INTERPLAN
INTEgrated opeRation PLAnning tool towards the Pan-European Network

Work Package 3

Requirements, scenarios and use cases definition

Deliverable D3.2

INTERPLAN use cases

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Abbreviations

ACE	Area Control Error
AGC	Automatic Generation Control
BEV	Battery Electrical Vehicles
CCS	Carbon capture and storage
CHP	Combined heat power
CIM	Common Information Model
DER	Distributed Energy Resource
DERlab	European Distributed Energy Resources Laboratories e.V.
DG	Distributed Generation
DSM	Demand side management
DSO	Distribution System Operators
DSR	Demand Side Response
ENS	Energy Not Supplied
EU	European Union
EV	Electric vehicles
FACTS	flexible alternating current transmission system
FRR	Fast Frequency Response
G2V	Grid-to-Vehicle
GHG	Greenhouse gas
HVAC	High voltage alternate current
HVDC	High voltage direct current
ID	identification
INTERPLAN	INTEgrated opeRation PLAnning tool towards the Pan-European Network
KPI	Key Performance Indicator
LCE	Low Carbon Energy
LNG	liquefied natural gas
NGO	Non-governmental organization
OHL	Overhead line
OpSim	Test- and simulation-environment for grid control and aggregation strategies
PC	Project Coordinator
PHEV	Plug-in Hybrid Electrical Vehicles
PU	Public
R	Report
RES	Renewable Energy Sources
RIA	Research and Innovation Action
RoCoF	Rate of change of frequency
SCN	Subversion
TSO	Transmission System Operator
TYNDP	Ten Year Network Development Plan
UGC	Underground cable
V2G	Vehicle-to-Grid
VPP	Virtual Power Plant
WP	Work package
XLPE	Cross-linked Polyethylene

Executive Summary

The European Union (EU) energy security policy faces significant challenges, as we move towards a pan-European network based on the wide diversity of energy systems among EU members. In such a context, novel solutions are needed to support the future operation of the EU electricity system in order to increase security of supply also accounting for the increasing contribution of renewable energy sources (RES). The goal of INTERPLAN is to provide an INTEgrated opeRation PLAnning tool towards the pan-European Network, to support the EU in reaching the expected low-carbon targets, while maintaining the network security. In this perspective, "integrated" means, both in terms of voltage levels, going from transmission down to distribution level, and in terms of building a bridge between static, long-term planning and considering operational issues by introducing controllers in the operation planning. The project involves 6 partners from 5 European countries. At the time of writing this report, the project is at Month 12 under the Grant Management phase.

In order to provide an integrated planning tool, one of the objectives of INTERPLAN is to find suitable scenarios where the future challenges of the Pan-European network and rising technologies are depicted and addressed in order to meet the 2050 goals of the European Union. It is challenging to bring different developed and presented scenarios from different institutions in a common ground. However, INTERPLAN came up with 4 different scenarios, with time horizons to 2030 and 2050,which comprise the different perspectives of development, from small-scale to large-scale, from centralized to decentralized, from conventional generation to renewables, from weak policies to strong policies, inter alia.

INTERPLAN scenarios present in a descriptive and quantitative manner each of the 4 scenarios with detailed focus on shares of generation and load, active demand side management, trend of network topologies and interconnections, amount of vehicles and demand according to estimated driven kilometres, storage technologies, and fuel and CO_2 prices.

The INTERPLAN consortium has also developed and described seven use cases for the INTERPLAN network models (TSO, DSO, and TSO-DSO interface), grid equivalent models and the resulting network operation planning tool. The definition and analysis of the use cases are based on the regulatory framework and grid code analysis performed in Project WP2 "Technical assessment and regulatory status of the European electricity grid". Besides, the consortium consulted with the advisory board and stakeholder groups to verify the alignments taken.

The seven INTERPLAN use cases are as following:

- UC1: Coordinated voltage/reactive power control
- UC2: Grid congestion management
- UC3: Frequency tertiary control based on optimal power flow calculations
- UC4: Fast Frequency Restoration Control
- UC5: Power balancing at DSO level
- UC6: Inertia management
- UC7: Optimal generation scheduling and sizing of DER for energy interruption management

This methodology of defining use cases is presented in Figure 1.

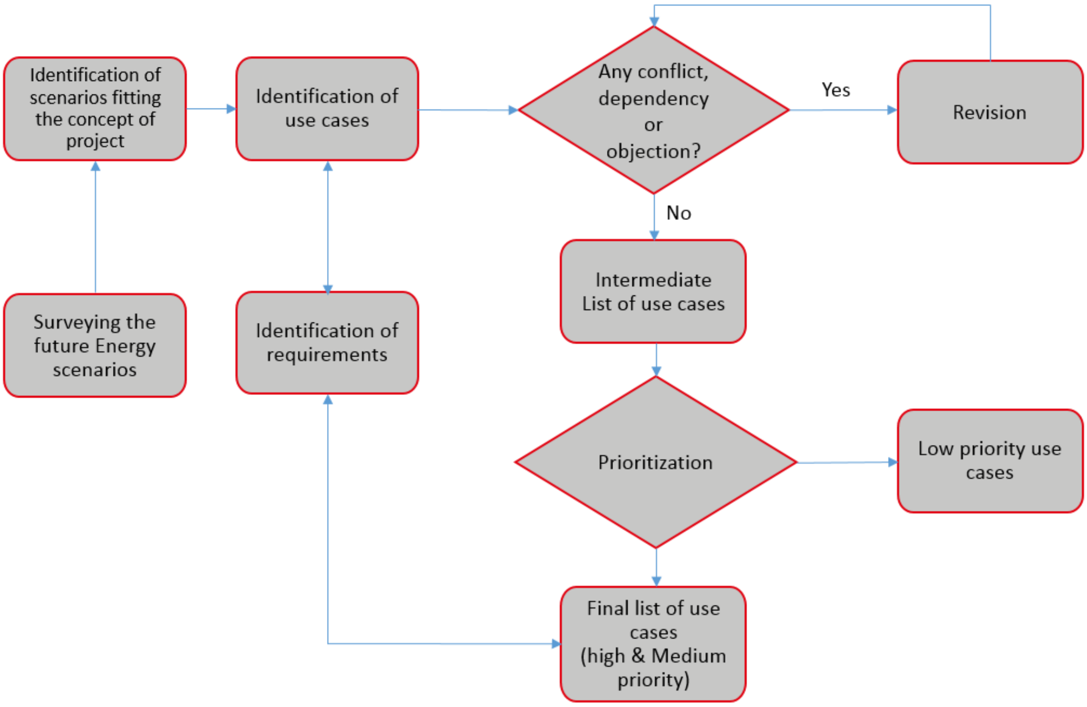


Figure 1: Methodology for use cases definition

Besides, the report presents the key performance indicators, which will be used for evaluating the use case implementation in the planned simulations.

In the further stages of the project, based on the defined use cases and identified EU grid scenarios, a series of showcases as well as required grid equivalent models will be developed for each use case. Finally a set of dynamic and semi-dynamic simulations for each showcase will be performed, and the possible criticalities as well as the possible solutions will be identified.

1 Introduction

1.1 Purpose of the Document

This document presents the final results of use cases definition and analysis as well as future European grid scenarios, which are going to be the basis for further activities of INTERPLAN project and more precisely for the implementation of the network operation planning tool as planned in the project.

1.2 Scope of the Document

This document describes the use cases for the INTERPLAN network models (TSO, DSO, TSO-DSO interface), grid equivalent models and the network operation planning tool. The definition and analysis of the use cases are based on the regulatory framework and grid code analysis performed in WP2[1]. Besides, the consortium consulted with the advisory board and stakeholder groups to verify the alignments taken. This activity was mainly performed at the first INTERPLAN workshop, which took place as a side event at ENERGYCON 2018[2] conference in Limassol, Cyprus.

The document also reports the future EU grid scenarios, which will be considered in INTERPLAN. These scenarios provide predictions on the status of generation, demand, storage technologies, network topologies, fuel and marginal costs in the time horizons 2030 and 2050. The collection of information was initiated by surveying existing scenarios which have been provided by different stakeholder groups, projects, initiatives and platforms both on national and international levels (e.g. Ten Year Network Development Plan - TYNDP 2018[3], e-Highway 2050[4] and ETIP SNET[5]). These data were analysed with regard to the project objectives, in order to find the relevant EU grid scenarios for INTERPLAN.

The results of these activities reported in this document will be used in the implementation phases in WP4[6], WP5[7] and WP6[8] of the project.

1.3 Structure of the Document

This document consists of seven chapters. The first chapter includes an introduction into the document. The second chapter gives an overview about the INTERPLAN project in general. The third chapter introduces the methodology applied for collection, evaluation and selection of the use cases. The fourth chapter provides information on the analysed and selected scenarios for INTERPLAN. The fifth chapter presents the Key Performance Indicators (KPI) considered for the use cases evaluation. The sixth chapter provides the full description of all the selected use cases. Finally, a summary of the report and an outlook for the future activities are presented in the last chapter. Besides, in Annex 1 includes a glossary of terms and definitions used in this document.

[1] WP2: Technical assessment and regulatory status of the European electricity grid

[2] 5th IEEE International Energy Conference (http://www.energycon2018.org/)

[3] https://tyndp.entsoe.eu/tyndp2018/

[4] http://www.e-highway2050.eu/e-highway2050/

[5] https://www.etip-snet.eu/

[6] WP4: Grid equivalenting

[7] WP5: Operation planning and semi-dynamic simulation

[8] WP6: INTERPLAN model validation and testing

2 INTERPLAN project

The EU energy security policy faces significant challenges, as we move towards a pan-European network based on the wide diversity of energy systems among EU members. In such a context, novel solutions are needed to support the future operation of the EU electricity system in order to increase security of supply also accounting for the increasing contribution of renewable energy sources (RES). The goal of INTERPLAN is to provide an INTEgrated opeRation PLAnning tool towards the pan-European Network, to support the EU in reaching the expected low-carbon targets, while maintaining the network security. The project involves 6 partners from 5 European countries. At the time of writing this report, the project is at Month 12 under the Grant Management phase.

A methodology for proper representation of a “clustered” model of the pan-European network is provided, with the aim to generate grid equivalents as a growing library able to cover all relevant system connectivity possibilities occurring in the real grid, by addressing operation planning issues at all network levels (transmission, distribution and TSO-DSO interfaces). In this perspective, the chosen top-down approach actually leads to an “integrated” tool, both in terms of voltage levels, going from high voltage down to low voltage up to end consumer, and in terms of building a bridge between static, long-term planning and considering operational issues by introducing controllers in the operation planning. In addition, novel control strategies and operation planning approaches are investigated in order to ensure the security of supply and flexibility of the interconnected EU electricity grids, based on a close cooperation between TSOs and DSOs.

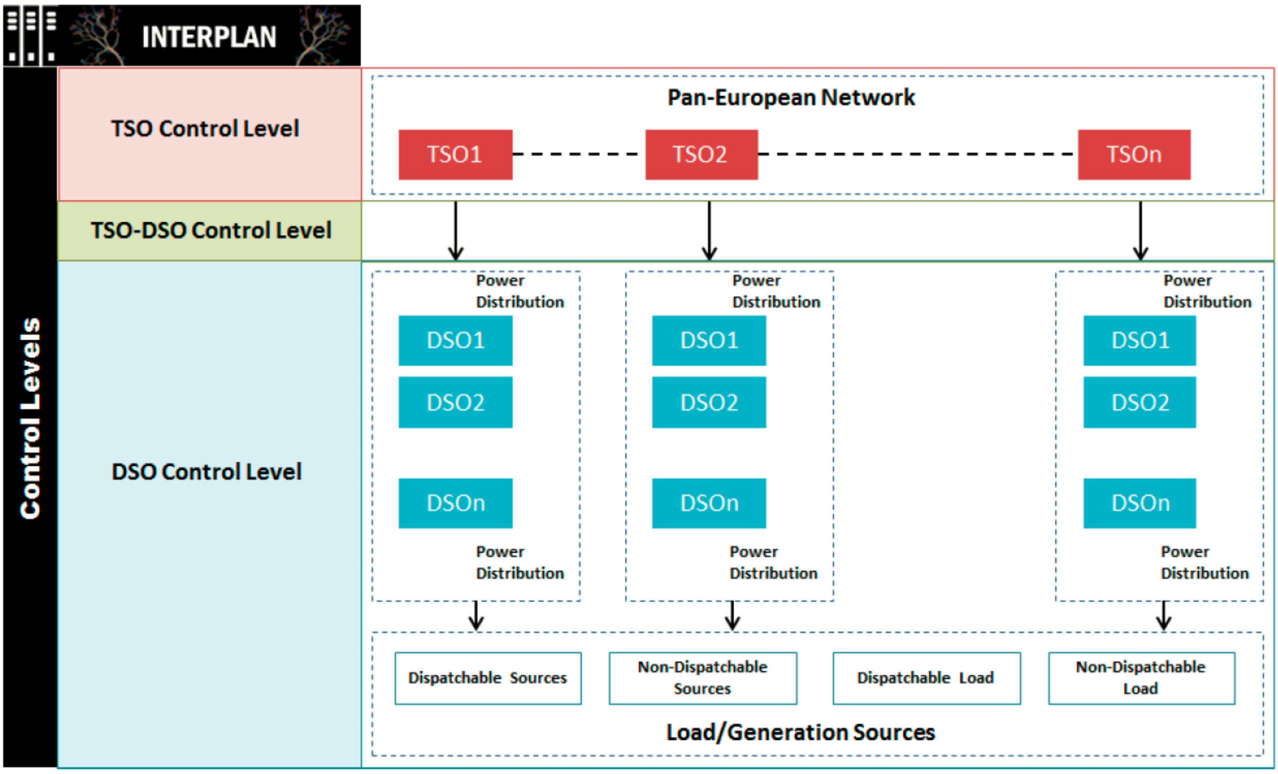


Figure 2: INTERPLAN concept

The basic idea of INTERPLAN Project to cover the greater number of possible system connections and address interconnectivity issues, which requires a thorough assessment of existing grid codes and regulations at European and National level. Current shortcomings to integration of emerging technologies and services such as renewables, storages, electric vehicles and demand response as well as associated best practices are identified. Additionally, the developments achieved through the project are transformed into policy requirements to be addressed to the regulators and grid operators for possible amendments to the grid codes. Based on this analysis, use cases and accordingly showcases for simulations are developed. The use cases address the main challenges for network operation planning considering the important role of emerging technologies i.e., high share of RES, demand response, high integration of demand response service, high share of electric vehicles. Examples of these challenges are inertia management and voltage stability.

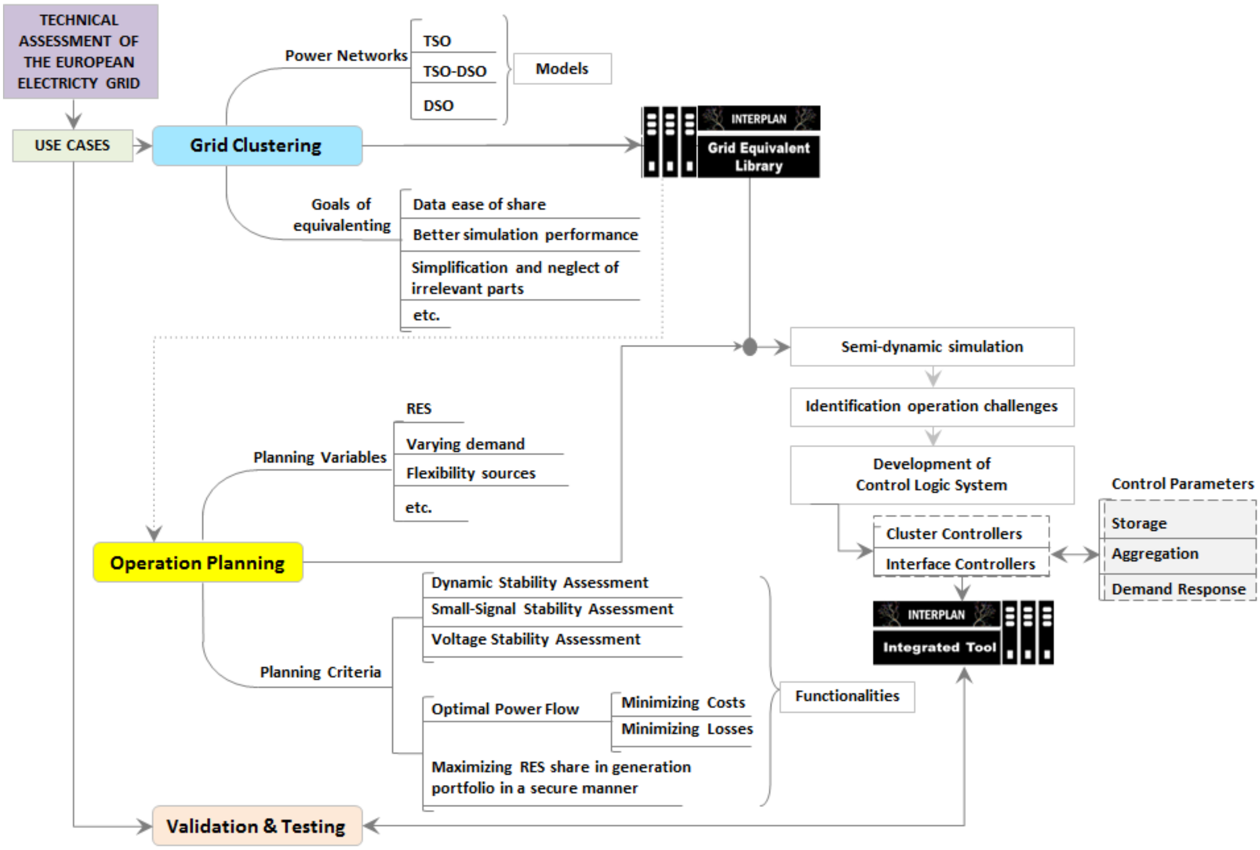


Figure 3: INTERPLAN MindMap

Based on the use cases and identified EU grid scenarios, a series of showcases are developed, which addresses issues such as resiliency of the interconnected grid with effective use of local resources. The “grid equivalenting”, which is conceptually the successive phase of the work, 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 previous use cases are designed in numerical power system simulation environment. Then, a clustering methodology for transmission and distribution systems up to the end user level is identified, and a detailed approach for generating grid equivalents is developed for different use cases. Dynamic and semi-dynamic simulations of grid equivalents for each showcase allow analysing the network behaviour and eventual operational problems (e.g. line congestion). The post-processing or parallel-processing of the results allow to identify operational problems to be solved by developing new control system strategies. These latter strategies are designed in order to apply adequate intervention measures through appropriate control parameters such as storage, demand response and aggregation through cluster and interface controllers. Finally, a validation process is applied through numerical simulation environment to prove the validity of the proposed concept.

3 Methodology

This chapter presents the methodology applied in order to define INTERPLAN use cases. The methodology is presented in Figure 4 and described in the following sub chapters.

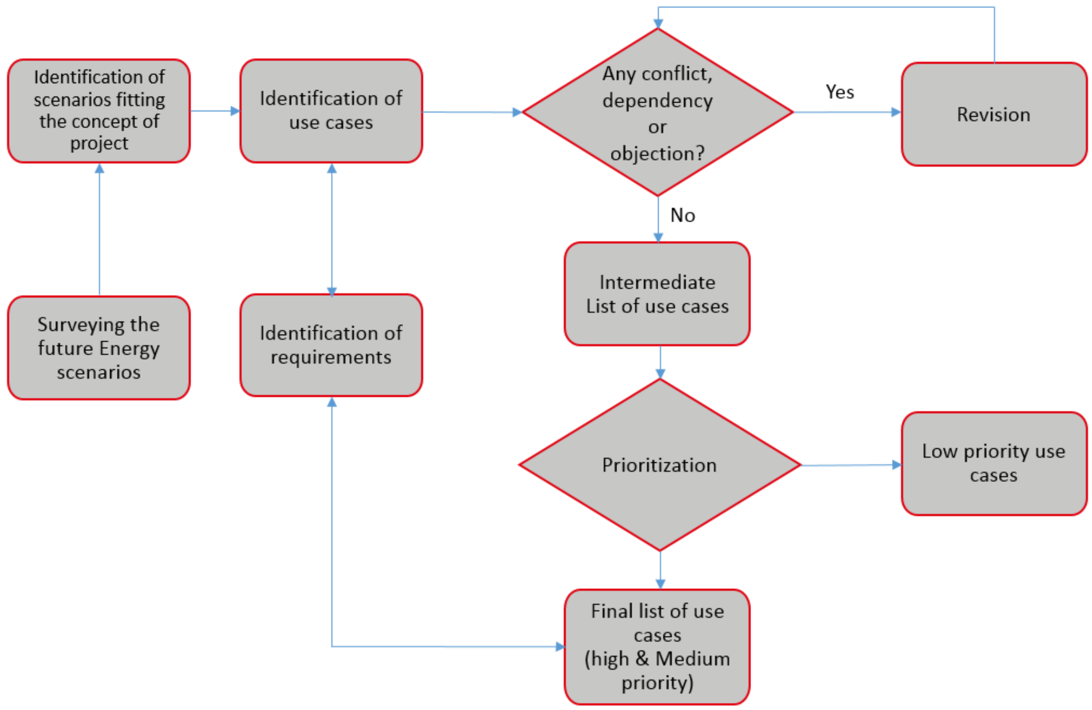


Figure 4: Methodology for use cases definition

3.1 Collection

In this step, a preliminary set of use cases was gathered by the project consortium. This was realised by considering the project's activities and objectives in technical work packages (WP4: Grid equivalenting, WP5: Operation planning and semi-dynamic simulation and WP6: INTERPLAN model validation and testing), as well as analysis done in WP2: Technical assessment and regulatory status of European electricity grid. Moreover, the use cases definition took into consideration INTERPLAN requirements defined in Task 3.1: INTERPLAN requirements.

In defining use cases, the shortcoming identified in the analysis of regulatory framework and current practices at consortium countries for operation of future EU grid (INTERPALN D2.1 [1]) was taken into consideration. The defined use cases look beyond the current regulation and grid codes and propose solutions in order to face the challenges that high share of technologies like RES, storage and EVs will cause for operation planning of the grid and the current grid codes and practices are not able to address them. In case the proposed solutions are evaluated positively in the simulations planned in the later stages of the project, they will be recommended for possible amendments to grid codes and implications on European regulations. This will be reported in a future deliverable (INTERPLAN D2.4: "Grid code recommendations").

3.2 Validation

After the initial definition of requirements, the validation process was performed. All the use cases were validated considering the following points by the identified partners.

- **Dependency:** Use cases that have any dependency on other use cases.

- **Conflict:** Use cases that cannot be implemented if another use case is implemented or there is a conflict due to an insufficient definition of the use case.
- **Objection:** A reason or argument offered in disagreement, opposition, refusal or disapproval of the use case.
- **Goal of the use case:** The use case must address only one goal. Examples:
    - Balancing (Frequency stability, OPF, etc.)
    - TSO-DSO interface congestion management
    - Congestion management at distribution level
    - Voltage/ reactive power management

Where several use cases are addressing similar goals, the selected internal reviewer should recommend to merge them.

- **Scope of the use case:** The use case should address the scope of the project, which include:
    - Future EU grid operation planning
    - TSO-DSO interaction
    - The role of emerging technologies in the future EU grid: RES, demand response, EVs, storage
    - Aggregated flexibility at distribution level
    - Grid clustering and equivalenting

  In case, the use case addresses a topic other than the ones mentioned above, the reason should be asked by the reviewer.

3.3 Revision

In this step, all the dependencies, conflicts, objections and other comments highlighted by the internal reviewers during the validation stage were revised and solved by the use case's authors. However, if the authors did not agree with the validator's comments they could include their own viewpoint.
The revision process consisted of four steps:

1. First, the authors identified which use cases were objected to or involved in any conflict or dependency.
2. Second, and after analysing the validator's view point, the authors chose one of the following:
    - Agree with the validator and proceed to modify or delete the use case or,
    - Disagree with the validator; therefore, the author should make appropriate comments trying to clarify the use case with a better explanation or justify the intention of the use case.

   In both cases, the author needed to define his/her agreement or disagreement by adding comments/ clarifications/ explanations on the modifications.

3. Third, the author defined that he/she revised the use case.
4. Finally, the consortium discussed about the revisions in a meeting and made the final decision about the use cases.

3.4 Refinement, Prioritization and final selection

After the validation and revision procedure, a new set of use cases was integrated into a new list. The use case team members including the leader were selected among the project partners.

Each use case leader with support of its team members, described the corresponding use case in a two-page template. These descriptions were presented to project stakeholders (System operators, utilities, researchers and academia) at the first INTERPLAN workshop in June 2018, which took place as a side event of ENERGYCON 2018 conference in Limassol, Cyprus. The stakeholder provided their viewpoints on all the use cases. Based on the provided feedback, some refinement was made to the use cases.

At the end, the use cases were prioritised in a meeting with participation of all partners and the final use cases to be considered in the project were selected.

4 Scenarios

Today, a great number of energy scenarios is developed and presented every year. These are developed with different purposes, by different institutions (Governmental and Non-governmental Organizations, Energy Companies etc.) using various techniques and concentrating on various segments of the energy sector. Therefore it becomes very challenging to analyse/compare various scenarios and derive meaningful conclusions.

INTERPLAN has tried to find suitable scenarios where the future challenges and rising technologies are depicted and addressed in order to meet the 2050 goals of the European Union. The scenarios taken as a reference for the INTERPLAN project are:

- **e-Highway 2050:** this is one of the few bottom-up scenario studies publicly available. The scenario is not a black-box type of study, but a fairly transparent analysis; it is public with very few exceptions (results from one of ENTSO-E questionnaires are confidential). The fact that this study has been developed by a broad international consortium under the EU FP7 umbrella considerably reduces the possibility of being biased, compared to studies developed by specific energy companies, interest organizations or other Non-governmental organizations (NGOs). The study resides on a comprehensive review of numerous existing scenarios and received an input from the key stakeholders via two questionnaire iterations with ENTSO-E.

- **TYNDP 2018:** provides a detailed overview of possible European energy futures up to 2040. All scenarios have been built as realistic and technically sound, based on forward looking policies, whilst also being ambitious in nature and aiming at reducing emissions by 80% to 95% in line with EU targets for 2050. They will be used by ENTSO-E and other organisations to analyse the future of the European energy system, starting with the yearly Mid-term Adequacy Forecast released for consultation by ENTSO-E in autumn 2017 and the Ten Year Network Development Plans for gas and electricity to be released in 2018.

The TYNDP 2018 scenarios cover the years 2020 to 2040. 2020 and 2025 are labelled as “Best Estimate” scenarios due to a lower level of uncertainty. As uncertainty increases over longer time horizons, the 2030 and 2040 scenarios have been designed with European 2050 targets as an objective, recognizing the work done in the e-Highway 2050 project. This is the reason why INTERPLAN takes the e-Highway 2050 project outcomes and databases as a main reference.

It was specifically stated in e-Highway 2050 project that the selected scenarios are neither predictions nor forecasts about the future. It was not concluded that one single scenario will be more likely to happen than another, nor that one scenario is more preferred or "better" than another. Rather each e-Highway2050 scenario is one alternative image of how the future of European Electricity Highways could unfold.

The next chapters are going to introduce different scenarios for INTERPLAN considering following aspects:

- Four scenarios for electricity generation
- Load and demand
- Network topologies and technologies
- Storage technologies

- Fuel costs and CO2 prices

4.1 INTERPLAN-1: Big & Market

In this scenario, a global agreement for climate mitigation is achieved. Thus, CO_2 costs are high due to the existence of a global carbon market. Europe is fully committed to meet its 80-95% Green House Gas (GHG) reduction orientation by 2050 but it relies mainly on a market based strategy.

