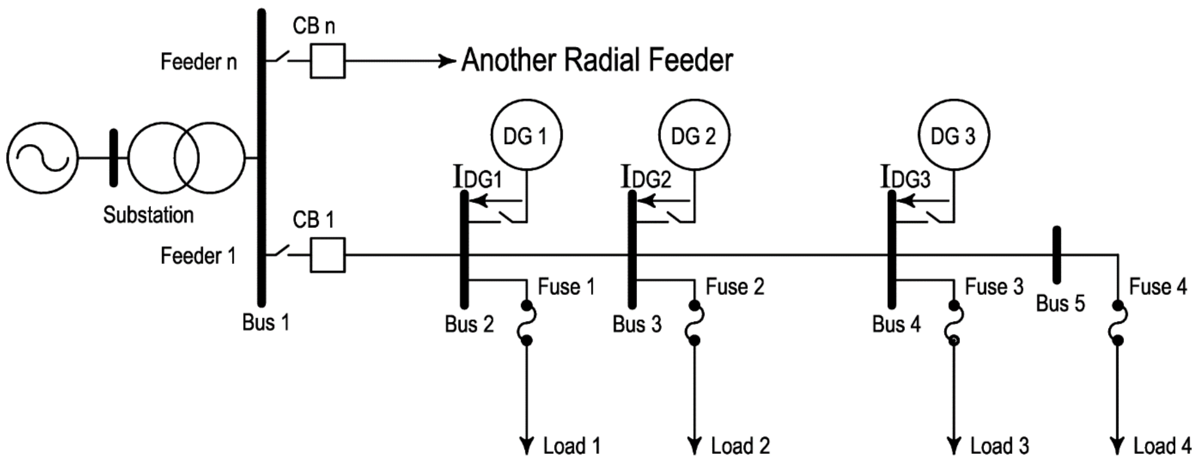


Figure 4: Schematic diagram for typical radial distribution system

The relevant characteristics of each new feeder have to be analysed thoroughly in order to correctly assign the feeder to one of the already identified classes. This could be performed automatically through computing the distances from each new object, i.e. feeder, to the obtained cluster centres according to the specified distance metric (for more details see Deliverable D4.1 “Method for clustering distributions grid” [2]). Minimum distance value would serve as a criterion for belonging to the nearest class of feeders.

Alternatively, determination of feeder classes could be realized by implementing a classification approach, such as for example, the Nearest Neighbours method. The class membership of each object will be defined by the most frequent class among its k nearest neighbours. Following this approach it is necessary to apply the identical distance measure previously used for K-means clustering.

3.3 Aggregation of Feeder Parameters

After identification of class membership all the feeders belonging to the same class can be aggregated to a representative feeder unit, representing the spectrum of properties for the whole feeder group. In this case, the above mentioned requirements for parameter interrelations should be taken into account.

The resulting equivalent grid can be designed based on the set of *m* feeders presenting each feeder class (see Figure 5) or the equivalent grid can be shown as a single equivalent element combining electrical and topological characteristics of feeders belonging to different classes (see Figure 6), e.g. total cable length, total number of nodes, total impedance.

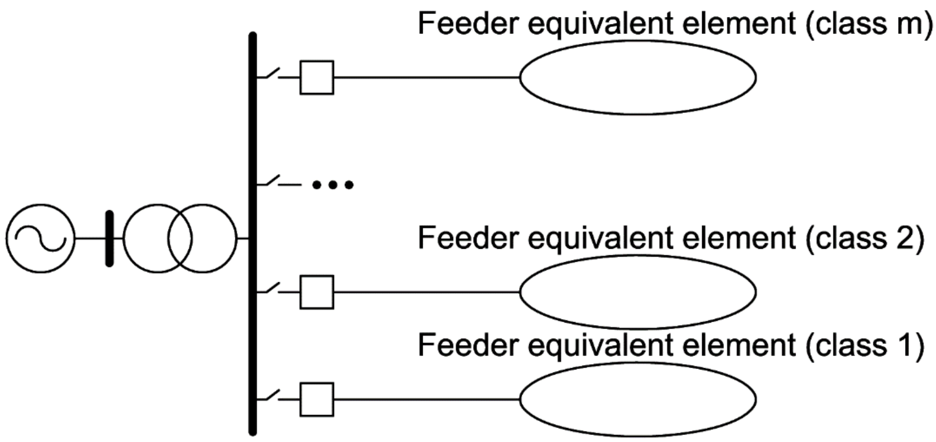


Figure 5: Equivalenting of the population of feeder classes

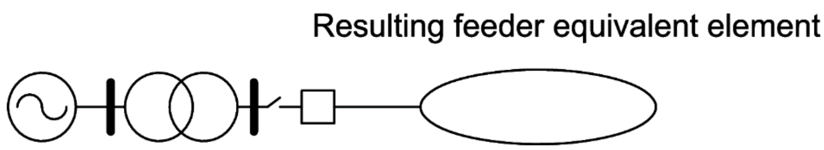


Figure 6: Single grid equivalent representation

3.4 Equivalent grid impedance

As a particular case of grid equivalenting, if the focus of the study lies on defining the equivalent grid impedance, it is recommended to apply the equal power loss method. The proposed method is based on the principle, that total power losses are equal to the sum of branch losses.

To divide active power losses in the given electrical grid ΔP_{grid} into two main components: active power losses in lines ΔP_L and active power losses in transformers ΔP_T, the equivalent grid impedance $Z_{eq\ Grid}$ is represented by equivalent line impedance $Z_{eq\ L}$ and equivalent transformer impedance $Z_{eq\ T}$ connected in series (see Figure 7).

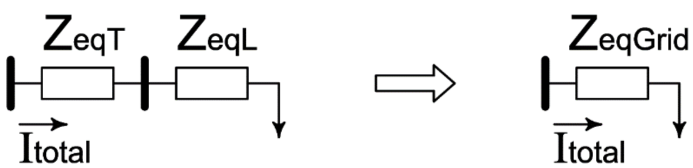


Figure 7: Concept of grid equivalenting based on equivalent impedance

The equivalent line impedance is the sum of the individual line losses divided by square of the total current. For each of *m* line segments with impedance Z_{Li} and current I_{Li} the equivalent impedance can be calculated as follows:

$$Z_{eq\ L} = \frac{\Delta P_L}{3I_{total}^2} = \frac{\sum_{i=1}^{m} I_{Li}^2 \cdot Z_{Li}}{I_{total}^2} \tag{2}$$

The same is true for equivalent impedance of *n* transformers:

$$Z_{eq\ T} = \frac{\Delta P_T}{3I_{total}^2} = \frac{\sum_{j=1}^{n} I_{Tj}^2 \cdot Z_{Tj}}{I_{total}^2} \tag{3}$$

3.5 Transition to the Network Level and Creation of Grid Equivalents

An evaluation of unique features derived from sets of feeder clusters is used as a basis for the network exploration in general; next steps would consider the network level. This allows creating the grid equivalents, able to represent the key properties of real electrical networks for individual use cases and showcases of the INTERPLAN Project. The preceding clustering approach could be initially performed at network level, a feeder-based cluster analysis yields, however, more accuracy according to our preliminary results.

To realize the transition from feeder to the network level, new grid elements have to be considered, for example transformers, generators or synchronous machines. Depending on the available data, variables dealing with these grid elements are to be examined to complete the grid representation.

3.6 Validation of Grid Equivalents

The proposed concept for generating grid equivalents has to be evaluated under real grid conditions and against full models. In order to modify and improve the developments, the equivalent models are to go through a validation process in simulation environments based on representative use cases of the INTERPLAN project. After verifying the results, the developed models can be implement into the grid equivalents library able to cover the relevant use cases.