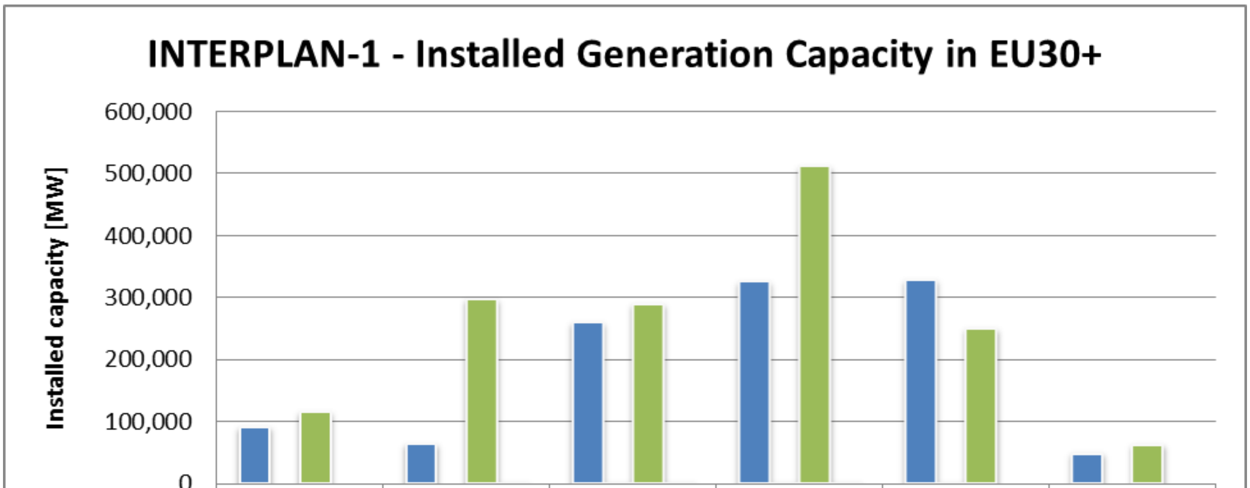
Moreover, in this scenario, there is a special interest on large-scale centralized solutions, especially for RES deployment and storage. Public attitude towards deployment of RES technologies is indifferent in the EU, while acceptance of nuclear and shale gas as energy sources is positive since being preferred over decentralized local solutions. Carbon capture and storage (CCS) technology is also assumed mature in this scenario.

Electrification of transport, heating and industry is considered to occur mainly at centralized (large-scale) level. Only a minor shift towards 'greener' behaviours is experienced in this scenario compared to present practices. Therefore, the efficiency level is low. In general, the public is somehow passive, and the players are active in a market-driven energy system.

4.1.1 Generation

Centralised projects (RES and non-RES) instead of decentralised projects are assumed and no source of energy is excluded. The scenario seeks a quick and economically sustainable CO_2 reduction by replacing coal and lignite by gas in the power sector. Gas also replaces some oil usage in heavy transport and shipping. CCS is considered to be mature. Gas-fired power generation flourishes due to relatively cheap global gas prices and strong growth of bio-methane. A regulatory framework in place decreases the use of coal-fired power stations. Gas-fired generation provides the necessary flexibility to balance RES as peak units in the power system. Overall, the number of nuclear plants in Europe will decrease. Also, the fossil-based generation is considered as main solution to balance RES, this means, as peak units. Thereby even with increased installed capacity, the energy produced is smaller in the time horizon 2050 than in 2030.

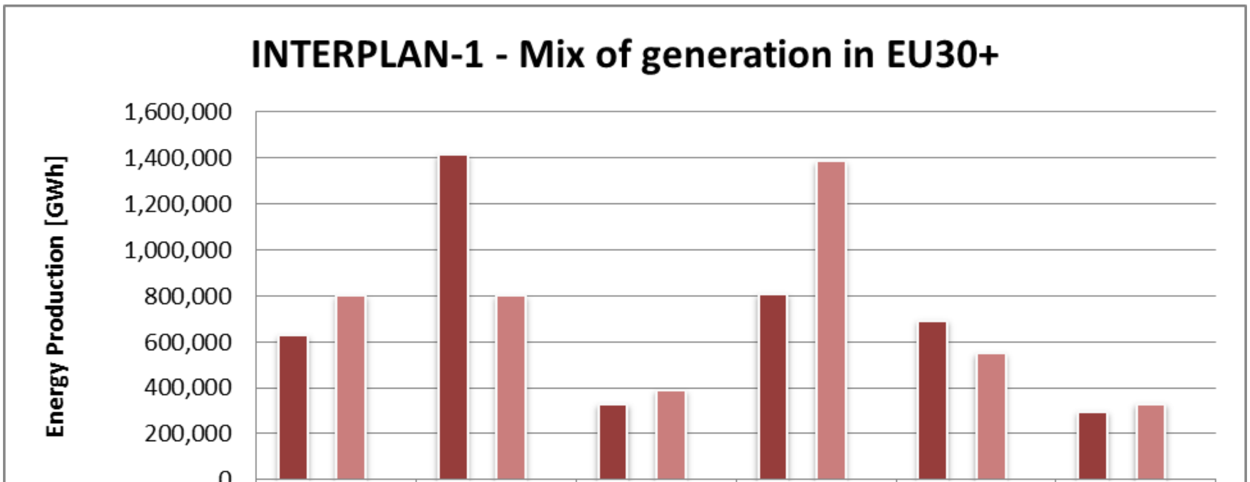
The installed capacity presented by the TYNDP 2018 (Sustainable Transition) for 2030 and the e-Highway 2050 (Big & Market) for 2050 scenarios is shown in Figure 5.



	Nuclear	Fossil	Solar	Wind	Hydro	Biomass
2030 [MW]	91,650	64,484	260,362	326,415	329,453	49,381
2030 [%]	8.17%	5.75%	23.21%	29.10%	29.37%	4.40%
2050 [MW]	116,200	298,100	290,283	512,289	250,422	63,250
2050 [%]	7.59%	19.48%	18.97%	33.47%	16.36%	4.13%

Figure 5: Installed generation capacity for INTERPLAN-1 scenario. Database from [2] and [3].

On the other hand, the mix of generation presented by the TYNDP 2018 (Sustainable Transition) for 2030 and the e-Highway 2050 (Big & Market) for 2050 scenarios is shown in Figure 6.



	Nuclear	Fossil	Solar	Wind	Hydro	Biomass
2030 [GWh]	630,646	1,415,939	330,824	809,974	694,695	298,285
2030 Share [%]	15.09%	33.87%	7.91%	19.38%	16.62%	7.14%
2050 [GWh]	801,951	802,383	390,776	1,386,492	551,800	333,132
2050 Share [%]	18.80%	18.81%	9.16%	32.50%	12.93%	7.81%

Figure 6: Mix of generation for INTERPLAN-1 scenario. Database from [2] and [3].

4.1.2 Load and demand

The relation between generation and demand stays quite stable; the residual demand is not a challenge and can be solved with the existent generation. Overall, electricity demand stagnates or grows moderately. Use of gaseous fuels increases for transport and power generation, but slightly decreases for heating. There are no significant changes in the heat generation sector; in most countries, gas will remain the most prominent source; however, the use will decrease due to increasing energy efficiency. Hybrid heat pumps are considered an option in new buildings. Industrial gas and electricity demand is relatively stable.

4.1.3 Transportation

Driven by cheap gas prices and bio-methane development, gas is the preferred option for passenger cars to switch from oil in reaching emission reduction goals, while electricity use for residential transport is growing moderately. There is an increase in Liquified Natural Gas (LNG) use in heavy goods and shipping sectors. There is a limited penetration of hydrogen vehicles.

The total amount of Battery Electrical Vehicles (BEV) and Plug-in Hybrid Electrical Vehicles (PHEV) is presented in Table 1.

Table 1: Electrical Vehicles in INTERPLAN-1. Database from [4].

Type of EV		***Units***	***INTERPLAN-1***	
			2030	***2050***
BEV	**Number of BEVs**	*million*	3	52
	Km driven by BEVs	*million km*	30,000	520,000
	Consumption	*kWh/km*	0.2	
	Energy demand	*GWh*	6,000	104,000
PHEV	**Number of PHEVs**	*million*	10	65
	Km driven by PHEVs	*million km*	120,000	780,000
	Consumption	*kWh/km*	0.125	
	Energy demand	*GWh*	15,000	97,500

4.2 INTERPLAN-2: Small and Local

In this scenario, the global community has not succeeded in reaching an agreement for climate mitigation. Yet, Europe is fully committed to meet its target of 80-95% GHG reduction. Compared to the other scenarios, the European member states have chosen a bottom-up strategy mainly based on small-scale/local solutions to reach this target. Common agreements/rules for transnational initiatives regarding the operation of an internal EU market, EU wide security of supply and coordinated use of interconnectors for transnational energy exchanges do not exist. The focus is rather on local solutions dealing with decentralized generation and storage and smart grid solutions at transmission and mainly on a distribution level.

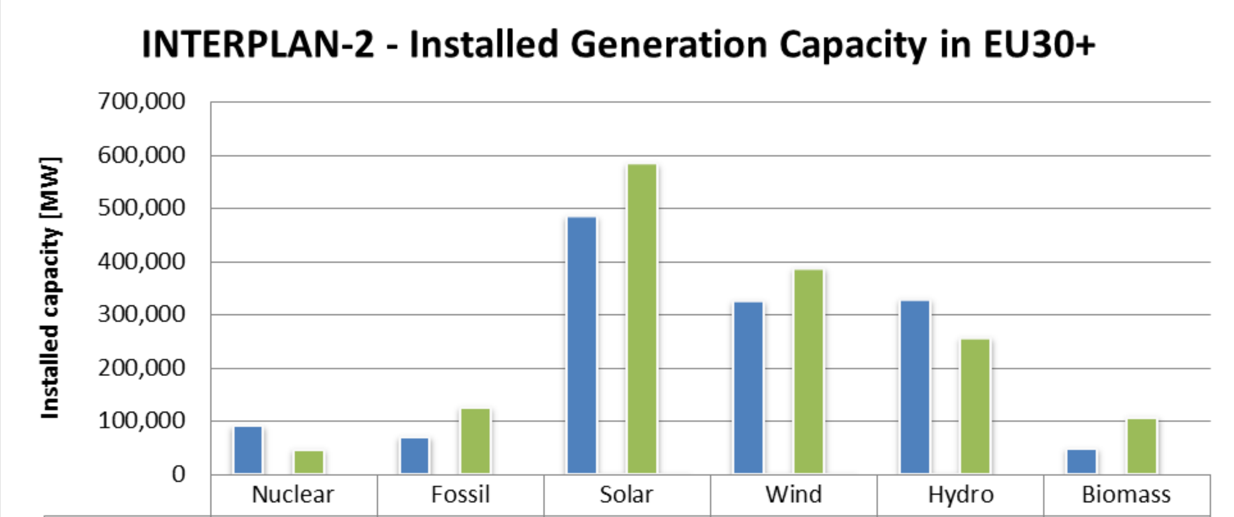
There is a high focus on deployment of decentralized storage and RES solutions, including combined heat power (CHP) and Biomass, while nuclear and CCS are not considered as options to reach the GHG emission reduction target. The public attitude towards the deployment of local decentralized RES technologies is positive in the EU.

A high degree of electrification of transport, heating and industry is considered to occur mainly at decentralized (small scale) level; there is a corresponding high focus on the deployment of energy efficient solutions, including demand side management (DSM) and flexibility of EV use.

4.2.1 Generation

Nuclear mostly will depend on country specific policies. Small-scale generation will challenge large-scale power generation, pressurizing the profitability of traditional power plants. System adequacy will be maintained through a centralized mechanism that retains enough peaking capacity, district heating CHPs will be suitable for both heating and electricity adequacy. As a result of the high share of RES and low demand, CO_2 emissions are well below the 70 Mt/year target (consistent with a 95% decrease compared to 1990 levels): CO_2 emissions are expected to amount to 48 Mt CO_2 per year. To ensure the reliability of the system, a significant amount of biomass and gas-fired peak units is needed. Also, the fossil-based generation is considered as main solution to balance RES, this means, as peak units. Thereby even with increased installed capacity, the energy produced is smaller in the time horizon 2050 than in 2030.

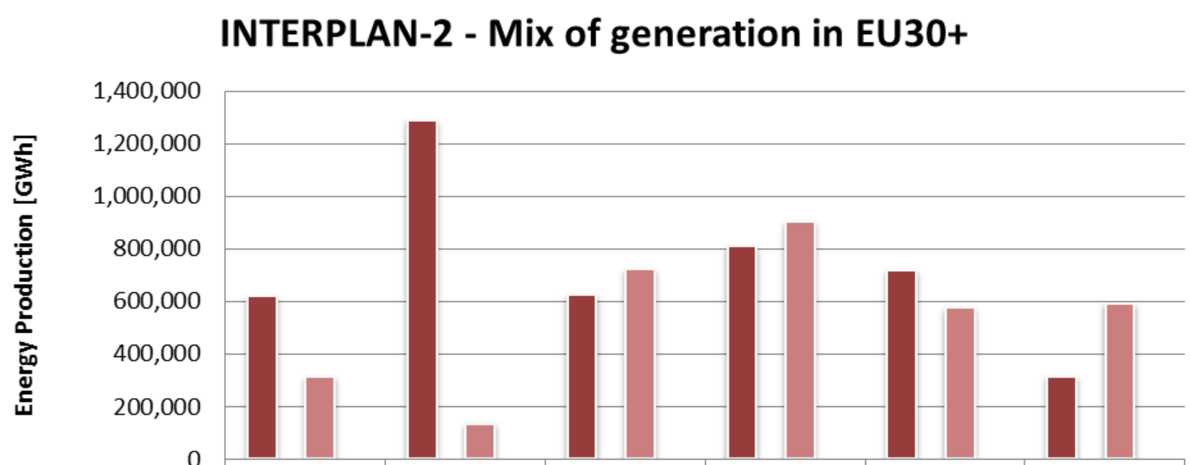
The installed capacity presented by the TYNDP 2018 (Distributed Generation) for 2030 and the e-Highway 2050 (Small & Local) for 2050 scenarios is shown in Figure 7.



	Nuclear	Fossil	Solar	Wind	Hydro	Biomass
2030 [MW]	91,650	71,169	485,296	326,179	329,453	49,381
2030 [%]	6.77%	5.26%	35.86%	24.11%	24.35%	3.65%
2050 [MW]	48,000	126,650	583,900	387,753	257,179	107,750
2050 [%]	3.18%	8.38%	38.64%	25.66%	17.02%	7.13%

Figure 7: Installed generation capacity for INTERPLAN-2 scenario. Database from [2] and [3].

On the other hand, the mix of generation presented by the TYNDP 2018 (Distributed Generation) for 2030 and the e-Highway 2050 (Small & Local) for 2050 scenarios is shown in Figure 8.



	Nuclear	Fossil	Solar	Wind	Hydro	Biomass
2030 [GWh]	619,218	1,289,215	623,464	809,261	718,622	313,942
2030 Share [%]	14.16%	29.48%	14.25%	18.50%	16.43%	7.18%
2050 [GWh]	313,261	135,406	721,449	900,714	574,756	593,442
2050 Share [%]	9.67%	4.18%	22.27%	27.81%	17.74%	18.32%

Figure 8: Mix of generation for INTERPLAN-2 scenario. Database from [2] and [3].

4.2.2 Load and demand

The electricity demand flexibility will substantially increase both in residential and industrial solutions, thereby helping electric power adequacy. The yearly electricity demand will increase in heating (e.g., heat pumps) and transports (e.g., EVs) sectors. The overall electricity demand growth will reduce in the residential sector due to the "prosumer" behaviour. Demand will respond well to market price, and the peak electricity demand will reduce.

4.2.3 Transportation

Electricity and gaseous fuels are both key components for the transport sector in reaching emission reduction goals. Lower battery costs have significantly increased demand for electricity in the transportation sector. There is an increase in the use of LNG for the transportation of heavy goods and also in the shipping sectors. There is limited penetration of hydrogen vehicles.

The total amount of BEV and PHEV is presented in Table 2.

Table 2: Electrical Vehicles in INTERPLAN-2. Database from [4].

Type of EV		***Units***	***INTERPLAN-2***	
			2030	***2050***
BEV	**Number of BEVs**	*million*	40	157
	Km driven by BEVs	*million km*	360,000	1,413,000
	Consumption	*kWh/km*	0.1	
	Energy demand	*GWh*	36,000	141,300
PHEV	**Number of PHEVs**	*million*	10	65
	Km driven by PHEVs	*million km*	100,000	650,000
	Consumption	*kWh/km*	0.1	
	Energy demand	*GWh*	10,000	65,000

4.3 INTERPLAN-3: Large Scale RES

In this scenario, a European agreement for climate mitigation is achieved and fossil fuel consumption is generally low worldwide. Therefore, fuel costs are relatively low. On the other hand, the CO_2 costs are high due to the existence of a global carbon market. The EU's ambition for GHG emission reductions is achieved: 80-95% GHG reduction.

The strategy focuses on the deployment of large-scale RES technologies, e.g. large-scale offshore wind parks in the North Sea and Baltic Seas as well as the Desertec project in North Africa. A lower priority is given to the deployment of decentralized RES (including CHP and Biomass) solutions.

Similarly, a high priority is given to the development of centralized storage solutions (pumped hydro storage, compressed air, etc.) which accompanies the large-scale RES deployment. Decentralized storage solutions are considered to be insufficient to support the large-scale RES deployment: they are not given priority.

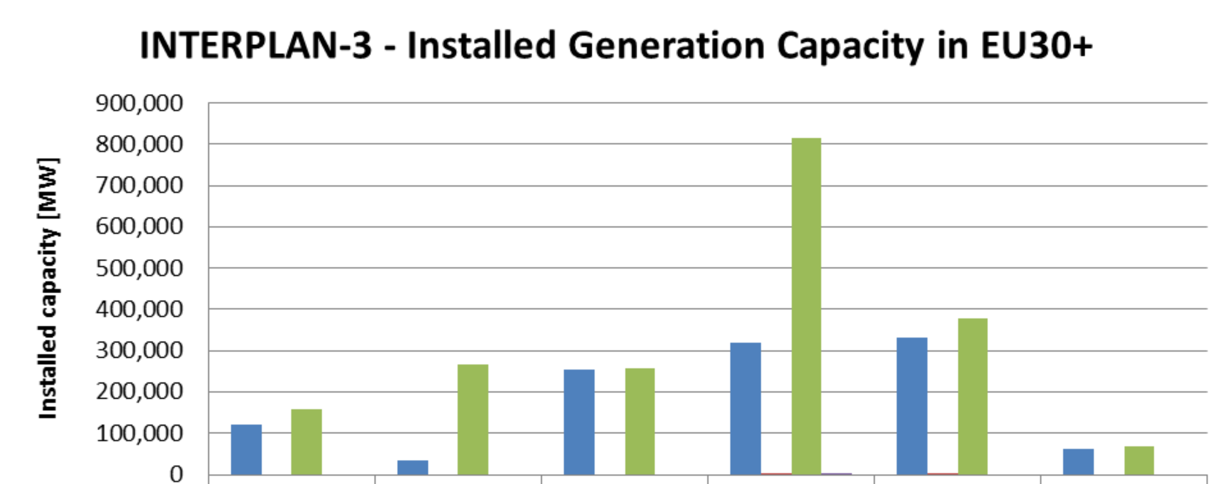
Electrification of transport, heating and industry is considered to occur both at centralized (large-scale) and decentralized (domestic) level. However, the political focus is mainly on the supply side: large amount of fossil-free generation will make investments in energy efficiency solutions less attractive.

A convergent and strong policy framework for the whole European Member States is in place: the deployment of the available RES potential is possible everywhere. Common agreements/rules for transnational initiatives regarding the functioning of an internal EU market, EU wide security of supply and coordinated use of interconnectors for transnational energy exchanges exist.
A little attention is given to large-scale solutions which lowers the priority for imports of fossil fuels at EU level. As a consequence, Europe's energy dependence is low. However, a high import of RES from North Africa – Desertec project is included.

4.3.1 Generation

Nuclear technology as a centralized technology is included in this scenario. Yet, no development in new nuclear technologies is assumed: the current level of deployment is maintained according to standard decommissioning rates for present nuclear plants up to 2050. Since only Europe has a strong policy for the reduction of GHG emissions, CCS technologies are not mature enough (high cost): they are not among the options to reach GHG reduction targets. This scenario gives the advantage to wind, hydro and nuclear solutions. PV is generally installed in North Africa, less in Europe and this provokes high power imports in addition to also high power imports of wind energy from North Sea. Nuclear units are also foreseen as a key contributor to reduce CO_2 emission since no CCS technologies are considered in this scenario. Also, the fossil-based generation is considered as main solution to balance RES, this means, as peak units. Thereby even with increased installed capacity, the energy produced is smaller in the time horizon 2050 than in 2030.

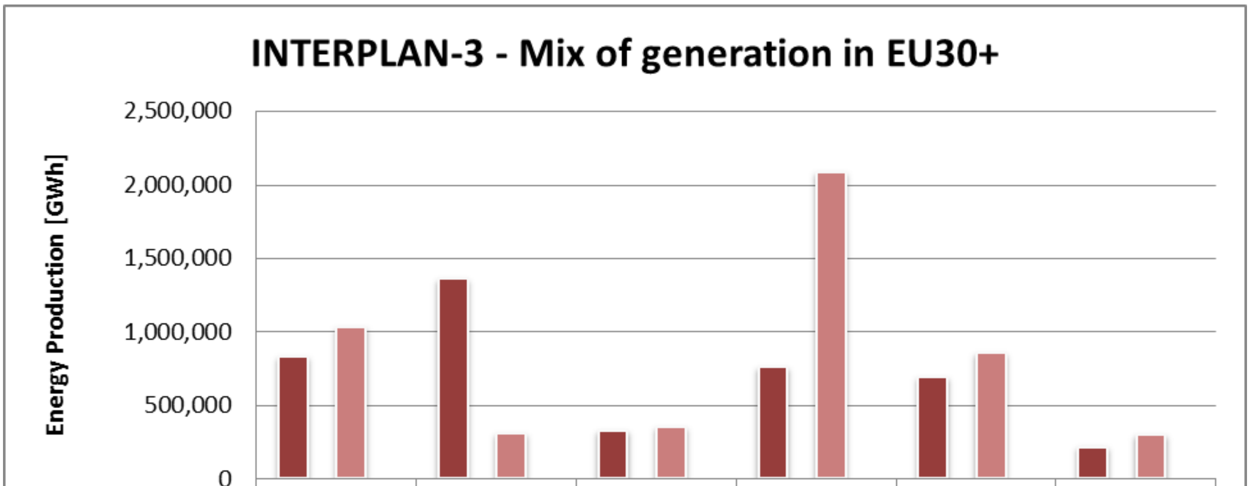
The installed capacity presented by the TYNDP 2018 (EUCO 2030) for 2030 and the e-Highway 2050 (Large Scale RES) for 2050 scenarios is shown in Figure 9.



	Nuclear	Fossil	Solar	Wind	Hydro	Biomass
2030 [MW]	119,491	32,978	254,054	319,330	330,956	62,114
2030 [%]	10.68%	2.95%	22.71%	28.54%	29.58%	5.55%
2050 [MW]	157,200	267,850	256,315	813,469	376,569	69,750
2050 [%]	8.10%	13.80%	13.20%	41.91%	19.40%	3.59%

Figure 9: Installed generation capacity for INTERPLAN-3 scenario. Database from [2] and [3].

On the other hand, the mix of generation presented by the TYNDP 2018 (EUCO 2030) for 2030 and the e-Highway 2050 (Large Scale RES) for 2050 scenarios is shown in Figure 10.



	Nuclear	Fossil	Solar	Wind	Hydro	Biomass
2030 [GWh]	827,880	1,356,045	325,211	757,941	690,053	214,883
2030 Share [%]	19.84%	32.50%	7.80%	18.17%	16.54%	5.15%
2050 [GWh]	1,030,110	307,175	349,804	2,083,933	852,146	298,481
2050 Share [%]	20.93%	6.24%	7.11%	42.34%	17.31%	6.06%

Figure 10: Mix of generation for INTERPLAN-3 scenario. Database from [2] and [3].

4.3.2 Load and demand

This scenario envisages the highest electricity demand to be supplied by large-scale centralized RES solutions. A low increase in energy efficient solutions is foreseen (including DSM and flexibility of EV use). Moreover, a clear shift towards 'greener' behaviours is expected compared to present practices (focus and active involvement towards more energy efficiency, focus and active involvement towards more use of sustainable energy by the European citizen).

4.3.3 Transportation

Electricity and natural gas are both key components for the transport sector in reaching emission reduction goals. The impact of electrification is that demand for electricity use in the private and small commercial transportation sector increases. There is an increase in the use of LNG for transportation especially where electricity does not represent an alternative fuel, such as heavy goods and shipping sectors. There is a limited penetration of hydrogen vehicles.

The total amount of BEV and PHEV is presented in Table 3.

Table 3: Electrical Vehicles in INTERPLAN-3. Database from [4].

Type of EV		***Units***	***INTERPLAN-3***	
			2030	***2050***
BEV	**Number of BEVs**	*million*	21.5	130
	Km driven by BEVs	*million km*	215,000	1,300,000
	Consumption	*kWh/km*	0.12	
	Energy demand	*GWh*	25,800	156,000
PHEV	**Number of PHEVs**	*million*	35.5	120
	Km driven by PHEVs	*million km*	426,000	1,440,000
	Consumption	*kWh/km*	0.1	
	Energy demand	*GWh*	42,600	144,000

4.4 INTERPLAN-4: 100% RES

In this scenario, the global community has not succeeded in reaching a global agreement for climate mitigation. Yet, Europe is fully committed to its target of 80-95% GHG reduction and the CO_2 costs in EU are high due to these strict climate mitigation targets.
The strategy to achieve this target has a higher ambition than the other scenarios: it bases Europe's energy system entirely (100%) on renewable energy. To reach this target, both large-scale and small-scale options are used: offshore wind parks in the North Sea and Baltic Seas and the Desertec project in North Africa, combined with EU-wide deployment of decentralized RES (including CHP and Biomass) solutions.

Electrification of transport, heating and industry is considered to occur both at centralized (large-scale) and decentralized (domestic) level and these solutions will reduce resulting energy demand as well as provide complementary flexibility and storage to account for variability of RES production from PV and wind. There is a strong drive towards 'greener' behaviours in the population with active involvement towards more energy efficiency, more use of sustainable energy and clean transport etc.

As part of the 100% RES strategy, no import of fossil fuels occurs. Only renewable sources (solar energy from Africa, biomass from FSU region etc.) are imported from outside Europe.

Compared with others, this scenario provides the most challenging conditions for the 2050-time horizon. The European energy mix will be based on 100% RES. To reach a 100% RES scenario high difficulties have to be faced to ensure security of supply due to the high share of wind and solar. It can be achieved only through one of these solutions:

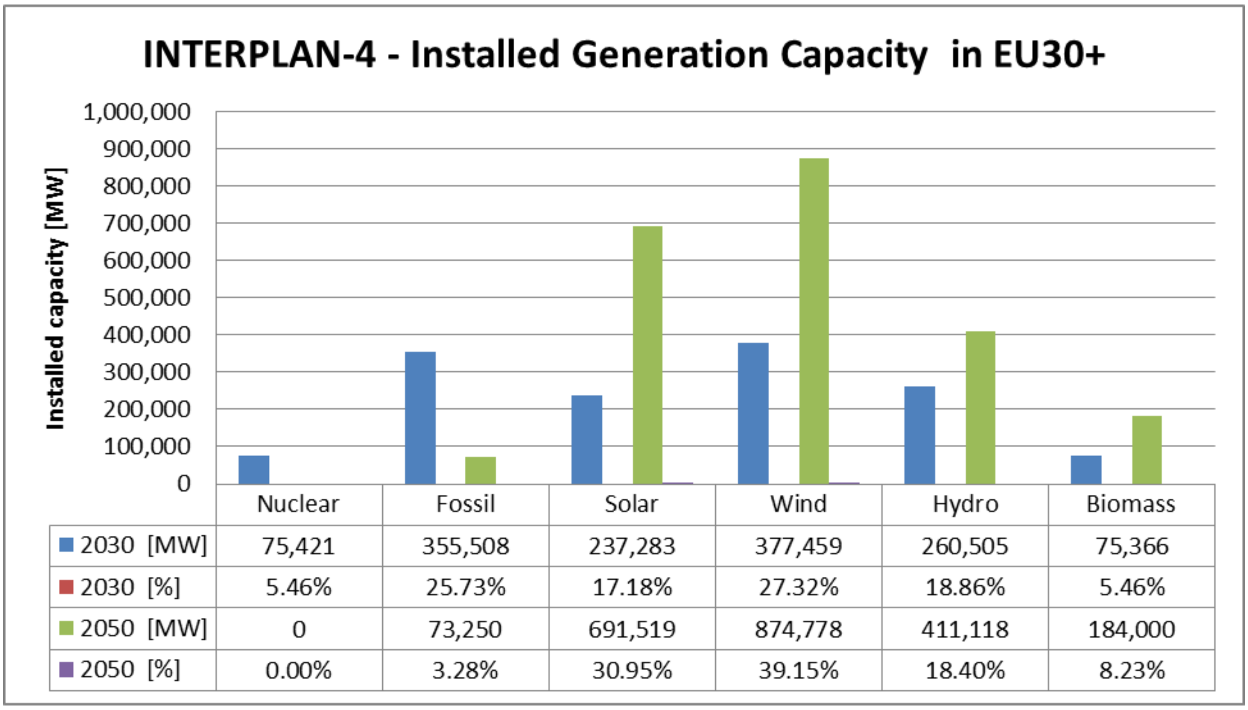
- Increase/development of long-term storage,
- Building peak units, which can be used during critical hours/weeks – fuel type could be biomass or fossil fuel units,
- Increase DSM,
- Install huge amounts of RES and acceptance of high energy spillage (ES).