4 Grid equivalents types

In the past, various methods for determining static and dynamic equivalents have been proposed. As described in [2] equivalenting methods can roughly be divided into two groups. The first group requires no knowledge about the configuration and parameters of the external system. Usually, these methods solely utilise measurements from the study system and its boundary (e.g. those described in [3], [4]). The second group requires knowledge about the external system and the methods are generally referred to as model reduction methods. The resulting equivalents can be suitable for static and/or dynamic studies.

One of the first developed static network equivalents is the so-called Ward equivalent, which was introduced in [5] and further developed in [6]. In the Ward equivalent, the generators and loads in the external system are converted into constant current injectors, which then allows elimination of all external buses. Aschmoneit and Verstege [7] presented an extension of the equivalent to enable steady-state assessment of generator outages. For that purpose, the effect of the speed governors of the generators in the external system was included in the derivation of the equivalent. In [8], the so-called generalised Ward equivalent was introduced. This extension allowed to account for changes in reactive power injection from the external system, by expressing it solely as a function of the bus voltages at the study system's boundary. A dynamic Ward equivalent for transient stability analysis was discussed in [9]. It allows to eliminate all buses in the external system where voltage-dependent loads are connected.

Another approach uses REI (radial, equivalent and independent) equivalents. The method was first presented in [10] and aimed at replacing a set of nodes by one new equivalent node. In order to perform the reduction, a zero-loss network is setup, which connects all load (resp. generator) buses of the external system with a new fictitious bus. Subsequently, the generators and loads of the external system are merged at the new buses and the external nodes are eliminated. A dynamic REI equivalent suitable for transient stability studies was presented in [11]. The authors propose to determine REI equivalents at the boundary buses of the study system. At the newly created nodes, equivalent generators of coherent generator groups are defined. Then the machine parameters of the equivalent generators are determined through participation factors. For aggregation of coherent generators, several other approaches were developed. In [12], the parameters of an equivalent generator and its controllers are determined through a least-square fit of the transfer function of the coherent generator group. A trajectory sensitivity method is used in [13] to determine the exciter parameters of the aggregated generators. In [14], the authors proposed a structure preserving technique to compute the parameters of the equivalent generator.

Depending on the topology of the required network and the focus voltage level, there are several possibilities when generating grid equivalents.

4.1 Basic grid equivalents (static)

The basic grid equivalent should represent in a simple model the complex grids by only considering basic characteristics like connection node voltages and reactive and active power values. This can be achieved by scaling up of most representative feeders based on grid clustering. Thus, the resulting grid equivalent should look like a small network model with one or more feeders depending on the different identified feeder/network classes. Figure 8 and Figure 9 depict the equivalenting method and how a simple equivalent can be represented.

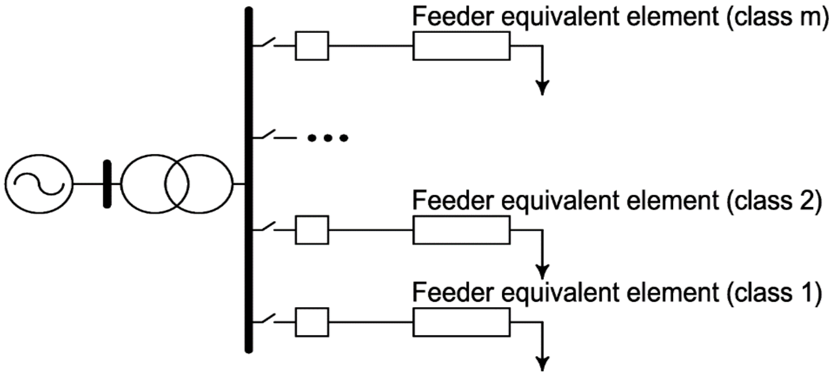


Figure 8 Equivalenting of the population of feeder classes

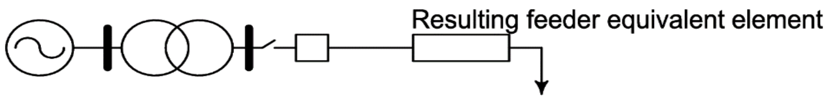


Figure 9: Single equivalent representation

4.2 Advanced grid equivalents (static)

This type of grid equivalents should be a combination of basic grid equivalents considering the topology and different voltage levels. The main idea is to keep as intact as possible the grid transformers parameters of the voltage levels under focus. Figure 10 shows for what parts of the network grid equivalenting should/could be performed.

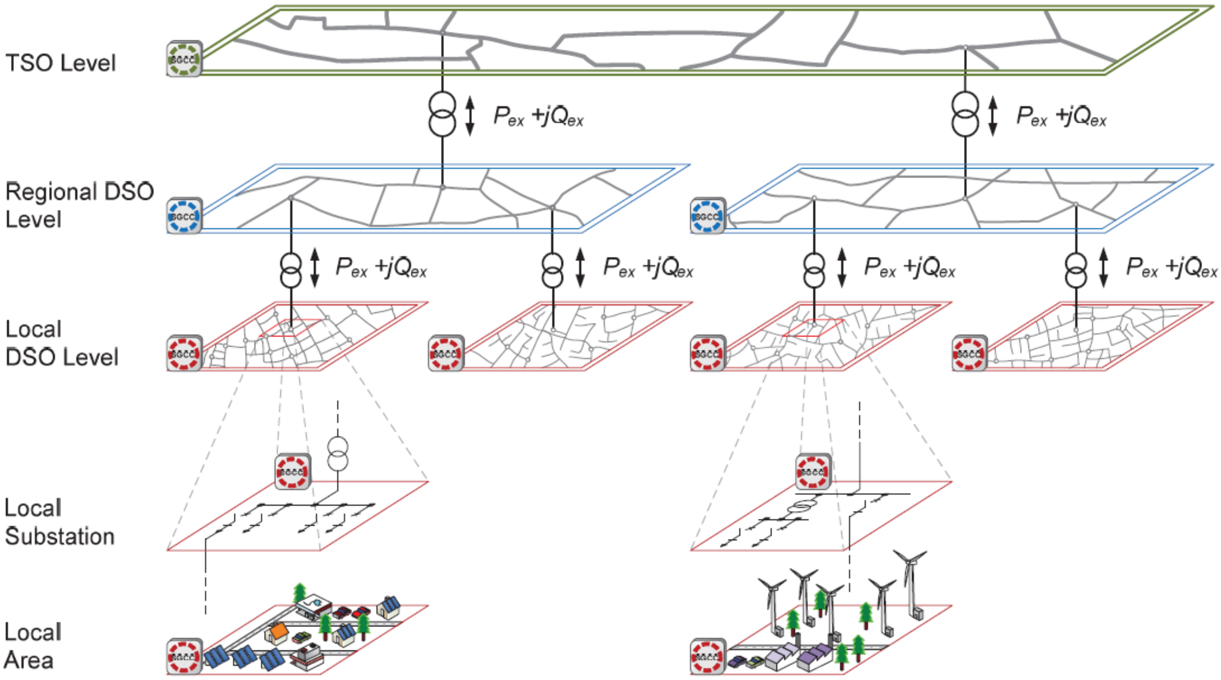
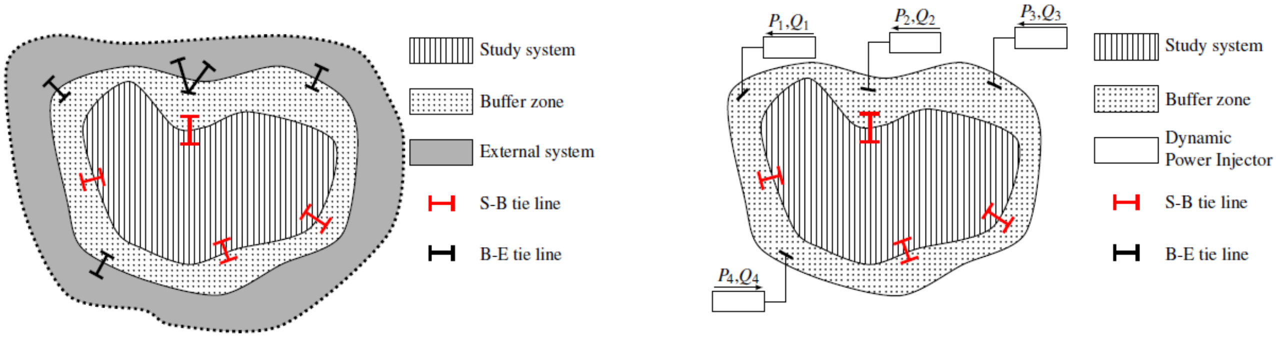