4.4.1 Generation

Public attitude towards the deployment of RES technologies is very positive in whole Europe, while attitude towards nuclear and shale gas is negative. Neither nuclear nor fossil fuels with CCS are used in this scenario. Thus, both centralized storage solutions (pumped hydro storage, compressed air, etc.) and decentralized solutions are needed to balance the variability in terms of renewable energy generation.

Although this scenario considers a 100% share of RES, 73,250 MW of peaking units are required to ensure adequacy. These units are used less than 100 hours per year. Thereby even with installed capacity, the energy produced is almost 0 (0.29%).

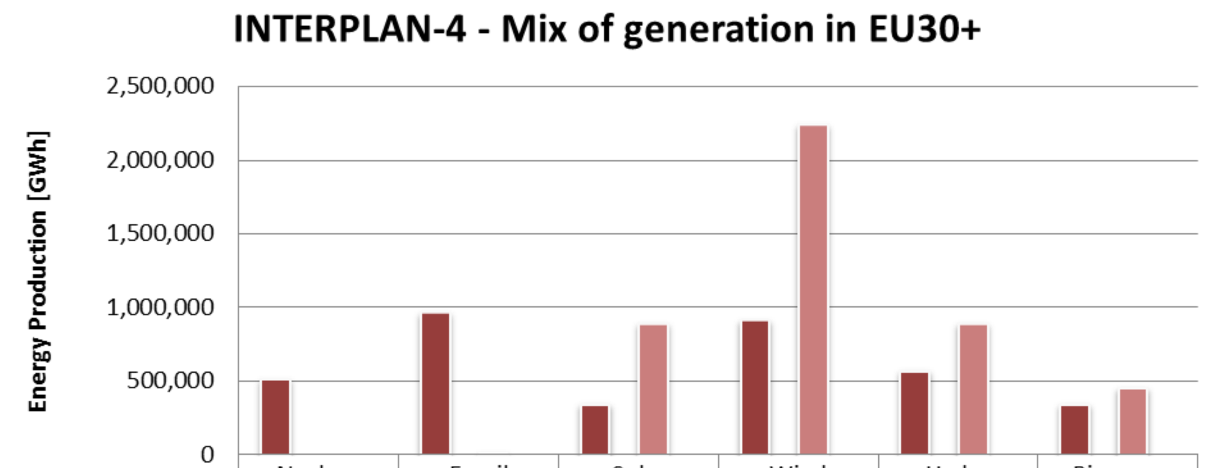
The installed capacity presented by the TYNDP 2016 (Vision 4) for 2030 and the e-Highway 2050 (100% RES) for 2050 scenarios is shown in Figure 11.



	Nuclear	Fossil	Solar	Wind	Hydro	Biomass
2030 [MW]	75,421	355,508	237,283	377,459	260,505	75,366
2030 [%]	5.46%	25.73%	17.18%	27.32%	18.86%	5.46%
2050 [MW]	0	73,250	691,519	874,778	411,118	184,000
2050 [%]	0.00%	3.28%	30.95%	39.15%	18.40%	8.23%

Figure 11: Installed generation capacity for INTERPLAN-4 scenario. Database from [2].

On the other hand, the mix of generation presented by the TYNDP 2016 (Vision 4) for 2030 and the e-Highway 2050 (100% RES) for 2050 scenarios is shown in Figure 12.



	Nuclear	Fossil	Solar	Wind	Hydro	Biomass
2030 [GWh]	512,703	964,916	345,171	913,194	570,936	343,631
2030 Share [%]	14.04%	26.43%	9.46%	25.02%	15.64%	9.41%
2050 [GWh]	0	13,096	892,085	2,238,259	890,175	454,115
2050 Share [%]	0.00%	0.29%	19.88%	49.88%	19.84%	10.12%

Figure 12: Mix of generation for INTERPLAN-4 scenario. Database from [2].

4.4.2 Load and demand

On the consumer side, a marked increase in energy efficiency (including DSM and flexibility of EV use) is assumed. The electricity demand flexibility will increase, both in residential and industrial sectors, thereby helping electric power adequacy. The overall electricity demand growth will reduce in the residential sector due to the "prosumer" behaviour. Demand will respond well to market price, and the peak electricity demand will reduce.

4.4.3 Transportation

The total amount of BEV and PHEV is presented in Table 4.

Table 4: Electrical Vehicles in INTERPLAN-4. Database from [4].

Type of EV		***Units***	***INTERPLAN-4***	
			2030	***2050***
BEV	**Number of BEVs**	*million*	40	157
	Nb of km driven by BEVs	*million km*	400,000	1,570,000
	Consumption	*kWh/km*	0.1	
	Energy demand	*GWh*	40,000	157,000
PHEV	**Number of PHEVs**	*million*	35.5	92.5
	Nb of km driven by PHEVs	*million km*	426,000	1,110,000
	Consumption	*kWh/km*	0.1	
	Energy demand	*GWh*	42,600	111,000

4.5 Load and demand

Unfortunately, [5] does not present information about demand side technologies and management, that is why this section would be based on [6] for the 2050 time horizon.

Table 5 presents the summary of generation, demand, imports, exports, energy not supplied (ENS) and ES figures per scenario for the 2050 time horizon.

Table 5: Generation and demand figures per scenario for 2050. Database from [2].

Demand Figures		***INTERPLAN-1***	***INTERPLAN-2***	***INTERPLAN-3***	***INTERPLAN-4***
Generation	**GWh**	4,266.53	3,239.03	4,921.65	4,487.73
Imports	**GWh**	440.96	161.27	972.22	588.72
ES	**GWh**	19.82	54.66	49.21	272.78
Demand	**GWh**	4,282.54	3,202.33	5,193.74	4,297.59
Exports	**GWh**	405.18	137.18	650.92	506.56
ENS	**GWh**	0.04	0.01	0.01	0.47
Gen.+Imp. -ES	**GWh**	4,687.68	3,345.64	5,844.66	4,803.68
Dem.+Exp. -ENS	**GWh**	4,687.68	3,339.51	5,844.66	4,803.68

In [6], the time series and DSM used for the analysis follow the methodology shown in Figure 13.

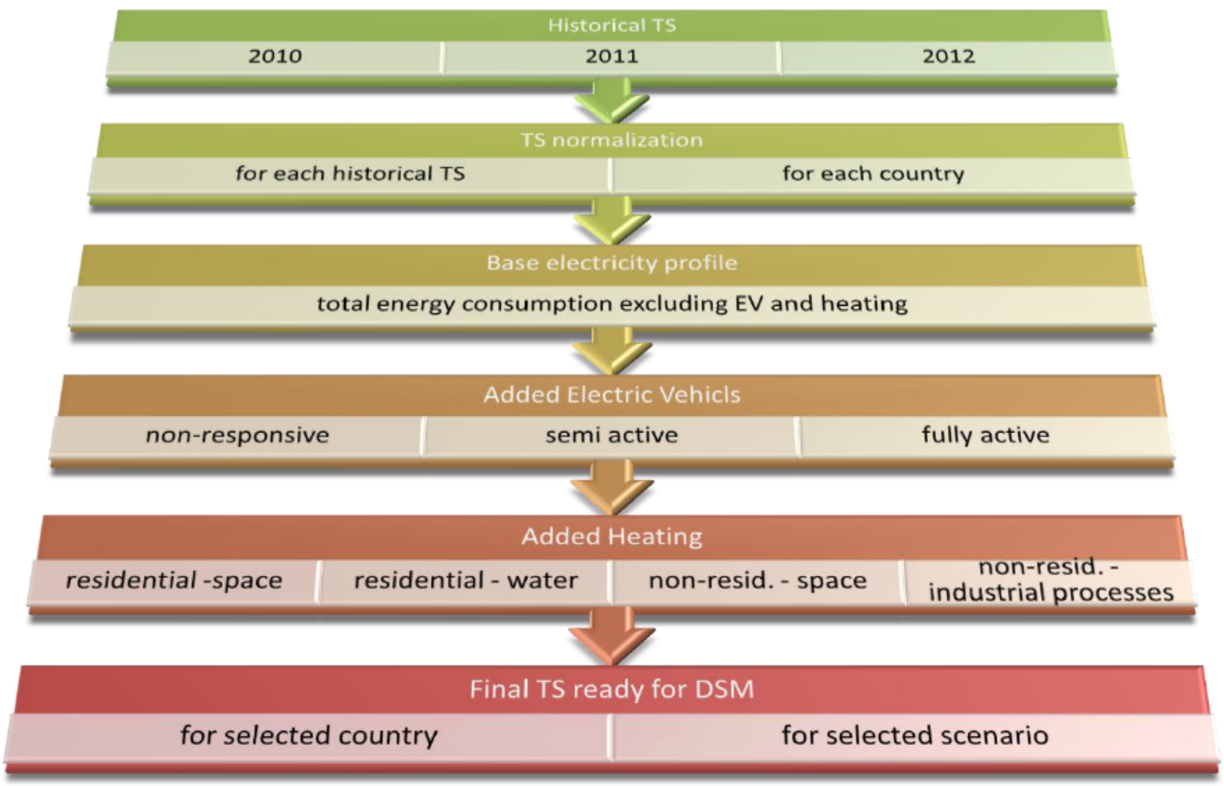


Figure 13: Demand TS for 2050 - methodology flow chart. [6]

It is assumed in [7] that the following technologies participate in DSM schemes:

- Fully active EV;
- Fully active electric heating;
- Other appliances (white good appliances).

The shares of demand types, controllable and non-controllable loads for EVs, residential heating, white good appliances and the final share of active demand for DSM is presented in Table 6.

Table 6: Demand types, controllable and non-controllable loads. Database from [7].

Demand Type	***INTERPLAN-1***	***INTERPLAN-2***	***INTERPLAN-3***	***INTERPLAN-4***
Non-controllable demand	77%	85%	69%	69%
EV	11%	8%	12%	12%
Residential heating	3%	2%	13%	13%
Non-residential heating	9%	5%	6%	6%
Electric vehicles				
Share of non-responsive EV	50%	40%	60%	40%
Share of semi-active EV	40%	30%	30%	30%
Share of fully-active EV	10%	30%	10%	30%
Residential heating				
Share of semi-active RH	15%	15%	20%	20%
Share of fully active RH	15%	22%	20%	26%
Share of semi-active non-RH	0%	0%	0%	0%
Share of fully-active non-RH	0%	0%	0%	5%
Other appliances				
White good appliances (Avg)	5%	2%	6%	6%
Max	8%	5%	10%	10%
Min	2%	1%	2%	2%
Share of active demand				
Average	2%	4%	4%	7%
Max	3%	6%	7%	12%
Min	1%	2%	2%	3%

For detailed information about white good appliances and share of active demand values per countries, as well as for the detailed description and methodology to get the time series for DSM, refer to the Annex D in [7].

4.6 Network topology and technologies

Figure 14 and Figure 15 depict the various gaps between the not yet covered areas (Transmission capacity vs. distance of terrestrial/submarine liaison) by available technological options and the new lines and reinforcement needs (orange cells) in a two-dimensional space, i.e. power and distance. The orange cells in both figures pinpoint the new lines and reinforcement needs. The light blue areas cover overhead line (OHL) technologies, whereas the dark blue ones stand for solutions under development. The purple colour in Figure 14 is dedicated to underground cable (UGC) solutions. The available technologies and the ones under development have been mapped with the list of technologies available in the e-Highway 2050 database in [2].

For terrestrial high voltage alternate current (HVAC) applications, in addition to the widespread technologies for 400 kV OHL (conventional conductors and reduced number of bundles), the following options are of interest:

- HVAC OHLs with different designs (number of circuits), various conductor types (high temperature low sag) and more bundles so as to reach higher power over short distances,
- HVAC Cross-linked polyethylene (XLPE) UGCs, in order to provide partial undergrounding solutions which will complement OHLs in sensitive areas or areas where public acceptance of OHL is low,
- HVAC OHL consisting of several lines for very high power and short to medium distances (interest for such solutions strongly relies upon the maximum capacity of one line which is acceptable from the TSO point of view, cf. N-1 security criteria in case of a contingency)

For terrestrial high voltage direct current (HVDC) applications, UGCs have proven their reliability and attractiveness for long distance power transmission and are now being seen as a solution for future long distance transmission based on the experience gained from long HVDC submarine cable links. For higher power submarine liaisons over all distances, the main challenges are to reach higher voltages and intensities, as well as to increase the installation depths so as to exceed 2,500 meters in the coming decades with lighter cables. Like for terrestrial applications, the development of HVDC meshed networks is expected (in the North Sea for instance for the interconnections of offshore windfarms) with multi-terminal HVDC systems at sea.

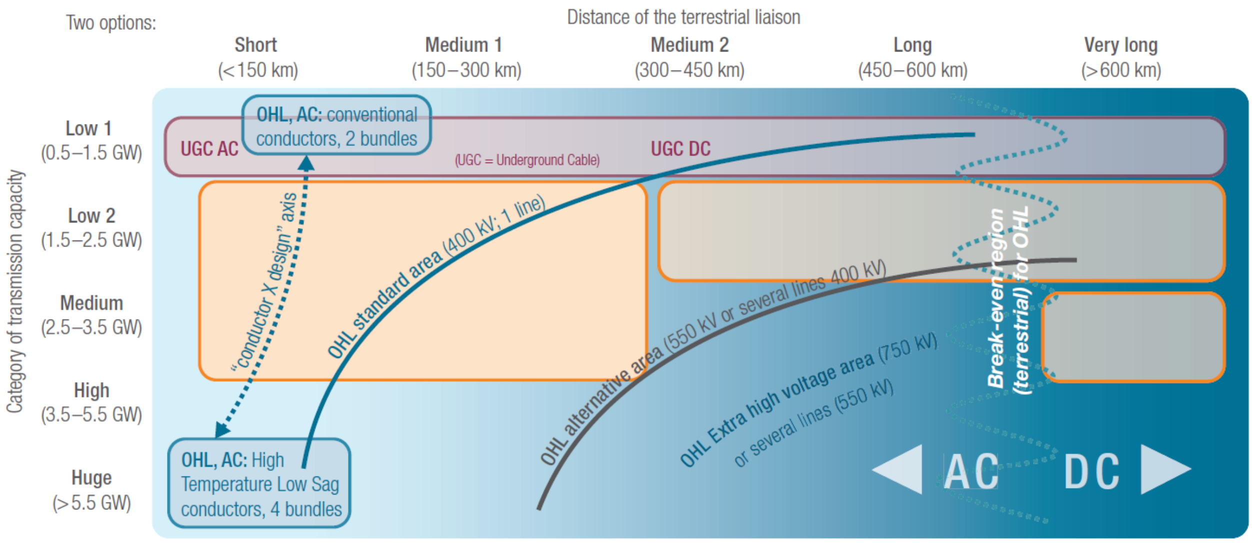


Figure 14: Terrestrial needs (orange cells) compared to available technology options (OHL options: various grades of blue, from the more conventional to the less conventional; terrestrial cables options: in purple colour). [6]

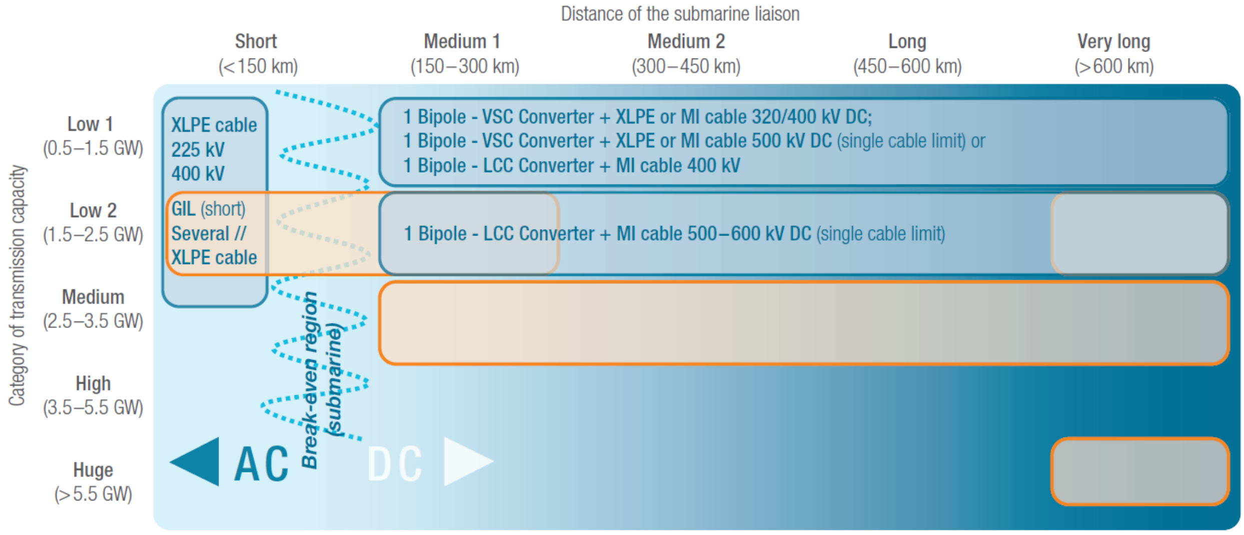


Figure 15: Submarine needs identified in the simulations (orange cells) compared to available technology options (blue cells). [6]

In the following subsections, a summary is presented according the main European needs for energy exchange. For detailed information about capacity and kilometres between each country and cluster interconnection, refer to Tables T93 and T94 of the database in [2].

4.6.1 Great Britain and Ireland to Spain through France

In all scenarios, the need to connect the UK to continental Europe appears with a minimum of 6 additional GW (Small & local) and up to 31 GW (Big & market). In parallel, another extra 1 to 6 GW is needed between Ireland and France: such interconnections are extended by a corridor crossing France down to Spain with a size ranging between 4 and 15 GW. The French-Spain interconnection is then reinforced between 8 GW (Small & local) and 20 GW (Big & market). This corridor is also extended to include Scotland via internal British reinforcements. The three main drivers identified for this major corridor are:

- ***Wind generation in the UK, Ireland and the North Sea.*** In all scenarios, the total wind capacity in these areas increases between 51 GW (Small & local) and 223 GW (100 % RES). This generation can exceed the local demand: it can then be exported to France and Spain.
- ***Nuclear in the UK and France.*** In the scenario Big & market, the nuclear capacities are increased in the UK by more than 10 GW.
- ***Solar in Spain and Portugal.*** The solar generation in Spain and Portugal increases no more than 110 GW (100 % RES). It creates an opportunity for this peninsula to export solar generation to northern Europe.

4.6.2 Greece to Italy and the Italian backbone

The Greece – Italy interconnection is reinforced in all scenarios between 2 GW (Big & market) and 9 GW (100 % RES), while reinforcements Italy – Sardinia and Italy – Sicily are also foreseen in all scenarios. The Italian corridor is reinforced in all scenarios, except for the Big & market one with a maximal value of 11 GW in the Large-scale RES scenario.

The main drivers for such reinforcements are:

- ***Wind generation in Greece.*** Wind capacity in Greece is increased about 24 GW (Large-scale RES, 100 % RES). This generation can exceed the local demand and be exported towards Italy.
- ***Solar generation in Italy.*** The solar generation in Italy increases with a maximum of 96 GW (Small & local). Although it is mainly located in the North of the country close to the demand centres, significant volumes still need to be transported from the South to the North of the country.
- ***Connection to North Africa.*** In the scenarios Large-scale RES and 100 % RES, significant connections from Northern African Countries to Italy are assumed (40 GW in Large-scale RES and 10 GW in 100 % RES). The solar generation coming from these countries need to cross Italy to reach large electricity demand centres.

4.6.3 Norway and Sweden to Continental Europe and the UK

In all scenarios, the need to further connect Norway and Sweden with the rest of Europe is emphasized. The additional interconnections between Sweden and Continental Europe range from 6 GW (Big & market) to 15 GW (100 % RES): they are extended by a 4 to a 9 GW corridor across Sweden. From Norway to Continental Europe and the UK, the additional capacity is between 1 GW (Big Market) and 19 GW (Large-scale RES). Significant reinforcements from Scandinavia are connected to the German North-South DC corridors which enable the further transport of electrical energy within Continental Europe.
The main drivers for these reinforcements are:

- ***Hydro power in Norway and Sweden.*** Hydro power in these two countries is currently around 50 GW. In the scenarios, an increase of between 11 GW (Big & market) and 50 GW (100 % RES) is assumed. The resulting generation can exceed local needs and be exported to the rest of Europe. Moreover, hydro power is crucial for the whole European system bringing critical flexibility levels to the electricity system. The resulting interconnections should be sufficient to allow for high export peaks during critical periods.
- ***Wind in Norway and Sweden.*** Wind capacity in Norway and Sweden is assumed to increase between 5 GW (Big Market) and 45 GW (Large-scale RES). The resulting generation can exceed local needs and be exported to the rest of Europe.
- ***Nuclear decommissioning in the UK and France.*** Connections from Norway to the UK appear only in the scenarios 100 % RES and Small & local. In such scenarios, almost all of the nuclear generation is decommissioned in France and the UK (− 47 GW and − 73 GW, respectively). As a result, the western part of Europe needs additional power supply from Norway and Sweden.

4.6.4 Finland to Poland through the Baltic States

A maximum of 5 GW (Large-scale RES) corridors connects Finland to Poland through the Baltic States. The main driver for this corridor is the development of wind generation in the area. For Finland, it increases between 2 GW (Small & local) to 37 GW (Large-scale RES). For Latvia, Lithuania and Estonia, it stands between 8 GW (Small & local) and 36 GW (Large-scale RES, 100 % RES). The large transmission needs are also explained by the relatively small system size; the peak load in Finland is currently 14 GW and in the Baltic area 4 GW.

4.6.5 The North Sea area

In the initial grid, the capacities of the radial links are only around half of the installed offshore wind capacities. Further reinforcements have been assessed within the study. The main conclusion is that by 2050 some offshore clusters with huge volumes of wind power are not close to the clusters exhibiting energy deficits. For instance, the offshore cluster near western Denmark appears interesting to provide energy to Continental Europe rather than to Denmark which does not need all of it. In this case, there are several possible routes to go from an offshore cluster to clusters exhibiting energy deficits (Germany for instance):

- either through Denmark (radial connection to Denmark and extra capacity between Denmark and Germany);

- and/or through a circular meshing between the offshore North Sea clusters (offshore cluster close to Denmark, towards the offshore cluster close to Germany and the cluster located in North Germany).

Another example deals with an offshore cluster close to southern UK: a huge part of its wind power is useful for northern Continental Europe through Belgium. The path could then be:

- either through the UK;
- or through a circular meshing between the offshore North Sea clusters (offshore cluster close to the UK towards the offshore cluster close to Belgium and then Belgium);
- or directly to Belgium.

4.7 Storage technologies

A table reporting about innovative grid-impacting technologies, including bulk storage, with a particular focus on the target year 2050, is extracted from [8] and shown in Figure 16.

Technology	Typical Capacity	Discharge Time	Efficiency	Life Time	Development Stage	Application	Transmission	Distribution	Customer Services
Pumped hydro energy storage (PHES)	5 MW – 2 GW	4 - 100 h	55-85%	50+ years	Mature	Primary / secondary / tertiary control, energy arbitrage	Suitable	Possible	Unsuitable
Compressed air energy storage (CAES)	25 MW – 2.5 GW	2 - 24 h	40-70%	15-40 years	Mature / premature (AA-CAES)	Tertiary control, energy arbitrage	Suitable	Possible	Unsuitable
Batteries	1 kW – 50 MW	1 min – 3 h	65-75%	2-10 years	Premature / mature	Uninterruptible power supply, RES fluctuation reduction, primary / secondary control	Possible	Unsuitable	Possible
Flywheels	5 kW – 20 MW	4 sec -15 min	90-95%	~20 years	Mature	Primary control, power quality	Suitable	Suitable	Unsuitable
Superconducting magnetic energy storage (SMES)	10 kW – 1 MW	5 sec – 5 min	95%	~30 years	Premature	Uninterruptible power supply, power quality	Suitable	Suitable	Unsuitable
Supercapacitors	< 150 kW	1 sec – 1 min	85-95%	~10 years	Premature	Uninterruptible power supply, power quality	Possible	Unsuitable	Possible

● Suitable ● Possible ● Unsuitable

Figure 16: Technical characteristics and applications of storage technologies. [8]

The e-Highway project just considers in its figures the installed capacity of pumped storage plants for 2050 horizon, which is taken from [2] and presented in

Table 7 for INTERPLAN scenarios. On the other hand, the TYNDP2018 considers in its figures Battery Storages for 2 different scenarios for the 2030 time horizon, and an additional figure in the 2040 time horizon, not considered in INTERPLAN scenarios.

Table 7: Pumped Storage Plant, Electrical Vehicles and Battery storage capacities. Database from [2] and [3].

Storage Technology		***INTERPLAN-1***	***INTERPLAN-2***	***INTERPLAN-3***	***INTERPLAN-4***
Pumped Storage Plants (2050)	**Installed Capacity [MW]**	73.913	73.913	96.243	113.943
Battery Storage (2030)	**Installed Capacity [MW]**	35.727	23.743 *218.634 (2040)*	N/A	N/A

4.8 Fuel costs and CO_2 price

While the CO_2 price assumed for the different scenarios in [6] is **270€/ton** in 2050, [5] presents estimated values for fuel and CO_2 prices for 2030 and 2040 time horizons, as shown in Figure 17. Unfortunately, e-Highway 2050 Project results do not present detailed information about fuel prices.

		Fuel & CO_2 prices					
	Year	**2030**	**2030**	**2030**	**2040**	**2040**	**2040**
	Scenario	Sustainable Transition	EUCO	Distributed Generation	Sustainable Transition	Global Climate Action	Distributed Generation
€/ net GJ	Nuclear	0.47	0.47	0.47	0.47	0.47	0.47
€/ net GJ	Lignite	1.1	2.3	1.1	1.1	1.1	1.1
€/ net GJ	Hard coal	2.7	4.3	2.7	2.5	1.8	2.8
€/ net GJ	Gas	8.8	6.9	8.8	5.5	8.4	9.8
€/ net GJ	Light oil	21.8	20.5	21.8	17.1	15.3	24.4
€/ net GJ	Heavy oil	17.9	14.6	17.9	14.0	12.6	20.0
€/ net GJ	Oil shale	2.3	2.3	2.3	2.3	2.3	2.3
€/ ton	CO_2 price	84.3	27.0	50.0	45.0	126.0	80.0
	Fuel Price Source	WEO 2016 New Policies with higher CO_2	Fuel Prices Provided by DG Energy	WEO 2016 New Policies with higher CO_2	WEO 2016 New Policies Fuel Prices adjusted to create a "Low Oil Price Scenario"	WEO 2016 450	WEO 2016 New Policies with higher CO_2

Figure 17: Fuel & CO_2 prices for 2030 and 2040 time horizons. [5]

5 Key Performance Indicators

This chapter lists and describes the key performance indicators, which will be used for evaluating the use case implementation in the simulations planned in the later stages of the project.

Table 8: List of Key Performance Indicators

ID number	KPI name
1	Level of losses in transmission and in distribution networks
2	Congestion detection
3	SAIDI (System Average Interruption Duration Index)
4	Costs of service interruption
5	Frequency Restoration Control effectivity
6	Response Time
7	Power losses
8	Energy not Supplied
9	Interrupted Energy Assessment Rate
10	Voltage quality performance of electricity (voltage variations)
11	Number of tap position changes per time
12	Quadratic deviation from global reactive power exchange target
13	Mean quadratic deviations from voltage and reactive power targets at TSO/DSO connection points
14	Level of DG / DRES utilization for ancillary services
15	Percentage utilization of electricity grid elements (lines and transformers)
16	Transformer loading
17	RES curtailment
18	SAIFI (System Average Interruption Frequency Index)
19	Generation costs
20	Frequency nadir
21	Rate of change of frequency (RoCoF)
22	Quadratic deviation from global active exchange target
23	Mean quadratic deviations from active power targets at TSO/DSO connection points

24	Reactive energy provided by RES and DG
25	Indication of stability
26	Oscillation damping
27	Share of RES
28	Amount of CO2 emissions in power generation

KPI ID	**1**
KPI name	Level of losses in transmission and in distribution networks
Description	The transport of electrical energy through the distribution or transmission network is associated with a certain amount of losses. Therefore, the amount of energy being produced has to be a few percentage points higher than consumption levels. When the marginal electricity production is based on fossil fuel, as is the case most of the time in most European countries, the losses result in additional CO_2 emissions.
Calculation	$Percentage\ of\ losses = \frac{Amount\ of\ injected\ energy\ -\ Amount\ of\ energy\ delivered\ to\ the\ customers}{Amount\ of\ injected\ energy} \times 100\ \ [\%]$

KPI ID	**2**
KPI name	Congestion detection
Description	During the congestion mitigation process, it is important to detect and localize the congested lines.
Calculation	Congestion = If abs(P_{line_i}) > $P_{rating\_line\_i}$ the line-*i* is congested. P_{line_i}[kW] is the active power that flows troughs the line *i* $P_{rating\_line\_i}$[kW] is the nominal active power of the line *i*

KPI ID	**3**
KPI name	SAIDI (System Average Interruption Duration Index)
Description	System Average Interruption Duration Index (SAIDI) is the average outage duration for each customer served.
Calculation	SAIDI = $\frac{sum\ of\ all\ customer\ interruption\ durations}{total\ number\ of\ customers\ served} = \frac{\Sigma U_i N_i}{N_T}$ U_i = Annual outage duration for location *i* N_i = Number of customers for location *i* N_T = Total number of customer served

KPI ID	**4**
KPI name	Costs of service/energy interruption
Description	It is the total cost due to the service outage of all customers.
Calculation	Costs of service interruption = $\sum_{i=1}^{Bus_{interr}} \sum_{j=1}^{Resources_{interr}} Coutage_{ij}$ $Coutage_{ij}$ = Cost outage of the resource *j* at busbar *i* Bus_{interr} = Total interrupted bus number $Resources_{interr}$= Total interrupted resources at busbar *i*

KPI ID	**5**

KPI name	Frequency Restoration Control effectiveness
Description	Difference between the restored frequency and the nominal one.
Calculation	$F_{restored} - F_{nom} \leq \varepsilon, \varepsilon \to 0$ $F_{restored}$= the frequency value after the frequency restoration process [Hz] F_{nom} = the nominal frequency value [Hz]

KPI ID	**6**
KPI name	Response Time
Description	The difference between the time instant when the frequency is restored (t_r) and the time instant when the frequency instability event occurs (t_0).
Calculation	$\Delta t = t_r - t_0$ frequency restoration process time [s]

KPI ID	**7**
KPI name	Power losses
Description	The transport of electrical energy through the distribution or transmission network is associated with a certain amount of losses. The distributed generation connected to power system can reduce system losses in distribution network through a rational optimization to the power network
Calculation	P_{losses}=$\sum_i^{N_{line}} \|I\|_i^2 \, xr_i$ [kW] r_i = resistance of line *i [Ω]* I_i= magnitude of current flow in line i [A]

KPI ID	**8**
KPI name	Energy not Supplied
Description	Energy Not Supplied, in units of [MWh/year], is the total amount of energy on average not delivered to the system loads during 1 year when comparing a reference case to a case study. The KPI might be applied to energy supplied from a certain source only, e.g. distributed generators in the DSO network. The reason for energy not supplied may be that active power injection by distributed generators is getting limited, e.g. by grid congestion avoidance or reactive power infeed for voltage control. In this case, the KPI is an important means of comparing different grid operation approaches.
Calculation	$ENS = \sum_i LPENS\ [MWh/a]$ $LPENSi = ACITi \cdot (Pdi + Psi)\ \ [MWh/a]$ LPENSi = Load Point i Energy Not Supplied ACITi = Average Customer Interruption Time Pdi = the weighted average amount of power disconnected Psi = the weighted average amount of power shed at load point i.

KPI ID	**9**
KPI name	Interrupted Energy Assessment Rate
Description	IEAR Interrupted Energy Assessment Rate, in units of [€/kWh], is the total expected interruption cost per not supplied kWh.
Calculation	IEAR = $\frac{EIC}{ENS}$ [€/kWh]

	EIC = Expected Interruption Cost, in units of [M€/y], is the total expected interruption cost ENS= Energy Not Supplied, in units of [MWh/year], is the total amount of energy on average not delivered to the system loads

KPI ID	**10**
KPI name	Voltage Quality: Voltage magnitude variations
Description	Maintain voltage quality by meeting requirements defined in EN50160 Voltage variation is the deviation of voltage in a certain range. Voltage deviations can be identified by monitoring the bus bar voltages of the grid substations. **For LV:** 95% of the 10 minute mean rms values for 1 week (±10% of nominal voltage). 100% of the 10 minute mean rms values for 1 week (+10% / -15% of nominal voltage) **For MV:** 99% of the 10 minute mean rms values for 1 week below +10% of reference voltage and 99% of the 10 minute mean rms values for 1 week above -10% of reference voltage. 100% of the 10 minute mean rms values for 1 week (±15% of reference voltage)
Calculation	According to the defined EN 50160 Standards, bus bar voltage magnitudes must comply with following allowed range of variation. LV: (±10% of nominal voltage) MV: (±5% of nominal voltage) Voltage deviation indices can be defined to find the frequency or duration that the bus bar voltages violate the allowed voltage range. • Number of voltage excursions exceeded n minutes per year • Percentage of time that the transmission voltage exceeds the permissible limits

KPI ID	**11**
KPI name	Tap position changes per time
Description	Minimizing this KPI is an optimization objective in voltage / reactive power control. Minimizing tap position changes of on-load tap changers reduces stress to the transformer and extends its lifetime.
Calculation	Let T be the set of all transformers equipped with tap changers in the considered grid area, *t* be the time of consideration, and n_i be the number of tap setting changes within that time for transformer *i*. Then, the KPI is: $\sum_{i \in T} n_i$

KPI ID	**12**
KPI name	Quadratic deviation from global reactive power production target
Description	Minimizing this KPI is an optimization objective in voltage / reactive power control. The rationale of the KPI is that the OPF objective function might be to target an overall produced reactive power while still upholding voltage limits at each busbar, e.g. by network reconfiguration.
Calculation	Let $q_{target}(t)$ be the global reactive power production target at time t. Let G be the set of generators producing reactive power, and $q_g(t)$ be the reactive power generated by generator g at a given time *t*. Then, the KPI at this time is: $\left(q_{target}(t) - \sum_{g \in G} q_g(t)\right)^2$

KPI ID	**13**

KPI name	Mean quadratic deviations from voltage and reactive power targets at each connection point between TSO and DSO grids
Description	Minimizing this KPI is an optimization objective in voltage / reactive power control. If applied to reactive power, this KPI may be used to judge how accurate a reactive power exchange schedule, calculated during grid operation planning, was executed in real-time grid operation. If applied to voltage, this KPI may be used to judge how well the OPF is able to limit voltage level deviations in the network, however it is limited to DSO/TSO connection points.
Calculation	Let *C* be the set of connection points between TSOs and DSOs. Let $q_{c,target}$ (*t*) [kVar] be the target value for reactive power transmission from DSO to TSO at connection point c and time *t*, as e.g. calculated by grid operation planning. Let $q_c(t)$ be the reactive power actually provided from DSO to TSO at connection point *c* and time *t*. Then the KPI related to reactive power at time *t* is defined as: $\frac{1}{\lvert C\rvert}\sum_{c\in C}\left(q_{c,target}(t)-q_c(t)\right)^2$ The KPI related to voltage is defined as follows. Let $u_{c,target}$ [V] be the nominal value for the line-to-line voltage at connection point *c*, calculated as mean over all phases. Let $u_c(t)$ be the actual line-to-line voltage mean over all phases. Then, the KPI at time *t* is: $\frac{1}{\lvert C\rvert}\sum_{c\in C}\left(u_{c,target}-u_c(t)\right)^2$

KPI ID	**14**
KPI name	Level of DG / DRES utilization for ancillary services
Description	The purpose of this KPI is to measure the utilization of DER for ancillary services (UAS). It is expressed as a ratio between the energy used for ancillary services and the total energy produced.
Calculation	$UAS\% = \frac{E_{AS}}{E_{total}} * 100\ [\%]$ E_{AS} = the energy used for ancillary services [MWh] E_{total} = the total energy produced [MWh]

KPI ID	**15**
KPI name	Percentage utilization of electricity grid elements (lines and transformers)
Description	This indicator assesses the loading of grid components and it is widely used among DSOs. It is calculated as both average and nominal value in percentage. This KPI is calculated as Average absolute value of loading of elements and/or number of hours with loading close to nominal loading.
Calculation	$Utilization_{average} = \frac{Average\ absolute\ value\ of\ loading\ of\ elements}{Nominal\ loading\ of\ grid\ elements}$ * 100 [%] $Utilization_{nominal} = \frac{Hours\ close\ to\ nominal\ loading\ of\ elements}{Nominal\ loading\ of\ grid\ elements}$ *100 [%]

KPI ID	**16**
KPI name	Transformer loading at TSO-DSO connection point
Description	Calculating HV/MV transformer loading provides information on power flow between TSO and DSO grid.
Calculation	$Loading\% = \frac{Power\ at\ transformer\ primary\ winding}{Transformer\ nominal\ power} * 100\ [\%]$

KPI ID	**17**
KPI name	RES curtailment
Description	Curtailment of RES occurs when there is an excess generation available and due to

	operation security or insufficient grid infrastructure some of RES units are turned off or their output power is limited.
Calculation	$Curtailment\% = 100 - \frac{Energy\ supplied\ by\ RES\ to\ the\ grid}{RES\ available\ energy} * 100$ [%]

KPI ID	**18**
KPI name	SAIFI (System Average Interruption Frequency Index)
Description	The System Average Interruption Frequency Index (SAIFI) is the average number of interruptions that a customer would experience
Calculation	SAIFI = $\frac{total\ number\ of\ customer\ interruptions}{total\ number\ of\ customers\ served} = \frac{\Sigma\lambda_i N_i}{N_T}$ N_i = Number of customers for location i N_T = Total number of customer served λ_i = failure rate

KPI ID	**19**
KPI name	Generation costs
Description	This KPI measures the total generation cost in a specified duration while planning for the grid operation. The aim is to minimise this cost considering the constraint like satisfying the load, maximum and minimum output of the generator, etc.
Calculation	$C_T = \sum_{i=1}^{n} C_i P_i$ C_i=Generation cost for generator i in duration of t [€/KW] P_i= Generation power of generator i in duration of t [KW] C_T= Total generation cost in duration of t [€]

KPI ID	**20**
KPI name	Frequency nadir/zenith
Description	Maximum drop/rise in frequency after a disturbance in a power system. Over- and under-frequency is dangerous for system secure operation as it can trigger protections and lead to load/generation disconnections.
Calculation	$max(\lvert f_n - f \rvert)$ [Hz] f_n = nominal frequency [Hz] f = system frequency [Hz]

KPI ID	**21**
KPI name	Rate of change of frequency
Description	The initial rate of change of frequency (RoCoF) after a disturbance is important for power system stability. If change in frequency is too fast, primary control does not have enough time to start acting which could lead to tripping of generating units, therefore increasing power imbalance in the grid. As high RoCoF can have severe consequences, it is crucial to keep its value low.
Calculation	$\frac{d\omega}{dt} = \frac{P_g - P_l}{2H_{sys}}$ [Hz/s] $\frac{d\omega}{dt}$ = Rate of change of frequency [Hz/s] P_g = generators active power [p.u.] P_l = demand active power [p.u.] H_{sys} = system inertia [s]

KPI ID	**22**
KPI name	Quadratic deviation from global active power production target
Description	This KPI will calculate the quadratic deviation from global active power production target

	which is based on the needed tertiary reserve. Minimizing this KPI is an optimization objective.
Calculation	Let p_{target} (t) be the global active power production target at time t. Let G be the set of generators producing active power, and p_g(t) be the active power generated by generator g at a given time t. Then, the KPI at this time is: $\left(p_{target}(t) - \sum_{g \in G} p_g(t)\right)^2$

KPI ID	**23**
KPI name	Mean quadratic deviations from active power targets at each connection point between TSO and DSO grids
Description	This KPI will calculate the mean quadratic deviations from active power targets (based on the needed tertiary reserve for each connection point) at each connection point between TSO and DSO grids. Minimizing this KPI is an optimization objective.
Calculation	Let C be the set of connection points between TSOs and DSOs. Let $p_{c,target}$ (t) [kW] be the target value for active power transmission from DSO to TSO at connection point c and time t, as e.g. calculated by grid operation planning. Let p_c(t) be the active power actually provided from DSO to TSO at connection point c and time t. Then the KPI related to active power at time t is defined as: $\frac{1}{\lvert C \rvert} \sum_{c \in C} \left(p_{c,target}(t) - p_c(t)\right)^2$

KPI ID	**24**
KPI name	Reactive energy provided by RES and DG
Description	This KPI calculates the reactive energy provided for voltage control by RES and DG at the DSO level networks during a pre-defined time. It is to compare to which extent according generators are taking part in maintaining voltage stability.
Calculation	Let G be the set of RES and DG generators producing reactive power, and q_g(t) be the reactive power generated by generator g at a given time t. Then, the KPI during the time interval t1..t2 is: $\sum_{g \in G} \sum_{t=t1}^{t2} \lvert q_g(t) \rvert$ [KVARh]

KPI ID	**25**
KPI name	Indication of stability
Description	A generic indicator describing whether the system reaches a stable and acceptable equilibrium after a reference incident. The reference incident is dependent on the type of stability analysed: - for frequency stability: trip of the largest infeed or load, - for transient stability: 3-phase to ground fault cleared after the longest allowable time as described in the grid code (e.g. 150 ms), - for voltage stability: any kind of disturbance causing the largest reduction in available reactive power reserves, - for small-signal stability: line trip causing the largest change in modes' shape
Calculation	No calculation needed; this KPI is a Boolean value (YES/NO)

KPI ID	**26**
KPI name	Oscillation damping
Description	Oscillation damping describes how oscillations in the system decay after a disturbance. Positive values indicate that the oscillation amplitude is decreasing in time, whereas

	negative values imply attenuating oscillations, which lead to protection triggering, equipment fatigue etc. Damping ratio not less than 5% is considered safe.
Calculation	Since an oscillation can be composed of many modes, a signal decomposition must be performed, e.g. by PRONY analysis or FFT. These algorithms readily provide damping ratio for identified modes. If these algorithms are not accessible, damping ratio can be calculated from the plot using the following formula: $$\sigma = \ln\left(\frac{p_1}{p_2}\right),$$ p_1, p_2 = maximum values of two consecutive swings of the signal.

KPI ID	**27**
KPI name	Share of RES
Description	The purpose of this KPI is to measure share of RES in the total generation portfolio
Calculation	$$RES\% = \frac{P_{RES}}{P_{total}} * 100\ [\%]$$ P_{RES} = RES installed capacity [MW] P_{total} = total installed capacity [MW]

6 Use Cases

This chapter describes the defined and selected use cases for the INTERPLAN project and the related integrating operational planning tool. The seven INTERPLAN use cases, which are strongly driven by the scenarios described above, are the following ones:

- UC1: Coordinated voltage/reactive power control
- UC2: Grid congestion management
- UC3: Frequency tertiary control based on optimal power flow calculations
- UC4: Fast Frequency Restoration Control
- UC5: Power balancing at DSO level
- UC6: Inertia management
- UC7: Optimal generation scheduling and sizing of DER for energy interruption management

Each use case sub chapter includes a general description, technical details, sub-use cases, diagrams of the sub-use cases and the related sequence of actions. The systems and the associated actors involved in each use case are grouped as described below:

1. Transmission systems - Transmission System Operator (TSO)
2. Distribution system - Distribution System Operator (DSO)
3. Generation: DG, RES, Synchronous generator - Owner/operator, Aggregator
4. Virtual Power Plant (VPP) - Operator
5. Load: controllable/uncontrollable load - Consumer, Prosumer, Aggregator
6. Storage, Electric Vehicles (EV) - Owner/Operator
7. Tools (can be associated to different systems):
    - Controllers
    - Optimal Power Flow (OPF) calculator
    - Load Flow (LF) calculator
    - Forecast unit
    - On-Line Tap Changer (OLTC)
    - Sensors, Measurement devices
    - Energy management

6.1 Use case 1: Coordinated voltage/reactive power control

6.1.1 Description of the Use Case

6.1.1.1 Name of Use Case

Use case identification	
ID	Name
1	Coordinated voltage/reactive power control

6.1.1.2 Goal, Objectives and Scope and of the use case

Goal, objectives and scope of use case	
Goal	Utilize reactive power provision capabilities of renewable energy resources (RES) and distributed energy resources (DER) as well as emerging technologies in the distribu-

	tion grids to increase the hosting capacity and to improve voltage profiles both in transmission and distribution grids.
Objectives	1. Maintain the voltage quality in the power system with a high share of renewable based generation 2. Maximize RES and distributed generation (DG) share and/or minimize number of must-run units in charge of voltage regulation 3. Enhance effectiveness of participation mechanisms for voltage and reactive power control by DG and RES 4. Reduce costs for additional reactive compensating equipment and voltage induced re-dispatch 5. Quantify the actual need of reactive power in the system 6. Reduce grid losses and associated costs 7. Improve margins for voltage quality 8. Coordinate reactive power flows at the TSO/DSO interface
Scope	The focus is on utilizing untapped reactive power resources at distribution system level in addition to conventional TSO resources and on increasing collaboration between DSO and TSO. The aim is to define optimal set points for the flexibility providing resources determined by different approaches and to analyse the system impact both at transmission and distribution system level.

6.1.1.3 **Narrative of Use Case**

Narrative of the use case
Short description
This UC utilizes untapped reactive power provision capability of RES and DER resources in the distribution grid (DSO level) in addition to conventional resources controlled by TSOs, taking into consideration new control schemes utilizing all possible flexibilities, which could be introduced by DG, DER and emerging technologies. The overall purpose is to increase the collaboration between TSOs and DSOs for an improved reactive power/voltage management scheme at interface level as well as evaluating available reactive power resources to be used both in transmission grids for counteracting voltage violations caused by RES and in distribution grids increasing RES hosting capacity.
Complete description
<u>Motivation and problem statement</u> With increasing share of DG/RES and the changing framework in the energy market, the number of conventional synchronous generators decreases, thus major sources for voltage control are missing. Additionally, voltages are changing much faster, depending on the system load and intermittent RES infeed. In unexpected high load / low RES infeed cases voltages drop significantly, especially in the absence of voltage control devices. Having this in mind, TSOs can no longer control the voltage profiles in their systems by just giving set points for the transmission grid connected generators voltage controllers. Therefore, it is vital to develop approaches/tools for the management and planning of voltage/reactive power control in the future control centres. Considering that reactive power is always a local challenge and state of the art DG and RES units, mainly connected at distribution system level, are technically capable of controlling voltage, capabilities of these generation units must be seen from the perspective of operational control as further flexibilities. Since reactive power must be transported to the TSO grid, intensive cooperation between DSO and TSO demanding simultaneous coordination is necessary. Thus, the optimal planning and operation of DG and RES located in distribution grids in order to contribute to local and regional reactive power management and reactive power provision to the transmission grid must be enabled. <u>Solution Approach</u> A coordination mechanism between TSO and DSO based on an Optimal Power Flow (OPF) tool featuring Multi-Objective (MO) optimization is envisaged as an effective mean to cater for future

operational challenges. This involves coordination between two real-time OPFs running at the TSO and DSO control centres. An interaction chain based on sequential optimizations and exchange of relevant data and set points is to be defined. A flexible and comprehensive OPF tool should be developed to be applied at both DSO and TSO level by introducing multi-step optimization. In order to apply the proposed tools as well as to study TSO-DSO interactions, functionalities, e.g. inclusion of control modes of RES and DG units, e.g. Q or V control, cosφ control or Q(V) control, individual voltage and reactive power set points in multi-objective function, multi-area optimization and definition of synchronous generators as PV or PQ nodes, should be attached.

OPF Objective Functions

The objective functions, which could be weighted as desired based on priorities of operators, are chosen among others as (i) smoothing of voltage profiles (ii) minimization of grid losses (iii) minimization of tap position changes (iv) minimization of quadratic deviation from global reactive power exchange target (v) minimization of sum of quadratic deviations from voltage and reactive power targets at each connection point between TSO and DSO grids.

General sequence of actions

The procedure is composed of three sequential steps by utilizing an OPF tool at each step. The steps may be carried out as part of the grid operator's day-ahead or hours-ahead operational planning, or as part of a real-time control scheme.

In the **first step**, a reactive power flexibility assessment is performed by the DSO using its own OPF tool. Flexibility margins at connection points are computed using control variables of OLTC transformers and controllable generation units in the DSO grid by respecting interrelation of connection points in terms of calculated flexibilities. In this step, the TSO grid is represented in terms of grid equivalent(s) including connection points to the distribution grid. As a result of the first step, the DSO announces available reactive power flexibilities at the TSO/DSO connection points to the TSO. In case of operational planning, these may be flexibility schedules; in case of real-time control, the flexibilities will relate to reactive power that can be delivered ad-hoc.

In the **second step**, the TSO uses the reactive flexibility thus communicated and the values declared for each TSO/DSO connection point to run the TSO-OPF where distribution grid transformers could be represented as virtual generators, and DSO grids may be represented by grid equivalents (e.g. in case a DSO grid connects to the TSO by two or more connection points). The TSO's OPF tool calculates the set points for the TSO/DSO connection points as well as generators connected to the TSO's control area prioritizing its own control objectives. The result of the second step are set points for the TSO reactive power assets and the flexibility usage. Again, in the operational planning case, there will be set point schedules, while in the real-time operation case, there will be single set points.

As **third and final step**, the DSO computes the set points for its individual assets through its OPF tool by respecting set points given by the TSO for its control area. The set points can be either in the form of reactive power exchange or optimal voltage values at the TSO/DSO connection points.

Simulation

The use case can be simulated by quasi-dynamic simulation. The grid model used must contain at least one TSO and one DSO network. The TSO network must contain sufficient number of nodes, ideally more than 100. The rest of the network can be represented by grid equivalents. For the DSO network(s), equivalents must be available. Information about minimal, maximal and current tap changer positions should be available. Time series profiles for generators and loads connected to TSO and DSO networks, including forecasted profiles and characteristics, are needed.

6.1.1.4 Key Performance Indicators

Key performance indicators (KPIs)

ID	Name	Addressed objectives
10	Voltage Quality - Voltage magnitude variations	1,7
1	Grid Losses	6
11	Number of tap position changes per time	3
12	Quadratic deviation from global reactive power exchange target	5
13	Sum of quadratic deviations from voltage and reactive power targets at each connection point between TSO and DSO grids	5,7,8
24	Reactive energy provided by RES and DG	2,3
27	Share of RES	2

6.1.1.5 **Use case conditions**

Use case conditions
Assumptions
1. Due to different voltage control mechanisms by TSOs in EU member countries, the practices adopted by the Italian TSO according to the regulations in CEI 0-16 and CEI 0-21 and by Swiss TSO operators are assumed as reference. 2. Regulating plants are assumed to follow given voltage set points and to be equipped with remote control. 3. Availability of controllable reactive power devices in the grid model. 4. An established communication channel with DER units and other active elements which can provide reactive power.
Prerequisites
1. Regulations and network codes for the above listed assumptions have to be complied with, before the implementation of the proposed interface controller. 2. Detailed models for TSO and DSO grids with a suitable number of nodes are available. There must be at least one balancing zone with one TSO and at least one DSO, and the number of nodes should be 100 or more. The grid model does not have to span all voltage levels down to the LV network, but needs to include at least the EHV level (TSO) and HV level (DSO) for the operation areas of the grid operators considered. There are no dynamic grid models needed. 3. Suitable grid equivalents for TSO and DSO are available. 4. Realistic reactive power capabilities, generation profiles and time series for each resource within the network model (storage, controllable loads, renewable generators, etc.) are available.

6.1.2 Technical details

6.1.2.1 Systems and associated actors/tools

Systems and associated actors/tools			
Group	System	Actor/tool	Remarks
1	Distribution system	DSO	-
7	Transmission system, Distribution system	OPF	Individual OPF tools at TSO and DSO for optimisation of grid losses and generation costs
1	Transmission system	TSO	-
3	Controllable DG, RES	DSO	In DSO grid, with reactive power provision capability
6	Controllable EV charging stations and PV-Battery storage systems	DSO	In DSO grid, with reactive power provision capability
3	Generators providing reactive power	TSO	Assets used for classic voltage control
7	Transmission system, Distribution system	Generation forecast unit	Used for forecasting RES infeed, for grid operation planning
7	Electric Loads, DG, RES	Load and generation forecast unit	-
7	Transmission system, Distribution system	OLTC controller	At TSO/DSO substations
7	Distribution system	DSO level online DG &	Cluster or interface controllers

		RES reactive power controller	
7	DG, RES, Distribution system	DSO level DG & RES reactive power local controller	
7	DG, RES, Distribution system	DSO level online or local storage inverter reactive power controller	
7	Transmission system	TSO level power compensation unit controller	Possible classic voltage control means
7	Transmission system, Generators	TSO level Cos phi controller at TSO level plants	Possible classic voltage control means. Synchronous generators, doubly fed induction generators, converters etc.
7	Transmission system	TSO level FACTS controller	Possible classic voltage control means
7	Transmission system, Distribution system	DSO and TSO grid equivalents	Mutually used by TSO and DSO to represent the other's grid for OPF
7	Distribution system	DSO level flexibility assessment tool	Calculates reactive power provision flexibility based on generation forecast, storage and generator status
7	Transmission system	TSO reactive power assessment and planning tool	

6.1.2.2 Control variables

Control variables

Control Variable	Corresponding actor / tool
Output reactive power	DG and RES units, inverter coupled storage units, assets for reactive power provision at transmission system
Output power factor	see above, alternative to reactive power
Tap changer setting	TSO/DSO substation transformers, DSO substation transformers

6.1.2.3 Simulation environment:

- DigSilent Powerfactory
- AMPL
- Matlab, Matpower

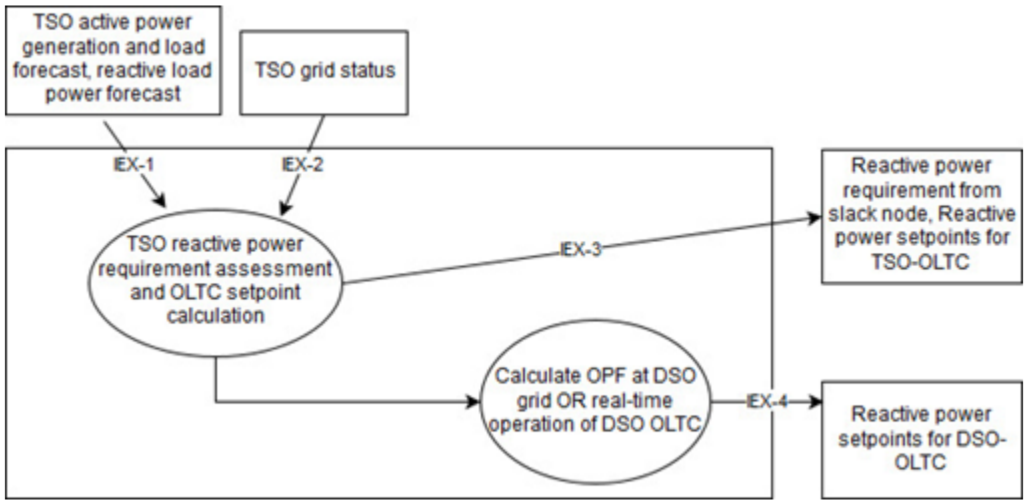
6.1.3 Sub-use cases

Sub-use cases	
Sub-use case number	Description
1.1	Base case, DG and RES at fixed cos φ = 1 / uncontrolled, OPF with OLTC control. In this scenario, reactive power is provided by a slack (comparison TS as slack or detailed model). OLTC transformers are defined as only voltage regulating tool for the DSO. The OLTC operation is not only conducted by a local control but also can be driven by the optimization tool. Therefore an OPF is also exercised here to simulate a possible solution.
1.2	A static Q=f(U) curve is applied for DG and RES units in the distribution grid without any optimization.
1.3	Static cosφ = f(P) curve for DG and RES units, Q control at critical level of voltage.
1.4	Coordinated TSO-DSO Optimization. Here, above described functionality, more specifically the described optimization chain, is applied. Different objective functions may be conceived. Q or V set-points are followed by the DSO at the TSO/DSO connection points.
1.5	Centralized Control: a signal to set the reactive power is sent from the TSO to DG and RES units.
1.6	Benchmark case: the whole grid is assumed to belong to a single unique system operator which optimizes both areas controlling DG and RES units, OLTC and synchronous generators at the same time.