Figure 10: Voltage levels used for the advanced grid equivalents

4.3 Dynamic grid equivalents

In [15], a new method is proposed for representing the inertial and primary frequency control effects of an external system in time-domain simulation. It is assumed that the unreduced system is large and contains the study system. As outlined so far, most techniques for external system equivalenting involve merging the original synchronous machines into a number of equivalent machines. This raises at least two issues: (i) find proper parameters to assign to those fictitious machines (and their associated controllers) and (ii) avoid creating artificial modes of oscillations (not present in the unreduced model) involving those machines. Both these issues are easily addressed with the model proposed in the paper. It consists of dynamic power injectors (DPIs) distributed along the boundary of the study system and emulating the response of the external system to active power imbalance and frequency excursions. Note that the equivalent is not aimed at preserving inter-area electromechanical oscillations, which are assumed to have proper damping. Instead, the equivalent focuses on the global mode (also referred to as common mode by some authors) of rotor oscillation, which is the well-damped oscillatory mode with the lowest frequency present in all machine speed responses. Figure 11 represents and abstract illustration of the reduction of a large power system considering as described above.



(a) Unreduced system divided into a study system, buffer zone and external system.

(b) Reduced system with external system replaced by DPIs.

Figure 11 Abstract illustration of the reduction of a large power system model [14]

Along the project's duration, the work on development of dynamic grid equivalent models will continue in order to identify and develop the best method for deriving such models.

5 Conclusions and further work

In order to define the grid equivalents, a mapping of the requirements for grid equivalents for the developed INTERPLAN use cases and showcases was done by the project partners. Based on the identified requirements, an approach to generate simplified grid equivalents representing the original networks according to the required granularity by the individual use cases was established and presented in this deliverable.

Depending on the topology of the required network and the focus voltage level, several types of grid equivalents were identified:

- Basic Grid Equivalents – simple representation of the grid focusing mainly on preserving Voltage, Active and Reactive power characteristics
- Advanced Grid Equivalents – More complex representation considering also different voltage levels and equivalenting different grid areas

and

- Dynamic Grid Equivalents – Simple or Advanced Grid Equivalents suitable for transient stability studies

Based on the developed INTERPLAN approach to generate simplified grid equivalents, the project will provide and deliver grid-equivalents covering all voltage levels to be incorporated in the operation planning and semi-dynamic simulations environment. In a further step, the developed grid equivalents will be validated during the project runtime. Hence, a validated set of grid equivalents will be provided accessible by public on the website and presented to the scientific community during international conferences and publications. Using appropriate grid equivalents for the distribution grid, the complexity of such investigations can be reduced significantly and can help DSOs to identify the optimal standard parametrization of small-scale DER.

The consortium intends to provide for the integrated operation planning tool the following features and advantages in respect to grid clustering and equivalenting: It will include a library of grid equivalents in CIM-Format responding to the needs of showcasing the project results and covering all voltage levels and their active components and it will provide easy to use grid clustering techniques that are adaptive and responsive to the dynamic growth of the evolving grid thus refreshing and valid as new technologies emerge and adapted in the grid.