6.1.4 Diagrams of the use case

6.1.4.1 Context diagram

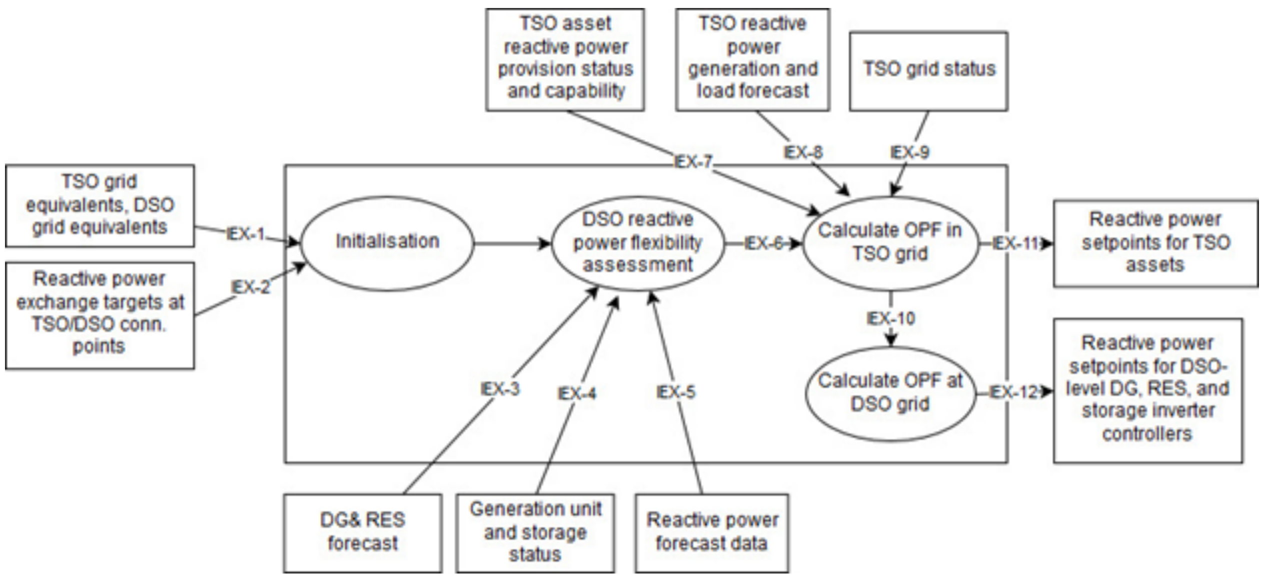
Sub use case 1.1



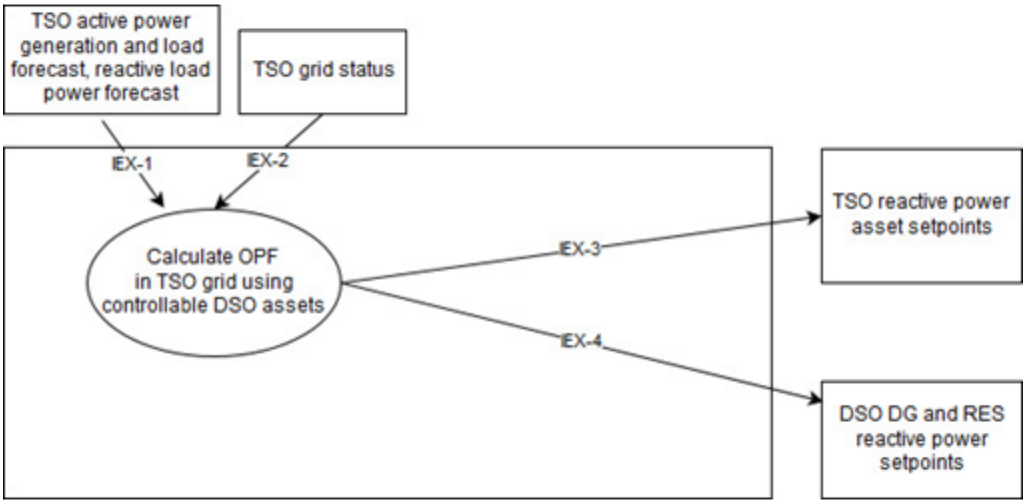
Sub use cases 1.2, 1.3

The diagram for this case is the same as for sub use case 1.1, cp. sequence of actions.

Sub use case 1.4



Sub use case 1.5

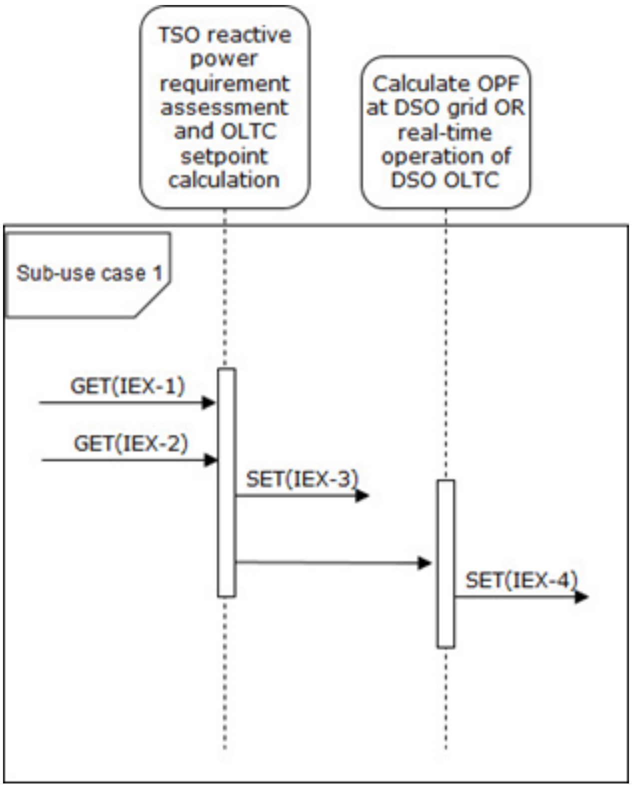


Sub use case 1.6

The diagram for this case is the same as for sub use case 1.5 except that TSO and DSO are replaced by a unique system operator and IEX-3 is replaced by an information element which contains reactive power set points to all controllable assets including DG and RES.

6.1.4.2 Sequence diagram

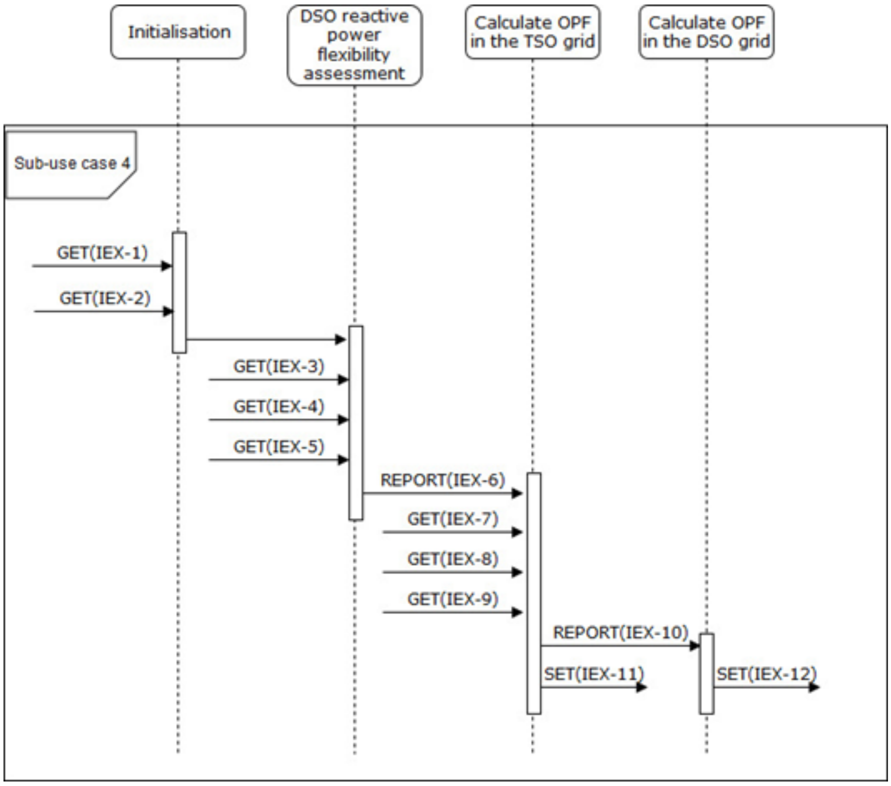
Sub use case 1.1



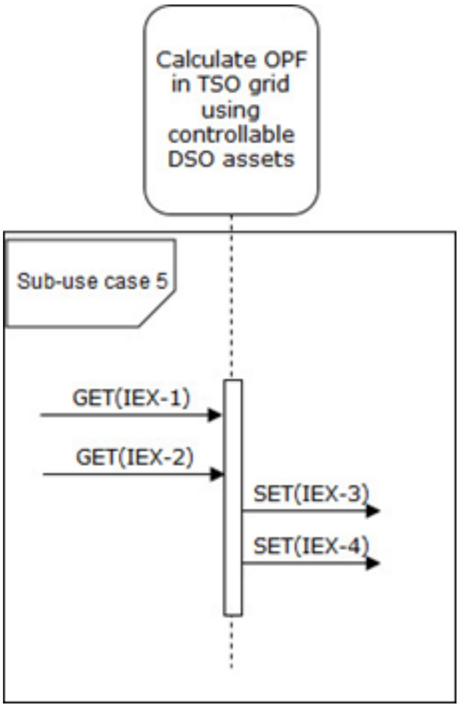
Sub use cases 1.2, 1.3

The diagram for this case is the same as for sub use case 1.1, cp. sequence of actions.

Sub use case 1.4



Sub use case 1.5

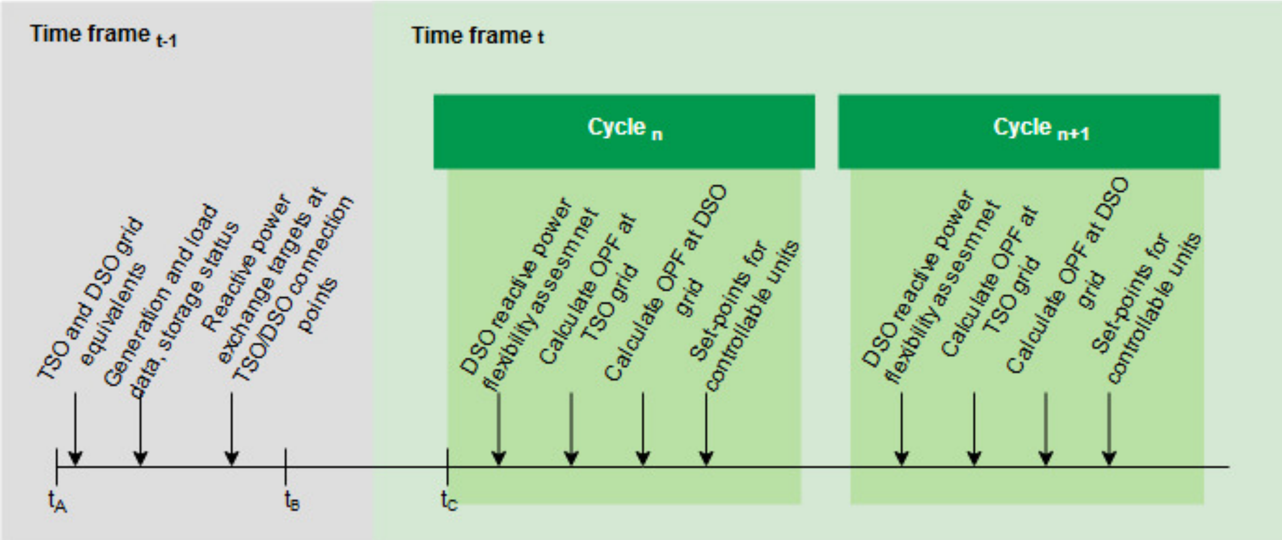


Sub use case 1.6

The diagram for this case is the same as for sub use case 1.5 except that TSO and DSO are replaced by a unique system operator and IEX-3 is replaced by an information element which contains reactive power set points to all controllable assets including DG and RES.

6.1.4.3 Timing diagram

Sub use case 1.4



6.1.5 Sequence of actions

Sub use case 1.1

Sequence of actions (based on sequence diagram) for sub use case number1.1						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1.1	TSO reactive power requirements assessment	The TSO forecasts the required reactive power in its grid as well as at TSO/DSO connection points. For this, predicted line loads, busbar voltage levels, planned reactive load power, and also active power flows need to be considered. For DG and RES in the DSO network, cos φ = 1 is assumed. The forecasted reactive exchange power at	TSO active power generation and load forecast, reactive load power forecast	Load and generation forecast unit	TSO OPF	1
			Current grid status	TSO SCADA / State Estimation	TSO grid operation planning	2

		TSO/DSO connection points may be set constant.				
1.2	TSO set point calculation	TSO calculates set points for its OLTC transformers which hold voltage levels in permitted limits. The required reactive power from the external slack node is also calculated.	TSO OLTC set points	TSO grid operation planning	TSO OLTC controllers	3
2	DSO OPF	During real-time operation, the DSO optimizes the set points for its OLTC transformers. This optimization may be replaced by OLTC local control.	TSO OLTC set points	DSO OPF or OLTC controllers	OLTC controllers	4

Sub use case 1.2

In this case, the sequence of actions is the same as in sub use case 1.1, except that in step 1.1 the TSO uses predefined static Q=f(U) curves in order to forecast the reactive power exchange at the TSO/DSO connection points. Here for, the TSO may use grid equivalent for the DSO network which represents major DG and RES units which behave according to named static Q=f(U) curves.

Sub use case 1.3

In this case, the sequence of actions is the same as in sub use case 1.1, except that in step 1.1 the TSO uses predefined static cosφ = f(P) curves in order to forecast the reactive power exchange at the TSO/DSO connection points. Here for, the TSO may use grid equivalent for the DSO network which represents major DG and RES units which behave according to named static cosφ = f(P) curves. Also, in step 2, the DSO DG and RES unit local controllers apply a predefined reactive power control scheme in case of critical levels of voltage during real-time operation.

Sub use case 1.4

Sequence of actions (based on sequence diagram) for sub use case number 1.4						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1	Initialization	TSO and DSO select	TSO grid	TSO, DSO	DSO, TSO	1

		individual optimization objectives for their OPF. Grid models and grid equivalents are mutually prepared.	equiva-lents, DSO grid equiva-lents			
			Reactive power ex-change targets at TSO/DSO conn. points	TSO	DSO	2
2.1	DSO flexibil-ity assess-ment - DER level	The DSO assesses the flexibility of its own DER resources to pro-vide reactive power within the time of con-sideration ad hoc or up to 24 hours in ad-vance, using appropri-ate forecasts.	DG & RES forecast	Load and generation forecast unit	DSO flexi-bility as-sessment tool	3
			Genera-tion unit and stor-age status	DG, RES, controllers, storage in-verter con-trollers	DSO flexi-bility as-sessment tool	4
			Reactive power forecast data	Load and generation forecast unit	DSO flexi-bility as-sessment tool	5
2.2	DSO flexibil-ity assess-ment DSO/ TSO connec-tion point level	Knowing the individual DER's reactive power flexibilities, the DSO calculates the amount of reactive power flex-ibility that can be de-livered to the DSO/TSO connection points. During this, line loads, busbar voltage levels, and (predicted) active power flows need to be considered in order to make sure that the reactive power can re-ally be transported to the TSO without prob-lems.	-			

2.3	DSO flexibility assessment - announcement	The DSO announces the resulting and verified reactive power flexibilities at the DSO/TSO connection points to the TSO.	Reactive power provision capability at DSO/TSO connection points	DSO	TSO reactive power assessment and planning tool	6
3.1	TSO OPF - TSO reactive power resource and requirement assessment	The TSO assesses available resources for reactive power, part of which are the flexibilities announced by the DSO(s). The TSO also assesses the amount of required reactive power in its grid, which will depend on network configuration, and operation planning of generators and loads.	TSO asset reactive power provision status and capability, TSO reactive power generation and load forecast, TSO grid status	TSO-level OLTC, generator, power compensation, Cos phi, FACTS controllers; TSO SCADA / State Estimation	TSO reactive power assessment and planning tool	7, 8, 9
3.2	TSO OPF - optimization	Knowing the reactive power availabilities and requirements and also the active power operational planning or current status, the TSO uses an OPF to calculate optimal set points for reactive power assets, including utilization of the DSO flexibilities, and respecting its individual optimization objectives. The OPF uses a detailed model of the TSO grid, and DSO grid equivalents to represent the DSO network as far as needed for correct load flow calculation.	-	-	-	-
3.3	TSO OPF -	The TSO announces the target set points	Reactive power set	TSO reactive power	DSO OPF	10

	set point announcement for DSO	for reactive power provision at the DSO/TSO connection points to the DSO	points at TSO/DSO connection points	assessment and planning tool		
3.4	TSO OPF - set points for TSO assets	The TSO fixes and transmits set points for reactive power transmission by its own assets	Reactive power set points for TSO assets	TSO reactive power assessment and planning tool	TSO-level OLTC, generator, power compensation, Cos phi, FACTS controllers;	11
4	DSO OPF	Using the TSO set points, the DSO utilizes an OPF to optimally distribute the requested reactive power provision amongst its assets. Here for, the DSO uses a detailed grid model of its own grid, and eventually uses grid equivalents to represent the TSO network, as far as needed for correct load flow calculations. Grid equivalents may also be used for parts of the DSO's own network which don't need to be modelled in detail, or even for networks of neighbouring DSOs.	Reactive power set points for DSO-level DG, RES and storage inverter controllers	DSO OPF	Controllable DG, RES; Controllable EV charging stations and PV-Battery storage systems	12

Sequence of actions (based on sequence diagram) for sub use case number 1.5						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1.1	TSO OPF - reactive power requirements	The TSO forecasts the required reactive power in its grid. For this, predicted line	TSO active power generation and load	Load and generation forecast unit	TSO OPF	1

	assessment	loads, busbar voltage levels, planned reactive load power, and also active power flows need to be considered. Also, DSO grid equivalents representing the controllable DG and RES are used.	forecast, reactive load power forecast			
			Current grid status	TSO SCADA / State	TSO OPF	2
1.2	TSO OPF - optimization	TSO uses an OPF to calculate optimal set points for its OLTC transformers, FACTS, power compensation units and generators as well as for the controllable DG and RES units in the DSO networks which provide reactive power.	TSO reactive power asset set points	TSO OPF	TSO OLTC, FACTS, power compensation units and generator controllers	3
			DSO DG and RES reactive power set points	TSO OPF	DSO DG and RES local controllers	4

Sub use case 1.6

In this case, the sequence of actions is the same as in sub use case 1.5, except that there is only a single system operator which calculating and communicating set points for all its assets. Therefore, information element 3 is omitted in this case, and DSO grid equivalents are not needed in step 1.1.

In this case, the sequence of actions is the same as in sub use case 1.5, except that there is only a single system operator which calculating and communicating set points for all its assets. Therefore, information element 3 and 4 are replaced by a single information element 3 which contains reactive power set points for all controllable reactive power assets. Furthermore, DSO grid equivalents are not needed in step 1.1.

6.2 Use case 2: Grid congestion management

6.2.1 Description of the Use Case

6.2.1.1 Name of Use Case

Use case identification	
ID	Name
2	Grid congestion management

6.2.1.2 Goal, Objectives and Scope and of the use case

Goal, objectives and scope of use case	
Goal	Mitigate/avoid grid congestion problems to improve system security and reliability
Objectives	1. Maintain the grid balance 2. Increase availability of new active resources 3. Increase the network flexibility 4. Increase TSO-DSO interactions
Scope	Mitigate network criticalities through a higher RES and storage involvement.

6.2.1.3 Narrative of Use Case

Narrative of the use case
Short description
This use case is about TSO and DSO using control logics to mitigate grid congestion problems at both transmission and distribution levels. During the operation planning phase, the tool evaluates the suitable resources through their proper generation schedule in order to re-dispatch the related active power flows for mitigating grid congestion. This use case acts both on DSO and TSO levels, by operating on the available controllable resources (e.g. storage, flexible loads , EVs, DG), and considering power flow re-dispatch. This use case will be addressed through semi-dynamic simulations.
Complete description
Motivation and problem statement With the increasing share of the distributed renewable energy, both transmission and distribution grids have to face new challenges. Indeed, generally the places with significant availability of renewable energy are oftentimes not very the densely populated areas, thus the local energy production may exceed the local demand. This situation may lead to network criticalities such as network overloading. In this scenario, the power flow re-dispatch during the operation phase plays a key role. Solution Approach for Sub Use Case 2.1 A use case is investigated, which does not consider controllers in order to identify grid congestion issues under the selected INTERPLAN scenarios. Once the grid congestion is identified, the solution approach is linked with the sub use cases 2.2 and 2.3 presented below. Solution Approach for Sub Use Case 2.2 **Objective**: the control logic acts on DSO level, operating on the available resources (e.g. RES, storage, flexible loads, EVs) to mitigate grid congestion. **Hypotheses**: 1. Each resource is involved in the congestion mitigation process The proposed solution methodology is based on the active power minimization provided by busses

to mitigate eventual congestion problems. For each bus, two possible contributions are defined: $\Delta P^{+}_{busbar-i}$, $\Delta P^{-}_{busbar-i}$, where the first one is the positive power variation at bus-*i* while the second one is the negative power variation at busbar-*i*.

For each busbar, the resources information are collected in order to evaluate the absolute maximum and minimum values for $\Delta P^{+}_{busbar-i}$ and $\Delta P^{-}_{busbar-i}$. These two values will be strongly linked to the resource-type connected to the busbar *i*:

Resource type	Absolute ΔP^{+}_{bus-i} max and min values	Absolute ΔP^{-}_{bus-i} max and min values
RES	(0,0)	$(0, P_{actual})$
Flexible Loads	(0,0)	$(0, P_{actual})$
Generator	$(0, P_{nominal} - P_{actual})$	$(0, P_{actual})$
Storage	$(0, P_{nominal} - P_{actual})$	$(0, P_{nominal} - P_{actual})$

The values in the table above indicate the flexibilities of the resources. P_{actual}, i.e., the power provided by the resources, is a time-dependent variable; $P_{nominal}$, i.e., the nominal value of the power for each resource, is a not-time-dependent value.
By minimizing the square of the rescheduling of generation, it is possible to obtain the power values to provide at each resource for solving the congestion problem. The objective function is defined as:

$$f = min \sum_{i=0}^{N_{bus}} (\Delta P^{+}_{busbar-i} + \Delta P^{-}_{busbar-i})^2$$

Where:

$\Delta P^{+}_{busbar-i}$ is the positive active power variation at busbar *i*

$\Delta P^{-}_{busbar-i}$ is the negative active power variation at busbar *i*

<u>Constraints for each line</u>:

$$P_{line\_i} + P_{rating\_line\_i} + \Delta P^{+}_{busbar-i} \geq 0$$
$$-P_{line\_i} + P_{rating\_line\_i} - \Delta P^{-}_{busbar-i} \geq 0$$

Where:
P_{line_i} is the active power that flows through the line *i*
$P_{rating\_line\_i}$ is the nominal active power of the line *i*

The obtained solutions will be positive or negative active power variation for each busbar considering each type of the connected resources.

<u>Solution Approach for Sub Use Case 2.3</u>

Objective: The control logic acts on TSO level, operating on the available resources at both transmission and distribution levels, to mitigate grid congestion.

Hypotheses:

1. Each resource is involved in the congestion mitigation process.
2. Each busbar at both transmission and distribution levels will be involved in the mitigation

congestion process.

The proposed solution methodology is based on the active power minimization provided by busses to mitigate eventual congestion problems. For each bus two possible contributions are defined: $\Delta P^{+}_{busbar-i}$, $\Delta P^{-}_{busbar-i}$ where the first one is the positive power variation at bus-*i* while the second one is the negative power variation at bus-*i*.

For each bus, the resources information are collected in order to evaluate the absolute maximum and minimum values for $\Delta P^{+}_{busbar-i}$ and $\Delta P^{-}_{busbar-i}$. These two values will be strongly linked to resource-type connected to the busbar-*i* :

Resource type	Absolute ΔP^{+}_{bus-i} max and min values	Absolute ΔP^{-}_{bus-i} max and min values
RES	(0,0)	$(0, P_{actual})$
Flexible Loads	(0,0)	$(0, P_{actual})$
Generator	$(0, P_{nominal} - P_{actual})$	$(0, P_{actual})$
Storage	$(0, P_{nominal} - P_{actual})$	$(0, P_{nominal} - P_{actual})$

The values in the table above indicate the flexibilities of the resources. P_{actual}, i.e., the power provided by the resources, is a time-dependent variable; $P_{nominal}$, i.e., the nominal value of the power for each resource, is a not-time-dependent value.
By minimizing the square of the rescheduling of generation, it is possible to obtain the power values to provide at each resource for solving the congestion problem. The objective function is defined as:

$$f = min \sum_{i=0}^{N_{bus}} (\Delta P^{+}_{busbar-i} + \Delta P^{-}_{busbar-i})^2$$

Where:

$\Delta P^{+}_{busbar-i}$ is the positive active power variation at busbar *i*

$\Delta P^{-}_{busbar-i}$ is the negative active power variation at busbar *i*

<u>Constraints for each line</u>:

$$P_{line\_i} + P_{rating\_line\_i} + \Delta P^{+}_{busbar-i} \geq 0$$
$$-P_{line\_i} + P_{rating\_line\_i} - \Delta P^{-}_{busbar-i} \geq 0$$

Where:
P_{line_i} is the active power that flows through the line *i*
$P_{rating\_line\_i}$ is the nominal active power of the line *i*

The obtained solutions will be positive or negative active power variation for each busbar considering each type of the connected resources.

6.2.1.1 **Key Performance Indicators**

Key performance indicators (KPIs)		
ID	Name	Addressed objectives
2	Congestion detection	1,2,3,4

6.2.1.2 Use case conditions

Use case conditions
Assumptions
1. Availability of controllable active power devices in the grid models
Prerequisite
1. A model of the grid is available both at TSO and DSO level 2. Exemplary load and generation profiles (including forecasted profiles) and characteristics are available for each bus

6.2.2 Technical details

6.2.2.1 Systems and associated actors/tools

Systems and associated actors/tools			
Group	System(s)	Actor(s)/tool(s)	Remarks
1	Transmission system	Transmission System Operator (TSO)	-
2	Distribution system	Distribution System Operator (DSO)	-
3	Generation: DG, RES, Synchronous generator, Controllable DG, RES	DSO	- In DSO grid, with active power provision capability
3	Generators providing active power	TSO	Assets used for frequency stability control
5	Controllable loads	Load and generation forecast unit	-
6	Controllable Storage Systems	TSO, DSO	In TSO and DSO grids, with active power provision capability
7	Electric Loads, DG, RES	Load and generation forecast unit	Used for forecasting load and generation.
7	Transmission system, Distribution system RES	Generation Forecast Unit	Used for forecasting RES infeed, for grid operation planning
7	Transmission system, Distribution system	TSO/DSO active power assessment and planning tool	
	Distribution system	DSO level flexibility assessment tool	Calculates active power provision flexibility based on generation forecast, storage and generator status, loads

6.2.2.2 Control variables

Control variables	
Control Variable	Corresponding actor / tool
Output active power	RES, storage units, controllable flexible loads, synchronous generators

6.2.2.3 Simulation environment:

- DigSilent Powerfactory
- Python

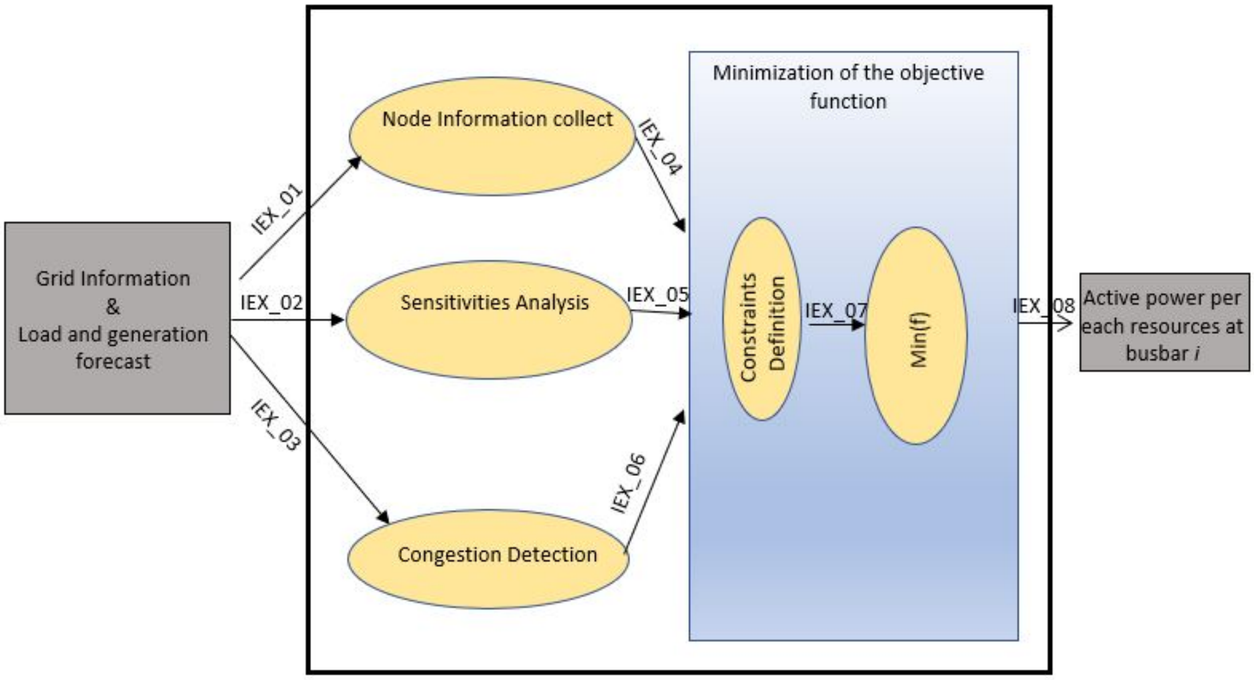
6.2.3 Sub-use cases

Sub-use cases	
Sub-use case number	Description
2.1	Base case - no controllers available. In this sub-use case, grid congestion issues will be identified under different scenarios.
2.2	In this sub-use case, the tool acts on DSO level, operating on the available resources (e.g. storage, load shedding, EVs, etc.) to mitigate grid congestion.
2.3	In this sub-use case, the tool acts on TSO level, operating on the available resources (e.g. RES, storage) connected to both TSO and DSO levels to mitigate grid congestion.

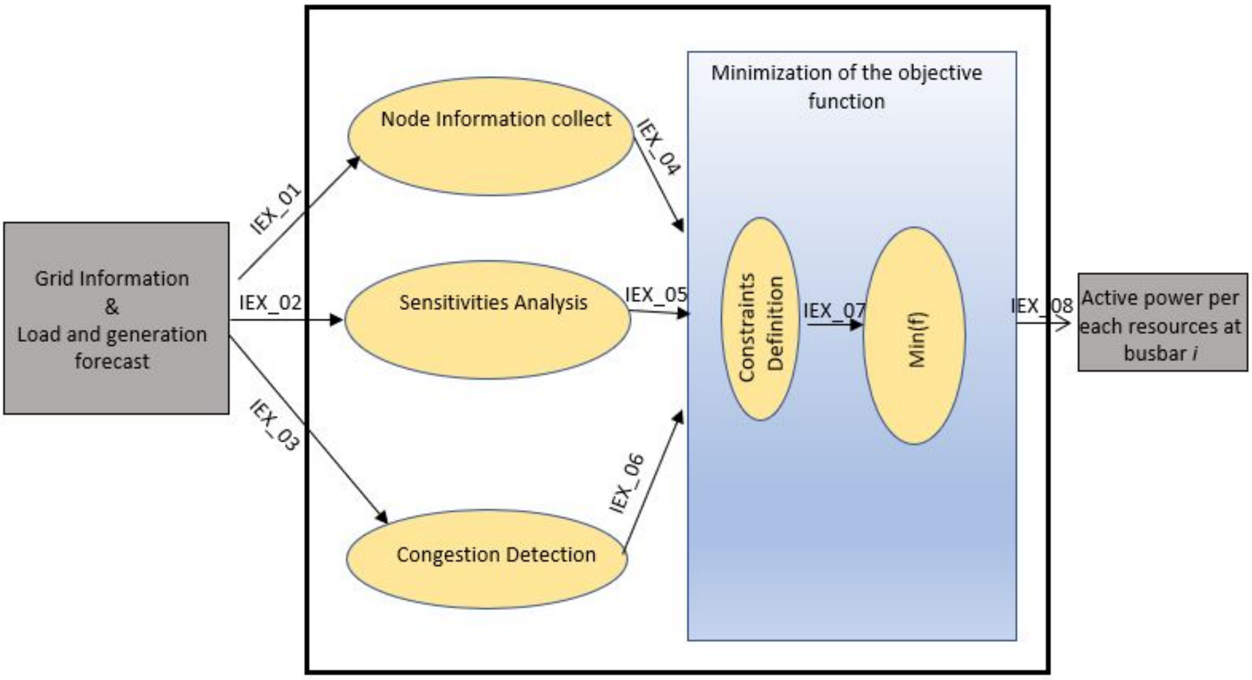
6.2.4 Diagrams of the use case

6.2.4.1 Context diagram

<u>Sub-use case 2.2</u>

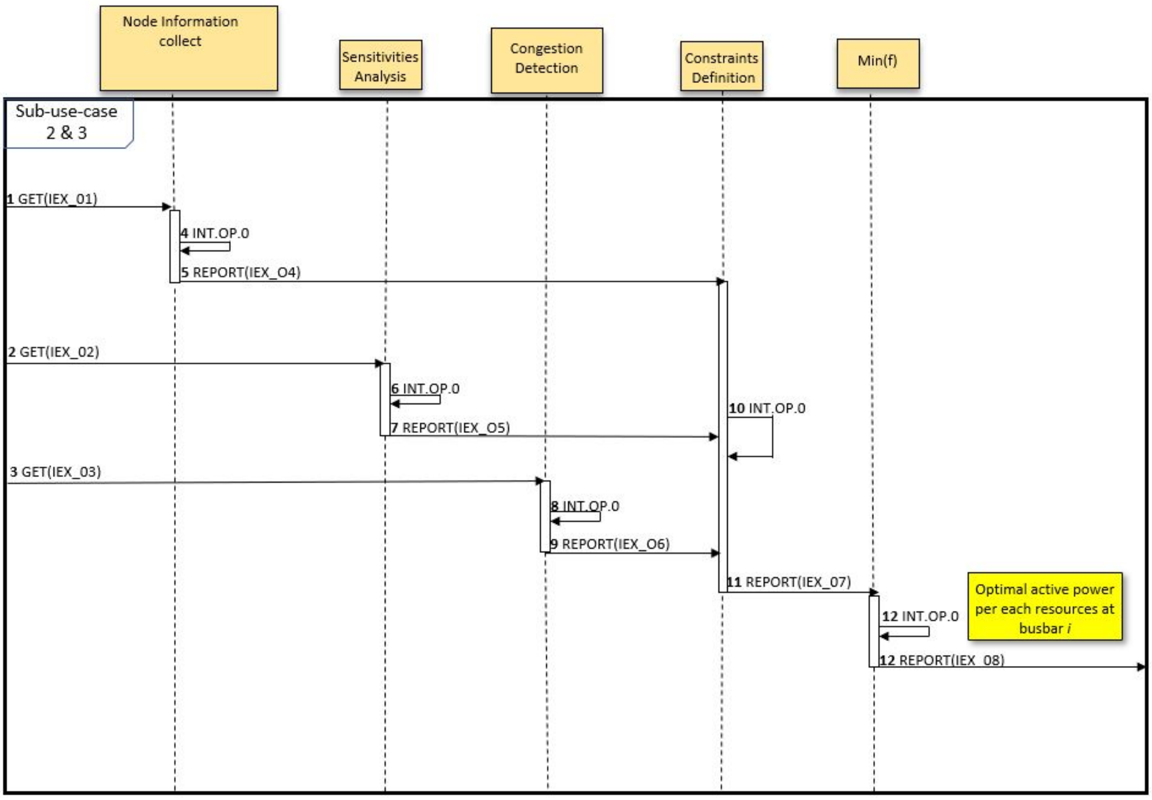


<u>Sub-use case 2.3</u>



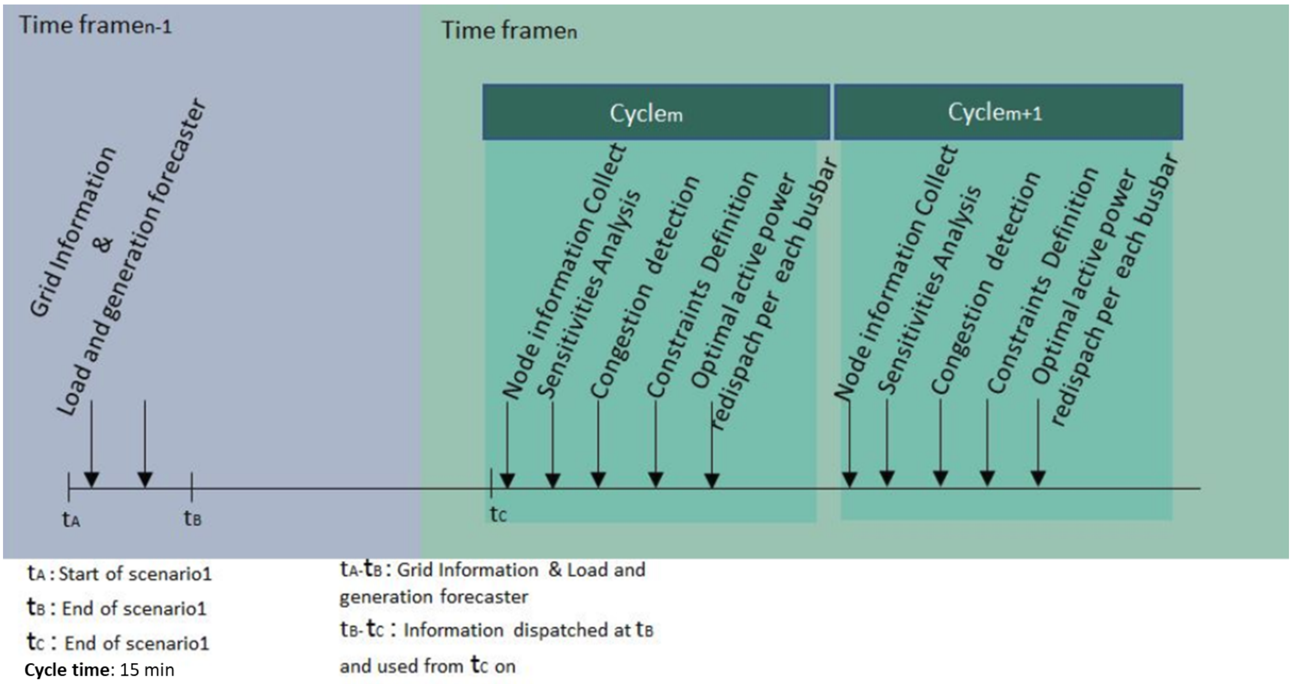
6.2.4.2 Sequence diagram

Sub-use case 2.2 and Sub-use case 2.3



6.2.4.3 Timing diagram

Sub-use case 2.2 and Sub-use case 2.3



6.2.5 Sequence of actions

Sequence of actions (based on sequence diagram) for sub use case number 2.2 and 2.3						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1	Grid information & load and generation forecast	The grid information, load and generation forecast are gathered for the grid model simulation.	Grid information & load and generation data	DSO/TSO	DSO/TSO	IEX-1, IEX-2, IEX-3
2	Node Information collect	This step is necessary to collect for each busbar the information related to the connected resources (Pmin, Pmax, Power reserves, etc)	Generators and Loads collection per each busbar	DSO, TSO/DSO for sub use case 2.3	*Constraints Definition* function at DSO level and *Constraints Definition* function at TSO level for sub use case 2.3	IEX-4
3	Sensitivities Analysis	The LFS (DigSilent function) is performed to calculate the sensitivities coefficients per each line.	Sensitivities Analysis	DSO, TSO/DSO for sub use case 2.3	*Constraints Definition* function at DSO level	IEX-5

					and *Constraints Definition* function at TSO level for sub use case 2.3	
4	Congestion Detection	This function evaluates possible congestion problem in the grid	Congestion Detection	DSO, TSO/DSO for sub use case 2.3	*Constraints Definition* function at DSO level and *Constraints Definition* function at TSO level for sub use case 2.3	IEX-6
5	Constraints Definition	In order to avoid all possible grid violations, suitable constraints are defined per each line.	Constraints Definition	DSO, TSO level for sub use case 2.3	Minimization of the objective function at DSO level and at TSO level for sub use case 2.3	IEX-7
6	Minimization of the objective function	The objective function is minimized to obtain the optimal active power values per each busbar (ΔP+ and ΔP- calculation per each busbar).	Minimization of the objective function	DSO, TSO/DSO for sub use case 2.3	Busbars at DSO level, and at TSO level for sub use case 2.3	IEX-8

6.3 Use case 3: Frequency tertiary control based on optimal power flow calculations

6.3.1 Description of the Use Case

6.3.1.1 Name of Use Case

Use case identification	
ID	Name
3	Frequency tertiary control based on optimal power flow calculations

6.3.1.2 Goal, Objectives and Scope and of the use case

Goal, objectives and scope of use case	
Goal	Improve frequency stability through provision of frequency tertiary control/reserve based on optimal power flow calculations and by involving as much as possible the flexible Renewable Energy Resources (RES) available at both transmission and distribution levels.
Objectives	1. Maintaining the grid balance and frequency stability

	2. Coordinate active power flows at the TSO/DSO interface 3. Improve the Distributed Generation (DG) units participation in the ancillary services 4. Maximising the RES and DG share in frequency control and balancing 5. Reducing grid losses and costs (fuel costs, grid losses, less investment in additional tertiary reserves)
Scope	The use case covers the aspect of providing the tertiary reserve through involving as much as possible the available RES resources at DSO level with a focus on optimising the power flow at distribution level as well as between transmission and distribution networks.

6.3.1.3 **Narrative of Use Case**

Narrative of the use case
Short description
The use case aims to ensure the frequency stability through tertiary control. The use case controller will engage the available flexibility of resources connected at both transmission and distribution level in order to participate in balancing and frequency tertiary control of the power systems in an optimal way and through TSO-DSO cooperation.
Complete description
<u>Motivation and problem statement</u> In the future EU grid, the share of distributed generation including renewable energy resources specifically in the distribution level will be noticeable high in comparison to the today's electrical grid. The system operators need to be prepared for such new grid and be able to operate the grid in an efficient and optimal way. One important aspect of operation and planning the operation of network is balancing and stabilising the network frequency. There are mainly three stages of balancing and stabilising the frequency in the grid in case of deviation including primary control (within seconds), secondary control (within minutes) and tertiary control (within minutes to hours). This use case address the tertiary control. Currently, only the TSOs have the responsibility of controlling tertiary reserve although, a noticeable share of the resources for tertiary reserve is connected at distribution level. Control of these resources by the TSO without a direct participation of DSOs may cause technical problems at distribution grid level. Therefore it is crucial that DSOs are also involved in controlling the tertiary reserve for a more stable network and optimal power flows in the electricity grid. <u>Solution Approach</u> This use case aims to involve both TSO and DSO in control and provision of the tertiary reserve through realising a coordination mechanism between TSO and DSO, and optimising the power flow within distribution and transmission networks. This will lead to a more stable network, less costs for fuel, less grid losses as well as more participation of DG and RES in provision of ancillary services. Two real-time OPF will be implemented at TSO and DSO control centres. An interaction chain based on sequential optimizations and exchange of relevant data and set points is to be defined. The OPF objective functions, which could be weighted as desired based on priorities of operators, are chosen among others as (i) Providing the required total tertiary reserve (ii) minimization of grid losses (iii) minimization of the fuel cost. The procedure is composed of three sequential steps by utilizing an OPF tool at each step. The steps may be carried out as part of the grid operator's day-ahead or hours-ahead operational planning, or as part of a real-time control scheme. The general sequence of actions is as following: In the **first step** an active power flexibility assessment is performed by the DSO using its own OPF tool. The maximum and minimum available active power based on the controllable generation units will be identified. In this step, the transmission grid is represented as reduced model along with connection points to distribution grid. The outcome of this step is available flexibilities list/assessment at the TSO-DSO connection points which will be communicated to the TSO. In case of operational planning, these may be flexibility schedules; in case of real-time control, the flexibilities will

relate to active power that can be delivered. In the **second step**, The TSO uses the active power flexibility communicated for the whole grid group and the values declared for each connection point to run the TSO-OPF where distribution grid transformers could be represented by a grid equivalent. The OPF tool of TSO calculates the set points (active power exchange) for the connection points to DSO as well as generators connected to its control area prioritizing its own control objectives. The result of the second step is set points for the TSO active power sources and TSO-DSO connection points. Again, in the operational planning case, there will be set point schedules, while in the real-time operation case, there will be single set points. As **third and final step**, The DSO computes the set points through its OPF tool by respecting set points (active power exchange) given by TSO for its control area.

6.3.1.4 **Key Performance Indicators**

Key performance indicators (KPIs)		
ID	Name	Addressed objectives
1	Level of losses in transmission and in distribution networks	5
7	Power losses	5
16	TSO-DSO connection point transformer loading	2
17	RES curtailment	3
19	Generation costs	5
22	Quadratic deviation from global active exchange target	1
23	Mean quadratic deviations from active power targets at TSO/DSO connection points	2

6.3.1.5 **Use case conditions**

Use case conditions
Assumptions
1. Flexible resources (DG, storage and RES) are controllable. 2. State of charge of EVs can be monitored and V2G and G2V service are available. 3. The fuel costs of involved power plants are available. 4. Necessary regulations and laws are enforced. 5. Different accuracy of weather forecast data will be assumed.
Prerequisite
1. Appropriate models of energy sources in the grid are available. 2. Grid models for distributions and transmission levels are available. 3. Forecast data for intermittent RES is available. Exemplary load and generation profiles.

6.3.1.6 **General Remarks**

General remarks
None

6.3.2 Technical details

6.3.2.1 **Systems and associated actors/tools**

Systems and associated actors/tools			
Group	System(s)	Actor(s)/tool(s)	Remarks
2	Distribution system	Distribution System Operator (DSO)	-
1	Transmission system	Transmission	-

		System Operator (TSO)	
4	Virtual Power Plant (VPP)	Operator, Aggregator	-
5	Controllable load , Uncontrollable load	Consumer, Aggregator	-
3	Generation: DG, RES, Synchronous generator	Owner/operator, Aggregator	-
6	Storage, Electric Vehicles (EV)	Owner/Operator	-
7	RES	Generation forecast unit	-
7	Transmission system	OPF	Optimisation of grid losses and generation costs
7	Distribution system	OPF	Optimisation of grid losses and generation costs
7	DG, RES, Synchronous generator, Storages, EVs, Flexible loads	Controllers	Cluster or interface controllers
7	DG, RES, Synchronous generator, Storages, EVs, Flexible loads	Sensors, measurement devices	-

6.3.2.2 **Control variables**

Control variables	
Control Variable	Corresponding actor / tool
Active power injection/ consumption	Synchronous generators, DG, RES, storages, EVs, controllable loads
State of charge	Storages, EVs

6.3.2.3 **Simulation environment:**

- DigSilent Powerfactory
- Python

6.3.3 Sub-use cases

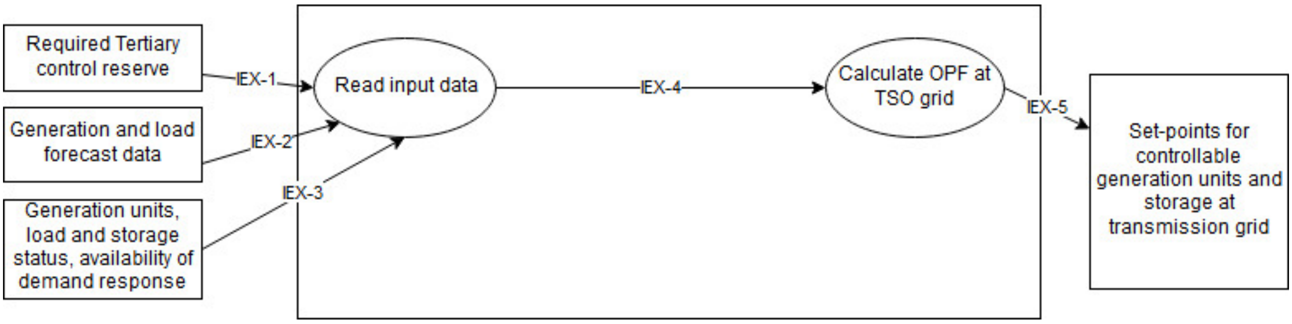
Sub-use cases	
Sub-use case number	Description
3.1	DSO does not participate in providing tertiary reserves. TSO will do OPF calculations at its own network and distribution networks will be considered as grid equivalent with no controllable active power.
3.2	**DSO participates** in providing tertiary reserves. **At distribution level only distributed energy** sources are controllable and no storage or Demand Response mechanism are available.
3.3	**DSO participates** in providing tertiary reserves. **At distribution level only distrib-**

	uted energy sources and storages are controllable and no Demand Response mechanism is available.
3.4	**DSO participates** in providing tertiary reserves. **At distribution level all classes of flexibility are available. It means that distributed energy** sources and storages are controllable and Demand Response mechanism is available.

6.3.4 Diagrams of the use case

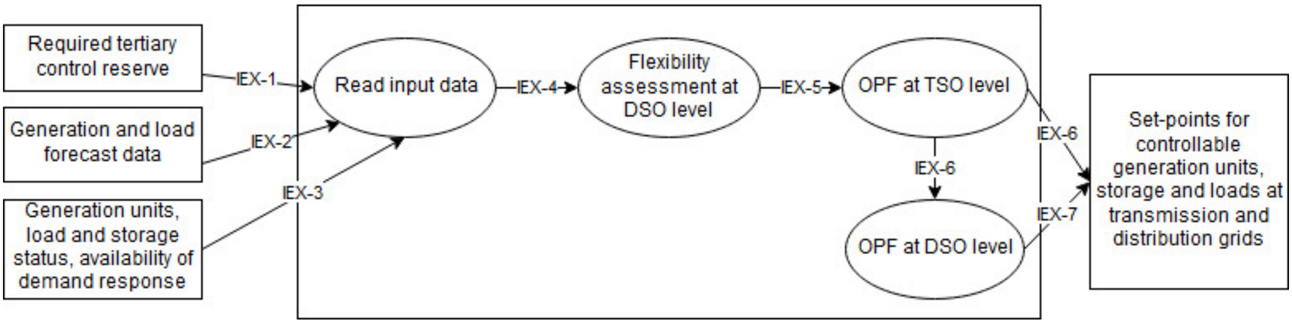
6.3.4.1 **Context diagram**

Sub-use case 3.1:



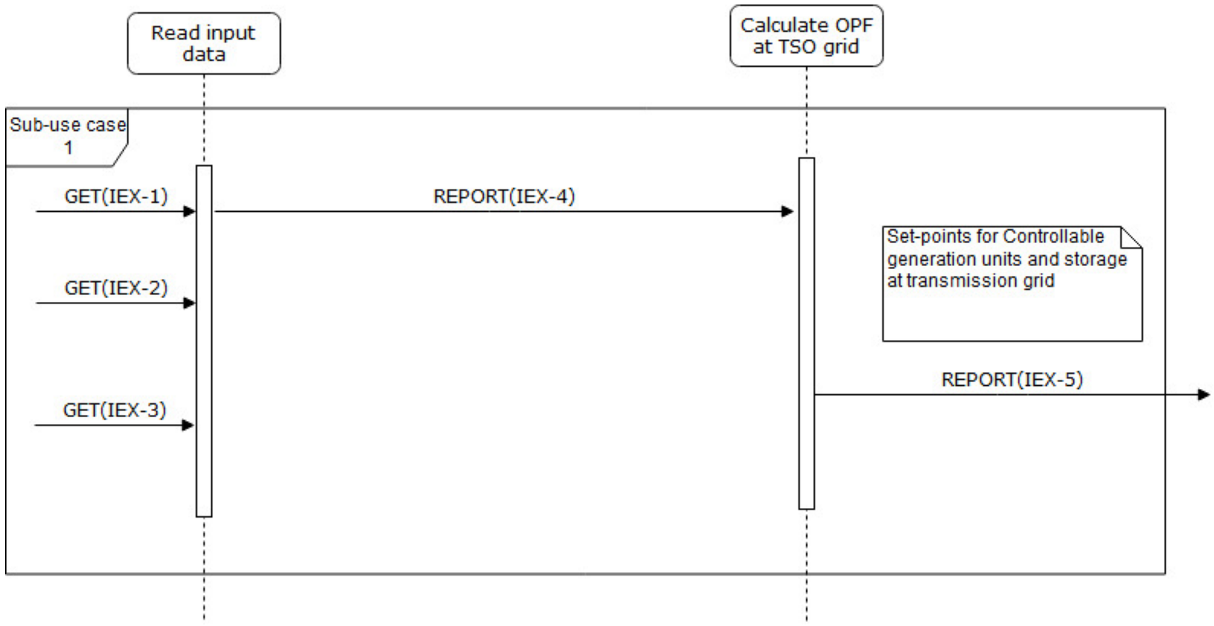
Sub-use case 3.2 and 3.3 have the same context diagram. The only difference is that in sub-use case 3.2, no set points will be sent to storage and in sub-use case 3.3, no set point will be sent for demand response

Sub-use case 3.4:



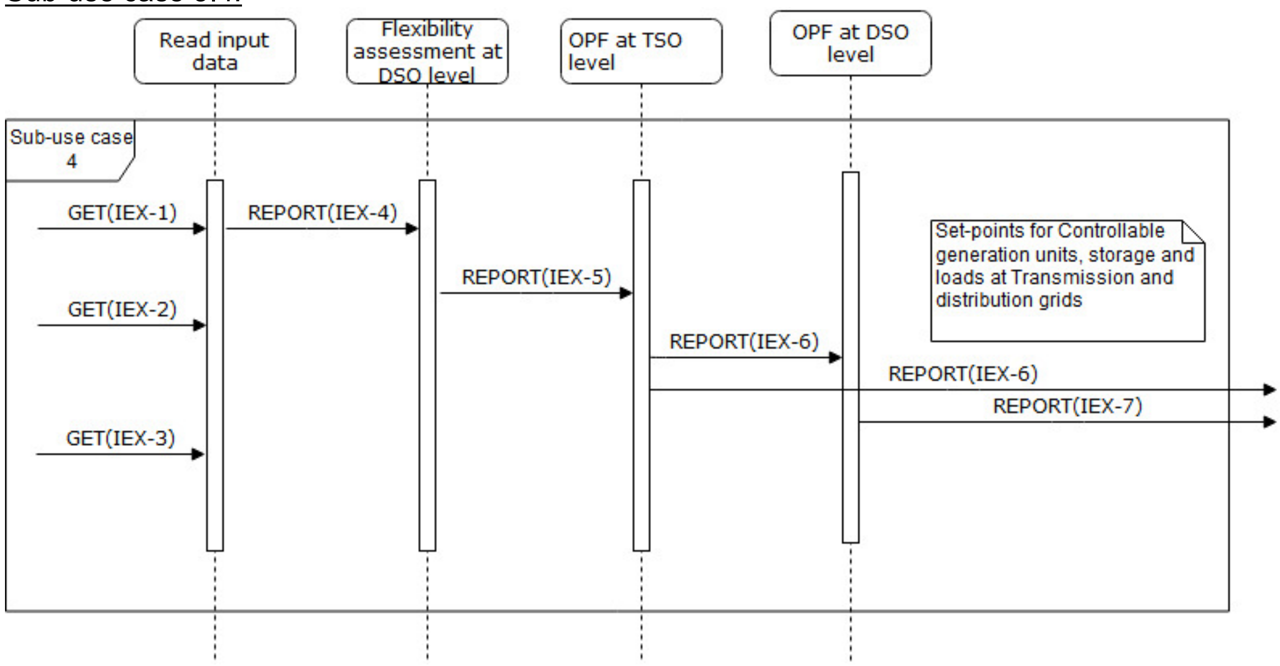
6.3.4.2 **Sequence diagram**

Sub-use case 3.1:



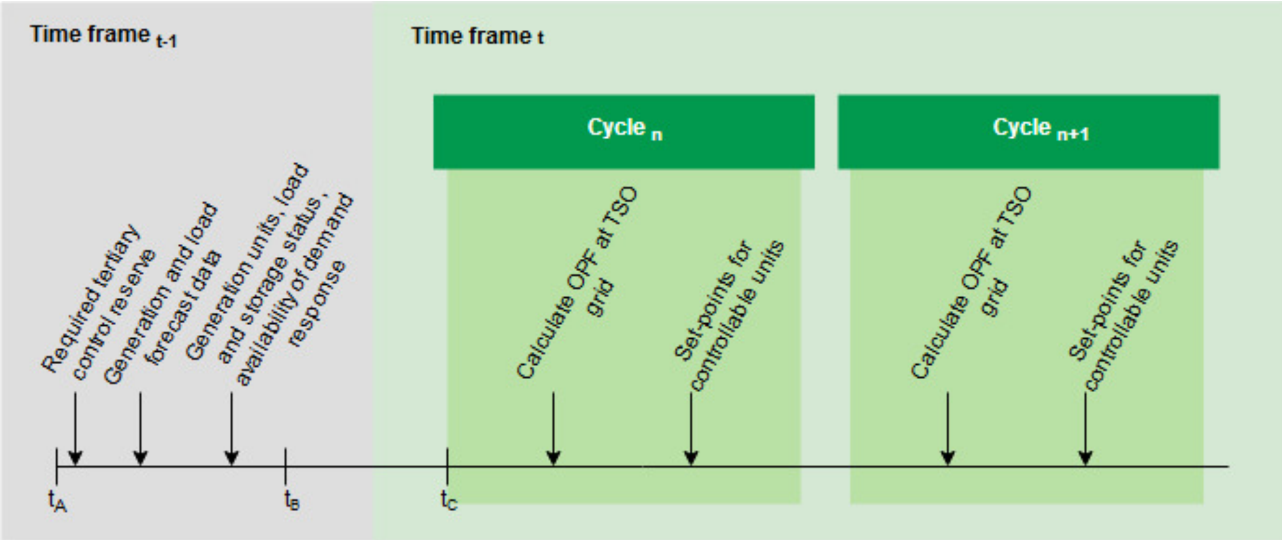
Sub-use case 3.2 and 3.3 have the same context diagram. The only difference is that in sub-use case 3.2, no set points will be sent to storage and in sub-use case 3.3, no set point will be sent for demand response.