The further development of the grid equivalents will also be documented in additional internal reports available to the consortium and will highlight the high interaction between different work packages and the iterative process of defining and refining grid equivalents.

6 References

[1] M. K. /. I. W. /. I. S. /. I. K. /. A. H. /. A. K. /. D. S. /. D. C. /. E. D. S. /. V. /. E. G. /. E. H. /, “Deliverable D5.1 INTERPLAN showcases,” 2018.

[2] A. P. /. A. A. A. /. A. C. /. A. K. /. D. D. S. /. E. C. /. E. G. /. E. V. /. E. B. /. A. R. /. I. H. /. I. H. /. FOSS, “Deliverable D4.1Method for clustering distributions grid,” INTERPLAN H2020 Project https://interplan-project.eu/, 2019.

[3] J. B. J. B. J. Machowski, Power system dynamics: stabilityand control, John Wiley & Sons,, 2009.

[4] J. D. M. L. J. e. a. Dopazo, “An external system equivalentmodel using real-time measurements for system security evaluation,” *IEEETrans. Power Appar. Syst,* vol. 96, no. 2, pp. 431-446, 1977.

[5] X. L. Z. B. J. Feng, “Identification based dynamic equivalencing,” in *IEEE PowerTech* , Lausanne, 2007.

[6] J. Ward, “Equivalent circuits for power-flow studies,” *AIEE Trans,* vol. 68, no. 2, pp. 373-382, 1949.

[7] A. D. S. G. A. e. a. Monticelli, “Real-time externalequivalents for static security, analysis,” *EEE Trans. Power Appar. Syst,* vol. 98, no. 2, pp. 498-508, 1979.

[8] F. V. J. Aschmoneit, “An external system equivalent for on-linesteady-state generator outage simulation’,” *IEEE Trans. Power Appar. Syst,* vol. 98, no. 3, pp. 770-779, 1979.

[9] R. v. M. H. van Amerongen, “A generalisedWard equivalent forsecurity analysis,” *IEEE Trans. Power Appar. Syst.,* vol. 101, no. 6, p. 1519–1526, 1982.

[10] T. M. L. P. A. Baldwin, “Dynamic Ward equivalents for transientstability analysis,” *IEEE Trans. Power Syst,* vol. 9, no. 1, pp. 59-67, 1994.

[11] P. Dimo, Nodal analysis of power system, Kent, England: Abacus Press, 1975.

[12] F. S. K. Milano, “Dynamic REI equivalents for short circuit andtransient stability analyses,” *Electr. Power Syst. Res,* vol. 79, no. 6, p. 878–887, 2009.

[13] A. P. R. Germond, “Dynamic aggregation of generating unitmodels,” *IEEE Trans. Power Appar. Syst,* vol. 97, no. 4, pp. 1060-1069, 1978.

[14] R. C. J. P. W. e. a. Galarza, “Aggregation of exciter modelsfor constructing power system dynamic equivalents,” *IEEE Trans. PowerSyst.,* vol. 13, no. 3, p. 782–788, 1998.

[15] M. D. L.-A. D. V.-Q. Ourari, “Dynamic equivalent modeling oflarge power systems using structure preservation technique,” *IEEE Trans.Power Syst.,* vol. 21, no. 3, pp. 1284-1295, 2006.

[16] T. Weckesser and T. V. Cutsem, “Equivalent to represent inertial and primary frequency control effects of an external system,” *IET Generation, Transmission & Distribution ,* vol. 11, no. 14, pp. 3467-3474, 2017.

[17] H. Farhangi, “The path of the smart grid,” *IEEE Power and Energy Magazine,* vol. 8, no. 1, pp. 18-28, 2010.

[18] SmartGrids, “SmartGrids,” [Online]. Available: www.smartgrids.eu. [Accessed 2009 03 15].

7 Annex

7.1 List of Figures

7.2 List of Tables