<u>Sub-use case 3.4:</u>



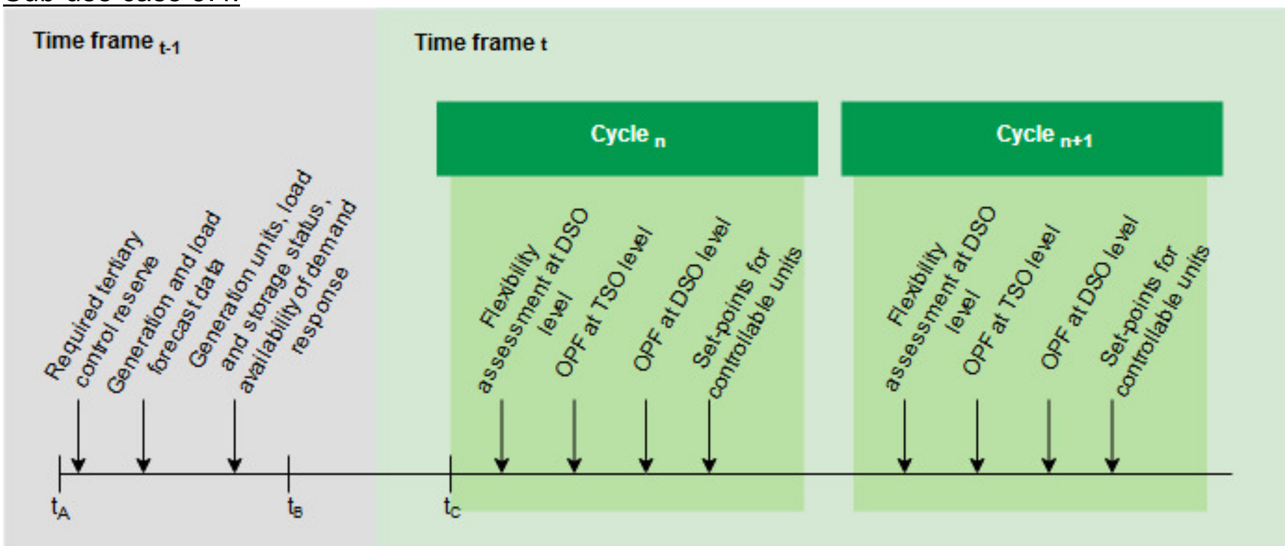
6.3.4.3 Timing diagram

<u>Sub-use case 3.1:</u>



Sub-use case 3.2 and 3.3 have the same context diagram. The only difference is that in sub-use case 2, no set points will be sent to storage and in sub-use case 3.3, no set point will be sent for demand response.

Sub-use case 3.4:



6.3.5 Sequence of actions

Sub-use case 3.1:

Sequence of actions (based on sequence diagram) for sub use case number 3.1						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1	Required tertiary control reserve data	The required tertiary reserve is calculated and transferred to the database	Required tertiary control reserve data	TSO	database	IEX-1
2	Generation and load forecast data	The information of generation and load forecast is gathered and transferred to the	Generation and load forecast data	Forecast tools	database	IEX-2

		database.				
3	Generation units, load and storage status, availability of demand response	The information about the status of generation units, load and storage as well as availability of demand response is gathered and transferred to the database.	Generation units, load and storage status, TSO/DSO transformer loading	TSO, DSO	database	IEX-3
4	Read input data	Required information for OPF calculations are sent to TSO OPF tool	All the gathered data from steps 1 to 3	Database	TSO OPF tool	IEX-4
5	OPF at TSO grid and set-points	The output of TSO OPF tool is defined and set-points are transferred to the controllable generation units and storage and loads at transmission grid	set-points (output active power, state of charge)	TSO OPF tool	Controllable generation units and storage and loads at transmission grid	IEX-5

Sub-use case 3.2 and 3.3 have the same context diagram. The only difference is that in sub-use case 2, no set points will be sent to storage and in sub-use case 3.3, no set point will be sent for demand response
Sub-use case 3.4:

Sequence of actions (based on sequence diagram) for sub use case number 4						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1	Required tertiary control reserve data	The required tertiary reserve is calculated and transferred to the database	Required tertiary control reserve data	TSO	database	IEX-1
2	Generation and load forecast data	The information of generation and load forecast is gathered and transferred to the database.	Generation and load forecast data	Forecast tools	database	IEX-2
3	Generation units, load and storage status, availability of demand response	The information about the status of generation units, load and storage as well as availability of demand response is gathered and transferred to the database.	Generation units, load and storage status, availability of demand response	TSO, DSO	database	IEX-3
4	Read input data	Required information for OPF calculations are sent to TSO and	All the gathered data from	Database	TSO OPF tool, DSO OPF tool	IEX-4

		DSO OPF tools	steps 1 to 3			
5	Flexibility assessment at DSO level	The available flexibility of DSO grid in form of a range of available active power is defined and transferred to TSO OPF tool	Range of available active power from distribution network	DSO	TSO OPF tool	IEX-5
6	OPF at TSO level and set-points	The output of TSO OPF tool is defined and set-points are transferred to the controllable generation units, storage and loads as well as TSO-DSO connection points	set-points (output active power, state of charge)	TSO OPF tool	Controllable generation units, storage and loads at Transmission level as well as DSOs	IEX-6
7	OPF at DSO level and set points	The output of DSO OPF tool is defined and set-points are transferred to the controllable generation units, storage and loads	Output of OPF at DSO level	DSO OPF tool	Controllable generation units, storage and loads at distribution level	IEX-7

6.4 Use case 4: Fast Frequency Restoration Control

6.4.1 Description of the Use Case

6.4.1.1 Name of Use Case

Use case identification	
ID	Name
4	Fast Frequency Restoration Control

6.4.1.2 Goal, Objectives and Scope and of the use case

Goal, objectives and scope of use case	
Goal	Fast frequency restoration in interconnected power systems based on a bottom-up approach through local measurements (tie-line power-flow deviations).
Objectives	1. Maintain the grid balance 2. Restore frequency next to balancing 3. Improve the DER units participation in the ancillary services 4. Increase availability of new active resources (e.g., RES and storage) 5. Reduce the needed time for restoring frequency 6. Improve TSO-DSO interaction
Scope	The Use Case 4 describes the fast Frequency Restoration Control (fFRC) functionality based on the use of local fast ramping resources (e.g., RES, storage units, flexible loads). The fFRC functionality allows to achieve a frequency restoration process which is faster than that attained with the traditional controllers commonly used in current power systems, also through a TSO-DSO collaborative interaction.

1.1.1.1 Narrative of Use Case

Narrative of the use case
Short description
The Use Case 4 describes the fFRC functionality based on the use of local fast ramping resources (e.g., RES, storage units, flexible loads). The fFRC resembles the current Frequency Restoration Control, except that it is not a slower (secondary) control, but instead it is a fast primary control using many local fast ramping resources. In this way, the fFRC would operate faster than the traditional controller AGC (Automatic Generation Control) commonly used in current power systems. The fFRC functionality monitors instantaneous active power profiles at the borders of the controlled area, comparing it with a set point profile. In response to the observed deviations (instability events), the fFRC regulates active power of available fast resources to correct the imbalances, by choosing, through a meritocratic list, which units have to be activated/deactivated and, in case of activation, how much power they have to provide. To select the most proper resources to be involved in the process, in fact, per each time step, the fFRC makes a merit order list based on some assigned properties (e.g., lower cost, available power, etc.). In detail, the TSO, who is responsible for frequency restoration processes in its control area, can benefit from the usage of the resources from both transmission and distribution grids through a collaborative approach with DSOs. This allows to enhance the frequency restoration process based on an improved TSO-DSO interaction. This use case will be addressed through dynamic simulations.
Complete description
<u>Motivation and problem statement</u> The rapid growth of renewable power is adding new challenges for maintaining balance into power systems, especially at distribution level where networks are more vulnerable. New instruments are required to avoid network criticalities such as frequency instability events. In this scenario, RES, energy storage and flexible loads as local fast ramping resources can become an opportunity if integrated into the grid together with proper management tools, which are able to regulate active power from resources in the most suitable way for frequency stability. <u>Solution Approach</u> The Use Case 4 aims to develop a fast Frequency Restoration Control (fFRC), which, based on the use of local fast ramping resources such as RES, storage units, and flexible loads, allows to achieve a frequency restoration process which is faster than that attained with the traditional controllers commonly used in current power systems, also through a collaborative TSO-DSO interaction. The fFRC is developed based on the Balance Restoration Control proposed under the ELECTRA IRP, FP7 project. In detail, four sub-use cases are considered. Firstly, a base case is analyzed with no controllers available. This first sub-use case (4.1) evaluates the network frequency response under specific instability events. The second and third sub use cases evaluate how the same grid reacts to an instability event in the presence of the fFRC (sub-use case 4.2) and AGC (sub use case 4.3), respectively. Then, the comparison between the results obtained (sub use case 4.4) provides information (see KPIs) on the effective improvement of the fFRC versus the existing AGC. The development of the fFRC is based on the following solution approach. During the operation, the fFRC monitors continuously the grid stability in the observed area by applying the following logic: 1. Per each time step, the fFRC orders in a list (Available Resource List) all the available resources in the grid according to predefined characteristics (e.g., cost and available power). 2. Per each time step, the fFRC receives the balance set point (= tie-line active power flow profile set points) and compares it with tie-line power flow measurements.

When an imbalance occurs (i.e., deviation from the set points), an imbalance error signal is generated, and the fFRC sends the active power activation/deactivation commands referring to the required power amount, involving the resources according to the order in the list above to involve a number of resources/power such enough for restoring the balance.

6.4.1.3 **Key Performance Indicators**

Key performance indicators (KPIs)		
ID	Name	Addressed objectives
5	Frequency Restoration Control effectivity	1, 2
6	Response Time	3, 5

6.4.1.4 **Use case conditions**

Use case conditions
Assumptions
1. Sufficient fast restoration resources to correct the imbalances.
Prerequisite
1. Use of dynamic simulations. 2. Availability of controllable active power devices in the grid model. 3. Availability of grid models including both transmission and distribution levels.

6.4.2 Technical details

6.4.2.1 **Systems and associated actors/tools**

Systems and associated actors/tools			
Group	System(s)	Actor(s)/tool(s)	Remarks
1	Transmission system	TSO	
2	Distribution system	DSO	-
3	Controllable DG, RES	Owner/operator, (Aggregator)	In DSO grid, with active power provision capability
5	Controllable loads	Consumer (Aggregator)	-
6	Controllable Storage Systems	Owner/Operator	In DSO grids, with active power provision capability
7	Electric Loads, DG, RES	Load and generation forecast unit	Used for forecasting load and generation.

6.4.2.2 **Control variables**

Control variables	
Control Variable	Corresponding actor / tool
Output active power	RES, storage units, controllable loads, synchronous generators

6.4.2.3 **Simulation environment:**

- DigSilent Powerfactory
- Python

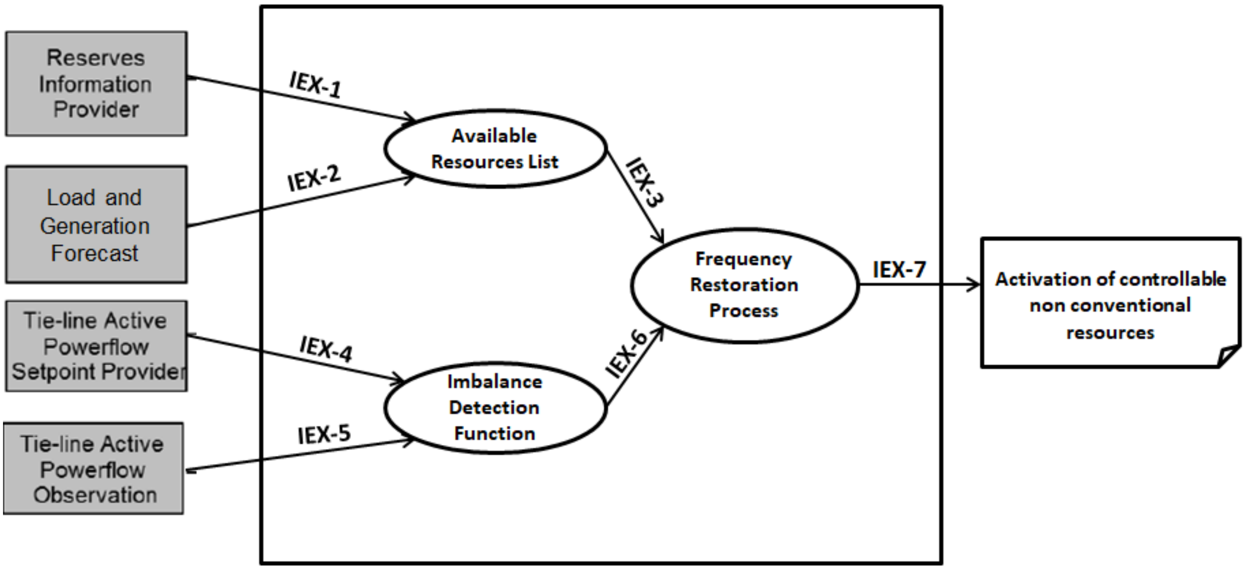
6.4.3 Sub-use cases

Sub-use cases	
Sub-use case number	Description
4.1	Base case - no controllers available. This sub-use case evaluates the network frequency response under specific instability events.
4.2	fFRC case: in this sub-use case, the fFRC acts operating on the available fast resources (e.g. storage, RES), to restore the frequency. This sub-use case maximizes the DER contribution to provide ancillary services.
4.3	AGC case: in this sub-use case, only AGC acts, operating on the available resources (traditional generators), to restore the frequency.
4.4	fFRC VS AGC: In this sub-use case, the fFRC is compared with the traditional AGC

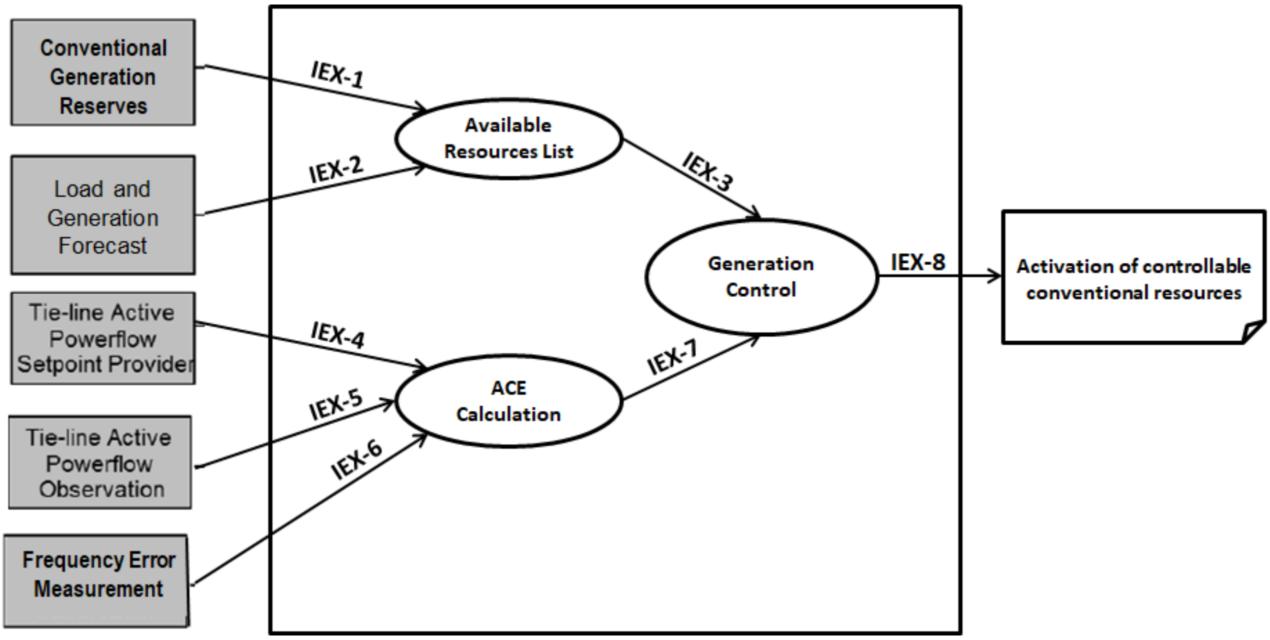
6.4.4 Diagrams of the use case

6.4.4.1 Context diagram

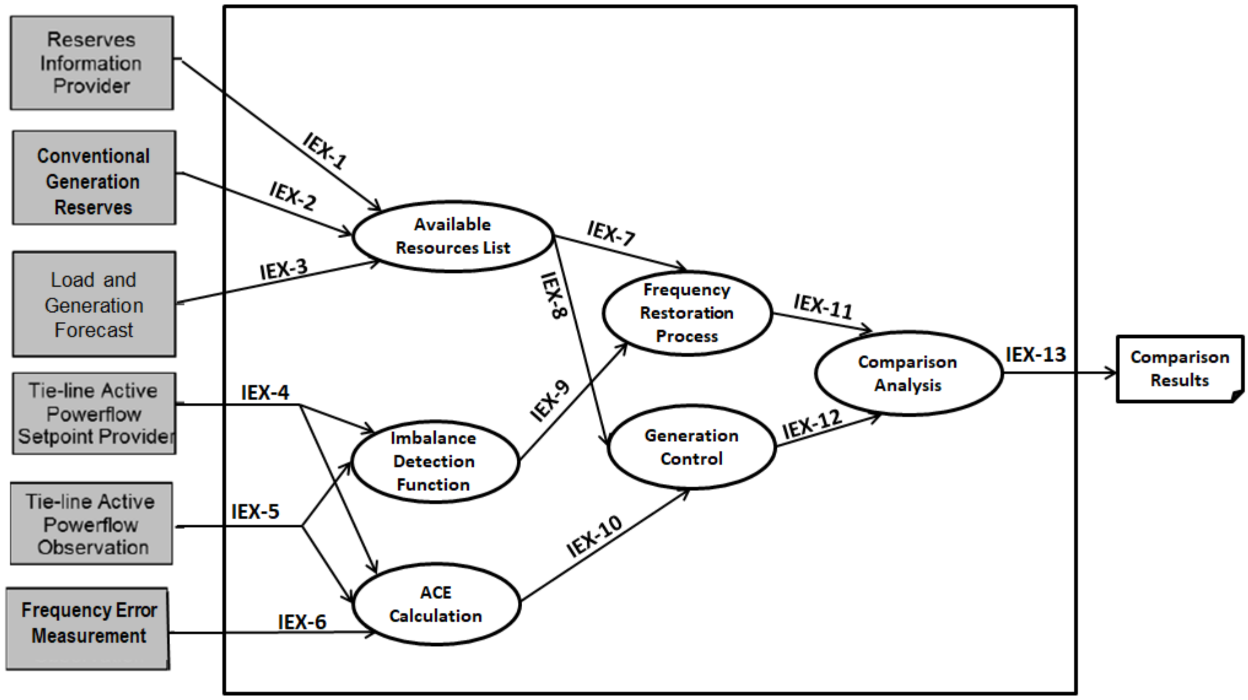
<u>Sub-use case 4.2</u>



<u>Sub-use case 4.3</u>

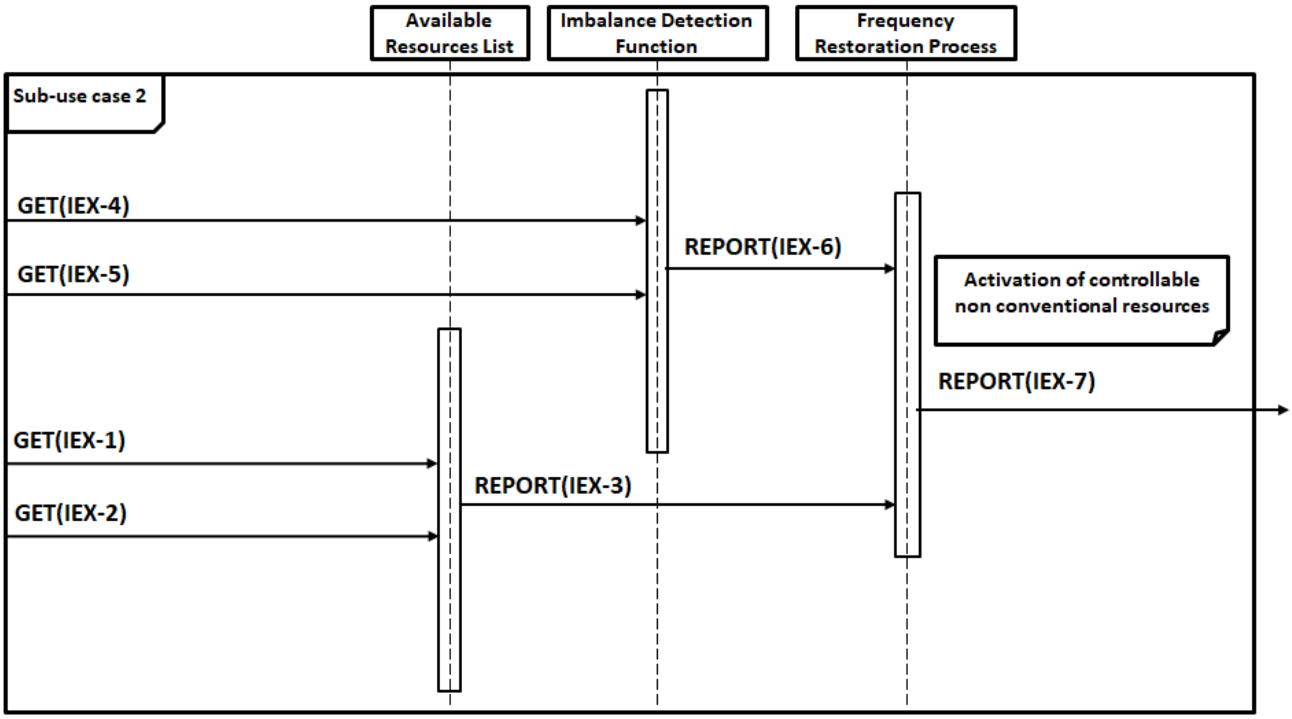


Sub-use case 4.4

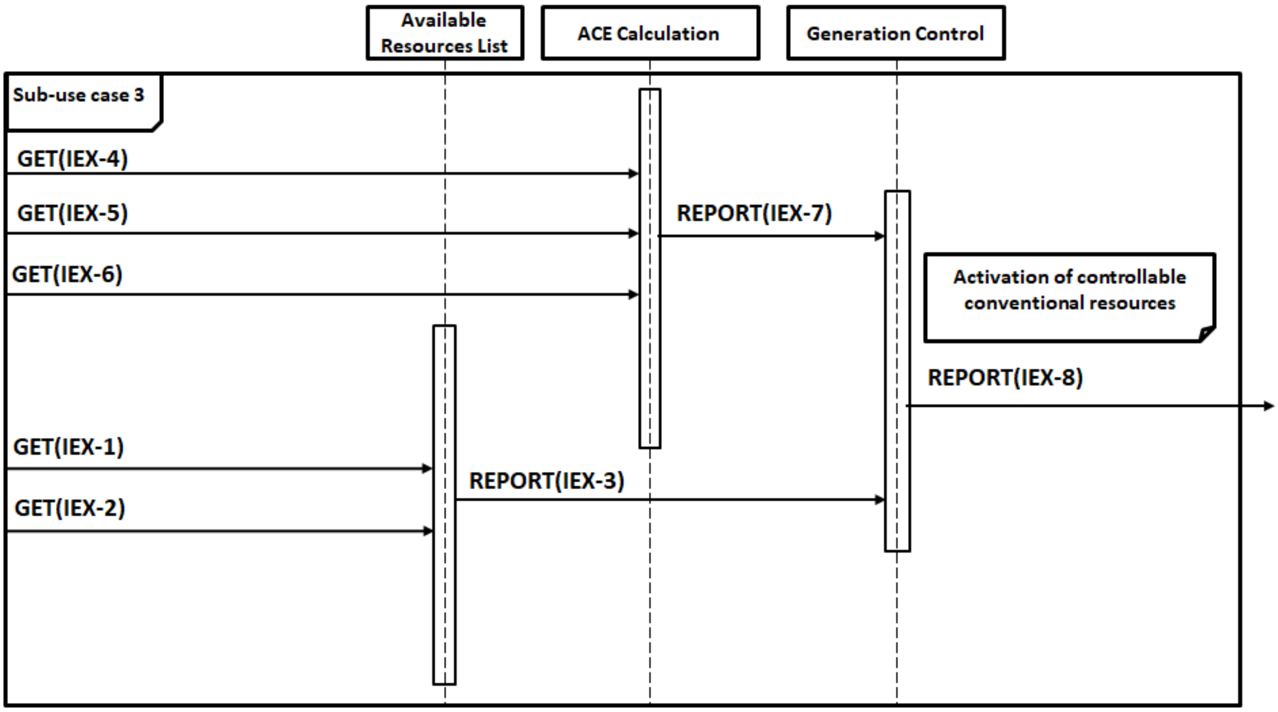


6.4.4.2 **Sequence diagram**

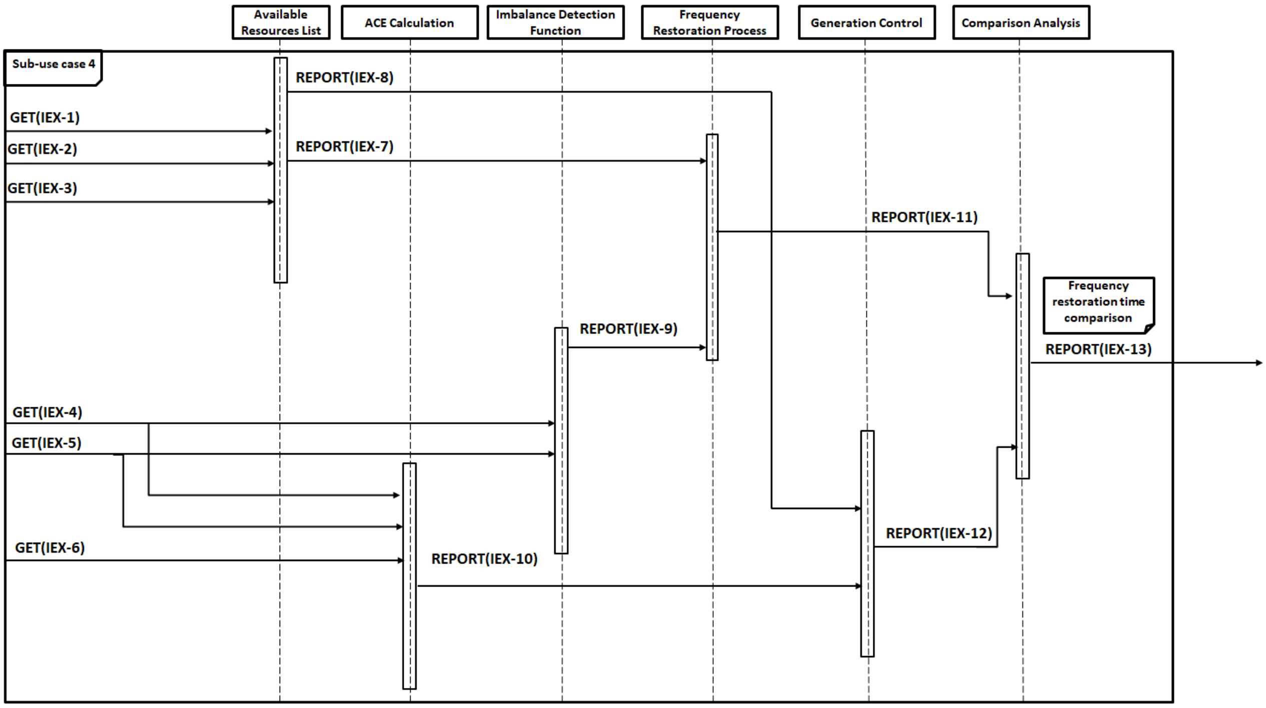
Sub-use case 4.2



Sub-use case 4.3

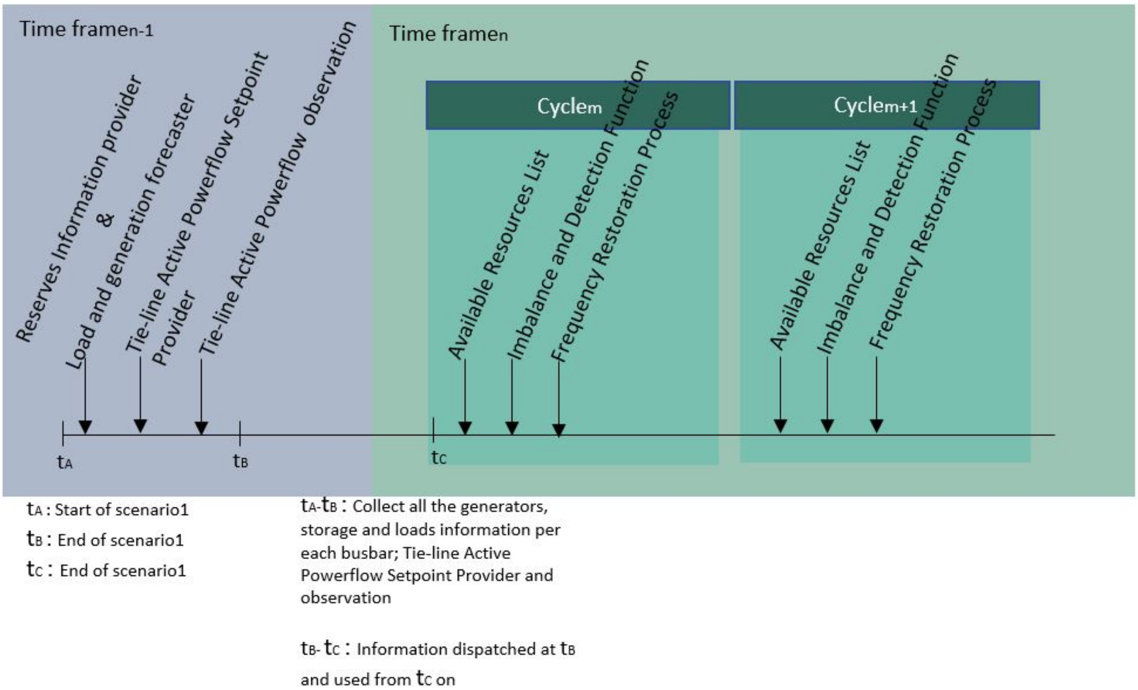


Sub-use case 4.4

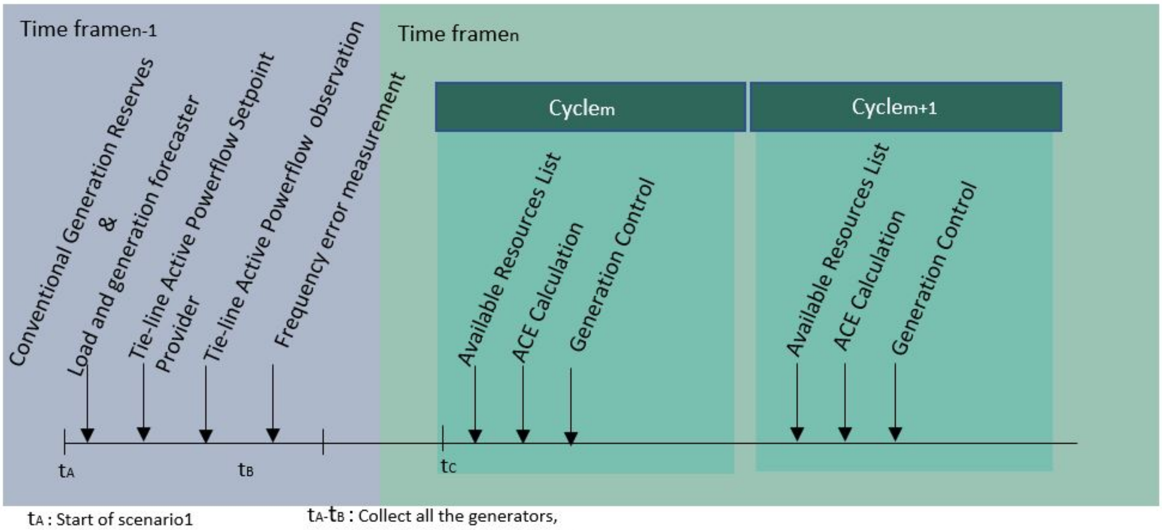


6.4.4.3 Timing diagram

Sub-use case 4.2



Sub-use case 4.3

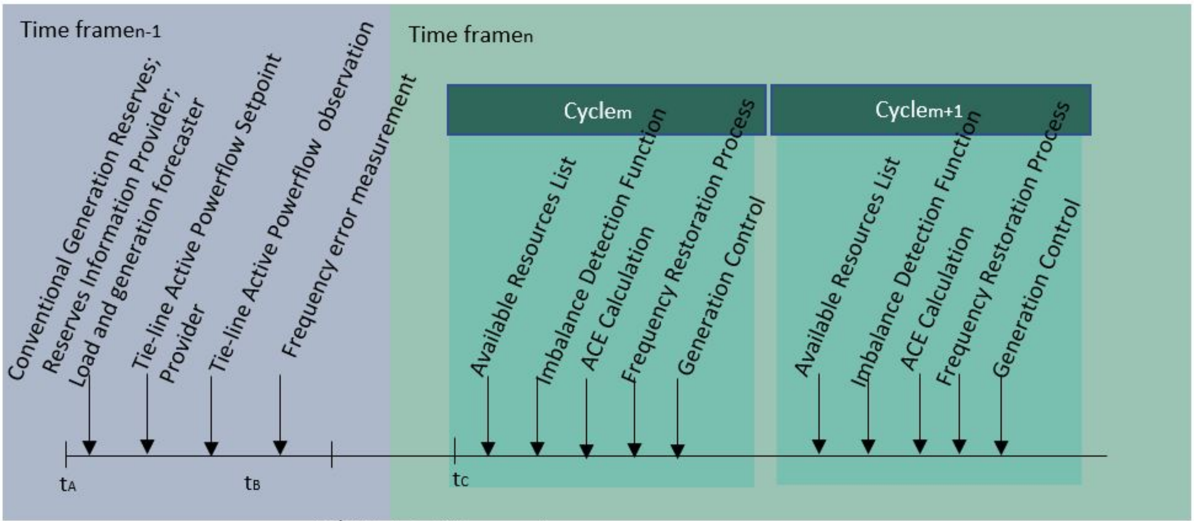


tA : Start of scenario1
tB : End of scenario1
tC : End of scenario1

tA-tB : Collect all the generators, storage and loads information per each busbar; Tie-line Active Powerflow Setpoint Provider and observation; frequency measurement

tB- tC : Information dispatched at tB and used from tC on

<u>Sub-use case 4.4</u>



tA : Start of scenario1
tB : End of scenario1
tC : End of scenario1

tA-tB : Collect all the generators, storage and loads information per each busbar; Tie-line Active Powerflow Setpoint Provider and observation; frequency measurement

tB- tC : Information dispatched at tB and used from tC on

6.4.5 Sequence of actions

Sequence of actions (based on sequence diagram) for sub use case number 4.2						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer	Information receiver	Information Exchanged

				(Actor/tool)	(Actor/tool)	IDs
1	Reserves information provider (INPUT)	The required reserves information is collected from the specific scenario.	Required reserve data	Owner/operator (Aggregator)	TSO / DSO	IEX-1
2	Load and generation forecast (INPUT)	The information of generation and load forecast is gathered and transferred to the database.	Generation and load forecast data	Owner/operator (Aggregator) Forecast tools	TSO / DSO	IEX-2
3	Available Resources List	This step is necessary to collect all the power information per each resource in the grid.	Matrix defined as [Pmax, Pmin, Pactual, Bus, Preserv, Cost, etc.] per each Unit	Resources list at DSO level	Frequency Restoration Process function at DSO level	IEX-3
4	Tie-Line Active Power flow Set point Provider (INPUT)	This step provides the individual tie-line power flows for calculating the total area imbalance.	Vector of individual tie-lines active power flow schedules	TSO	Imbalance Detection function at TSO level	IEX-4
5	Tie-Line Active Power flow Observation (INPUT)	This step calculates and provides active power flow measurements to the Imbalance Detection function.	Value of tie-lines power flow	TSO	Imbalance Detection function at TSO level	IEX-5
6	Imbalance Detection function	This step collects and aggregates the tie-line information from step 5 and compares this against the set point received from the step 4 to determine a balance error signal to send at the Frequency Restoration Process function.	Balance error signal	Imbalance Detection function at TSO level	Frequency Restoration Process function at DSO level	IEX-6
7	Frequency Restoration Process function	This step receives the balance error signal from the Imbalance Detection function, and using the information "Available Resources List" (step 3), sends active power dispatch commands to Controllable non-conventional devices.	Vector defined as [New Active Power per each controllable non-conventional device]	Frequency Restoration Process function at DSO level	Controllable non-conventional devices at DSO level	IEX-7

Sequence of actions (based on sequence diagram) for sub use case number 4.3						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1	Conventional Generation Reserves (INPUT)	The required reserves information is collected from the specific scenario.	Required reserve data	TSO	TSO	IEX-1
2	Load and generation forecast(INPUT)	The information of generation and load forecast is gathered and transferred to the database.	Generation and load forecast data	TSO forecast tool	TSO	IEX-2
3	Available Resources List	This step is necessary to collect all the power information per each resource in the grid.	Matrix defined as [Pmax, Pmin, Pactual, Bus, Preserv, Cost, etc.] per each Unit	Resources list at TSO level	Generation Control function at TSO level	IEX-3
4	Tie-Line Active Power-flow Set point Provider (INPUT)	This step provides the individual tie-line power flows for calculating the total area imbalance.	Vector of individual tie-lines active power flow schedules	TSO	ACE (Area Control Error) Calculation at TSO level	IEX-4
5	Tie-Line Active Power flow Observation (INPUT)	This step calculates and provides active power flow measurements to ACE Calculation.	Value of tie-lines power flow	TSO	ACE Calculation at TSO level	IEX-5
6	Frequency Error Measurement	This step determines the frequency error signal.	Frequency error signal	Frequency Error Measurement function at TSO level	ACE Calculation at TSO level	IEX-6
7	ACE Calculation	This step collects and aggregates the tie-line information from step 5 and compares this against the set point received from the step 4, and using the frequency error information (step 6) determines a balance error signal to send at Generation Control function.	Balance error signal	ACE Calculation function at TSO level	Generation Control function at TSO level	IEX-7

8	Generation Control	This step receives the balance error signal from the ACE Calculation, and using the information "Available Resources List" (step 3) and sends active power dispatch commands to controllable conventional devices.	Vector defined as [New Active Power per each controllable conventional device]	Generation Control function at TSO level	Controllable conventional devices at TSO level	IEX-8

Sequence of actions (based on sequence diagram) for sub use case number 4.4						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1	Reserves information provider (INPUT)	The required reserves information is collected from the specific scenario.	Required reserve data	Owner/operator (Aggregator)	TSO / DSO	IEX-1
2	Conventional Generation Reserves (INPUT)	The required reserves information is collected from the specific scenario.	Required reserve data	TSO	TSO	IEX-2
3	Load and generation forecast(INPUT)	The information of generation and load forecast is gathered and transferred to the database.	Generation and load forecast data	Owner/operator (Aggregator) Forecast tools (fast resources) TSO Forecast tools (conventional resources)	TSO / DSO	IEX-3
4	Available Resources List	This step is necessary to collect all the power information per each resource in the grid.	Matrix defined as [Pmax, Pmin, Pactual, Bus, Preserv, Cost, etc.] per each Unit	Resources list at DSO level (fast resources) Resources list at TSO level (conventional resources)	Frequency Restoration Process function at DSO level Generation Control function at TSO level	IEX-7, IEX-8
5	Tie-Line Active Powerflow Set point Provider (INPUT)	This step provides the individual tie-line powerflows for calculating the total area imbalance.	Vector of individual tie-lines active powerflow	TSO	Imbalance Detection Function and ACE Calculation	IEX-4

			schedules		function at TSO level	
6	Tie-Line Active Power-flow Observation (INPUT)	This step calculates and provides active powerflow measurements to ACE Calculation function.	Value of tie-lines power flow	TSO	Imbalance Detection Function and ACE Calculation function at TSO level	IEX-5
7	Frequency Error Measurement	This step determines the frequency error signal.	Frequency error signal	Frequency Error Measurement function at TSO level	ACE Calculation function at TSO level	IEX-6
8	Imbalance Detection function	This step collects and aggregates the tie-line information from step 6 and compares this against the set point received from the step 5 to determine a balance error signal to send at the Frequency Restoration Process function.	Balance error signal	Imbalance Detection function at TSO level	Frequency Restoration Process function at DSO level	IEX-9
9	ACE Calculation	This step collects and aggregates the tie-line information from step 6 and compares this against the set point received from the step 5, and using the frequency error information (step 7) determines a balance error signal.	Balance error signal	ACE Calculation function at TSO level	Generation Control function at TSO level	IEX-10
10	Frequency Restoration Process function	This step receives the balance error signal from the Imbalance Detection function (step 8), and using the information "Available Resources List" (step 4) and sends active power dispatch commands to Controllable non-conventional devices.	Vector defined as [New Active Power per each controllable non-conventional device]	Frequency Restoration Process function at DSO level	Controllable non-conventional devices at DSO level	IEX-11
11	Generation Control	This step receives the balance error signal from the ACE Calculation, and using the information "Available	Vector defined as [New Active Power per each	Generation Control function at TSO level	Controllable conventional devices at TSO level	IEX-12

		Resources List" (step 4) and sends active power dispatch commands to Controllable conventional devices.	controllable conventional device]			
12	Comparison Analysis	This step receives the information from step 10 and step 11 and compares them in terms of frequency restoration time.	Frequency restoration time	Generation Control function and Frequency Restoration Process function	-	IEX-13

6.5 Use case 5: Power balancing at DSO level

6.5.1 Description of the Use Case

6.5.1.1 Name of Use Case

Use case identification	
ID	Name
5	Power balancing at DSO level

6.5.1.2 Goal, Objectives and Scope and of the use case

Goal, objectives and scope of use case	
Goal	**Minimization of the energy flow between transmission and distribution network by optimal power flows at** DSO level
Objectives	1. Reduction of energy flow between transmission and distribution network 2. Optimal usage of flexible resources 3. Avoiding congestions and unnecessary grid losses
Scope	Utilization of DSO level resources and flexibilities for better energy management and loss minimization through local usage of electrical energy

1.1.1.1 Narrative of Use Case

Narrative of the use case
Short description
Optimization of power balancing at DSO level by optimizing the local available flexible and/or controllable resources (DG, storage, demand response, etc.) in order to manage the exchange profile in the EHV/HV substations.
Complete description
Motivation and problem statement In today's power system large conventional generation connected to EHV and HV grid is being replaced by distributed generation (including RES). Storage units are also being connected mainly deep in the distribution grid. Not only generation portfolio is changing but also new type of load has been emerging (EVs), which will have a significant impact on grid operation. Due to these factors new ways of operation will be needed and it will become important to include DG, storage and loads capabilities in system energy management in order to avoid congestions, preserve minimal losses and maintain voltage stability, functions typically performed within optimal power flows. Solution Approach The main goal of this use case is to maximize local balancing of load by distributed grid energy sources (including RES, EVs, ESS and DSR) through their local usage. Fulfilling this objective will also contribute to the reduction of losses due to a lower need to supply power by the transmission grid, and potentially will also limit congestions.

The main indicator for the above objective is the flow between TSO and DSO grid measured at the EHV/HV transformers. Thus an OPF employing all controllable resources (incl. RES, EVs, ESS and DSR) will be used with an objective function to minimize the transformers' loads, while ensuring stable and secure operation of the grid. In order for this approach to be feasible, the resources would have to be accessible and controllable from the DSO perspective either by means of aggregation or direct access from the DSO control centre, for whom it would create a new area of responsibility in power system operation. This, in turn, would require new or amended regulatory framework and market solutions.

6.5.1.3 **Key Performance Indicators**

Key performance indicators (KPIs)		
ID	Name	Addressed objectives
16	Transformer loading	1
1	Level of losses in transmission and in distribution network	3
17	RES curtailment	2
7	Power losses	3

6.5.1.4 **Use case conditions**

Use case conditions
Assumptions
1. Flexible sources (DG, ESS, DSR) and RES are available and controllable by the DSO (for example through bilateral contracts with flexible sources operators and/or aggregators) 2. State of charge of EVs can be monitored 3. Necessary regulations and laws are enforced
Prerequisite
1. Detailed model for DSO grid and equivalent model for TSO grid 2. Forecast data for intermittent RES is available. Load and generation profiles (including forecasted profiles) and characteristics are available for each network bus 3. ESS state of charge is known

6.5.2 Technical details

6.5.2.1 **Systems and associated actors/tools**

Systems and associated actors/tools			
Group	System(s)	Actor(s)/tool(s)	Remarks
1	Transmission system	Transmission System Operator	-
2	Distribution system	Distribution System Operator	-
3	Generation: DG, RES, Synchronous generator	Owner/operator, Aggregator	-
6	Storage	Owner/operator	-
6	Electric Vehicles	Owner/operator	-
5	Controllable load	Aggregator	-
7	Generation: RES	Forecast units	-

7	Generation: DG, RES, Synchronous generator	Controllers	-
7	Controllable load	Controllers	-
7	Storage	Controllers	-
7	Electric Vehicles	Controllers	-

6.5.2.2 **Control variables**

Control variables	
Control Variable	Corresponding actor / tool
Output active power	DG, RES, ESS, EVs, controllable load, synchronous generators
State of charge	Storages, EVs

6.5.2.3 **Simulation environment:**

- DigSilent Powerfactory, Python

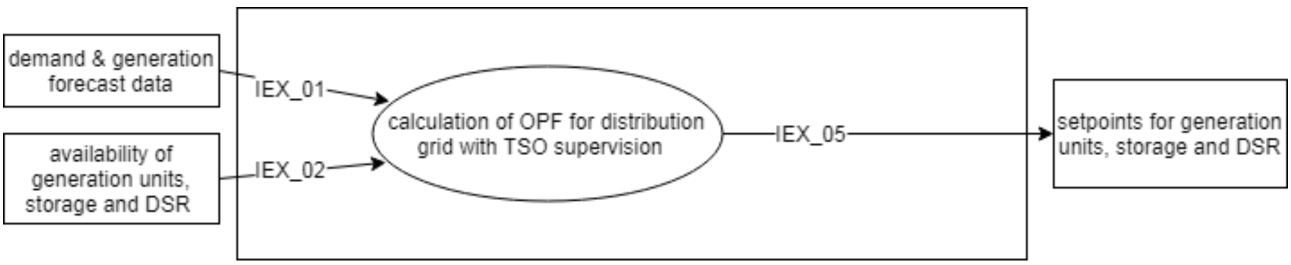
6.5.3 Sub-use cases

Sub-use cases	
Sub-use case number	Description
5.1	Base case - no controllers available
5.2	In this sub use case the 110 kV grid is considered to be a radial network
5.3	In this sub use case the 110 kV grid is considered to be a meshed network

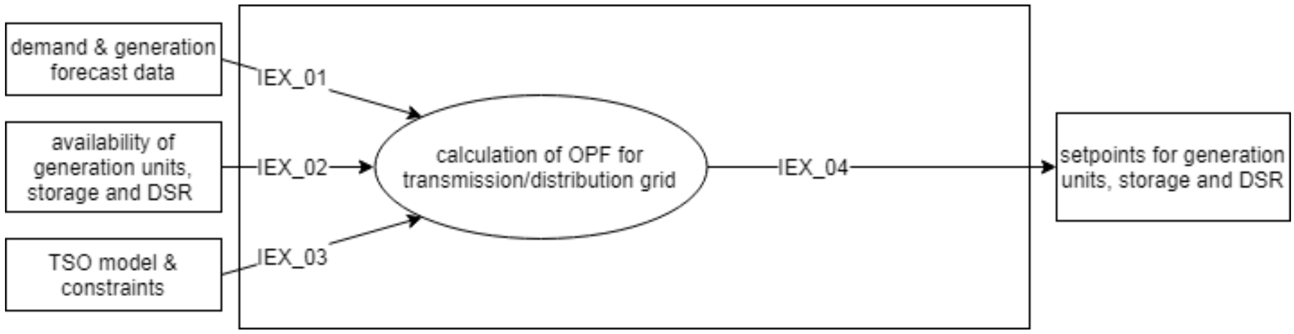
6.5.4 Diagrams of the use case

6.5.4.1 **Context diagram**

Sub-use case 5.2

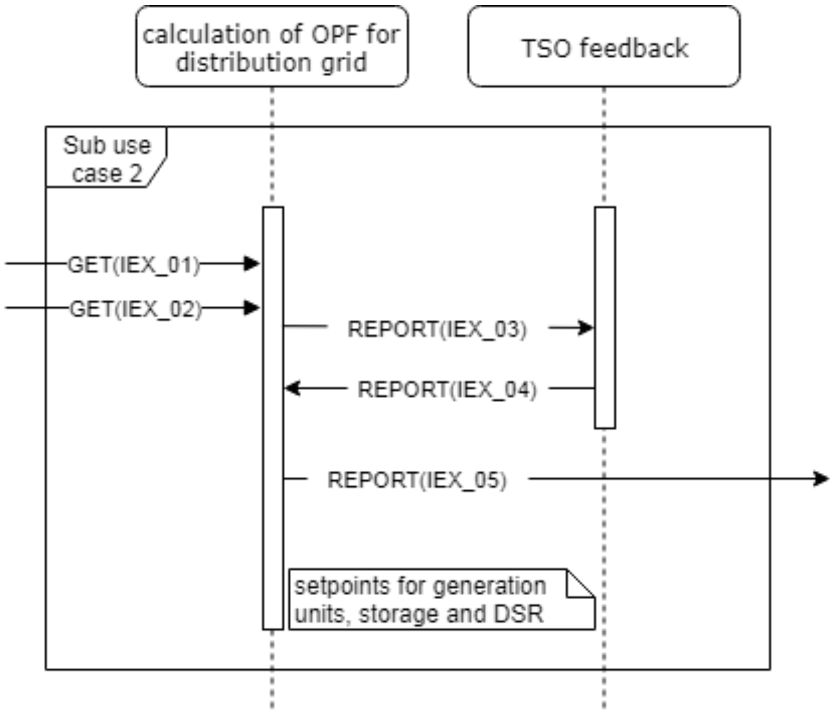


Sub-use case 5.3

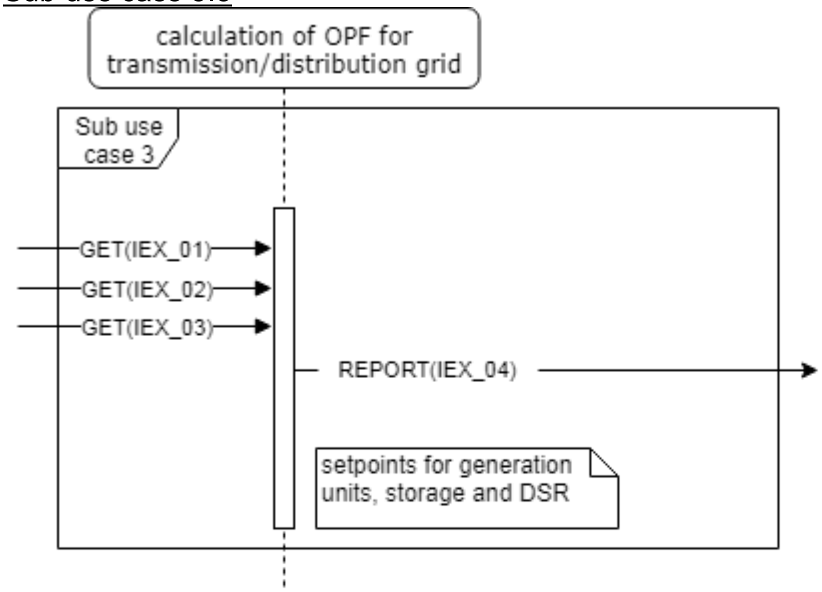


6.5.4.2 Sequence diagram

<u>Sub-use case 5.2</u>

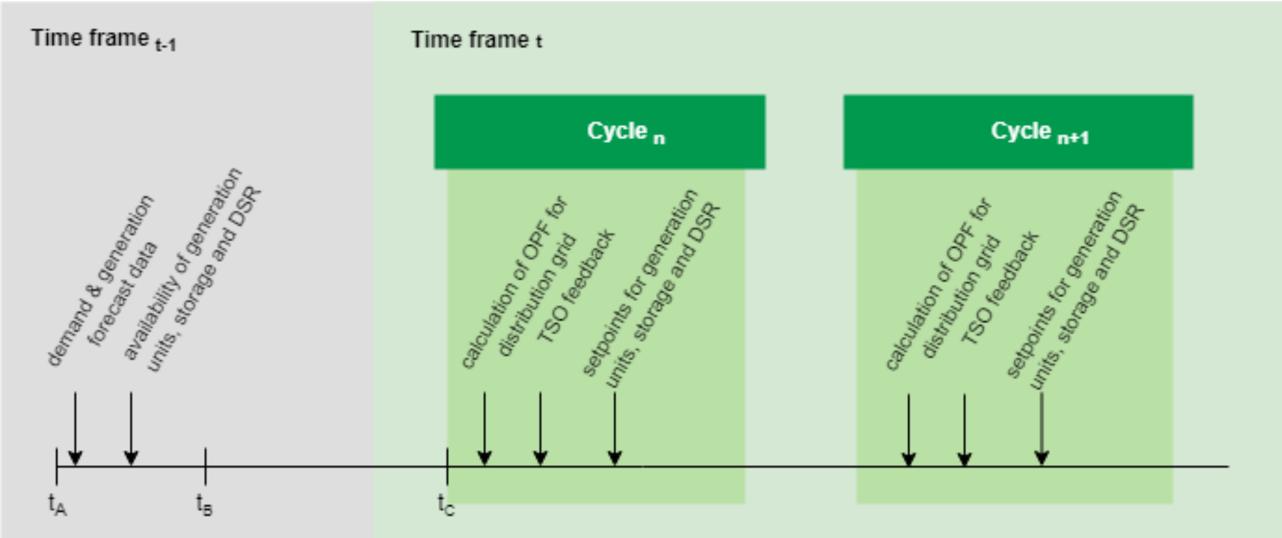


<u>Sub-use case 5.3</u>

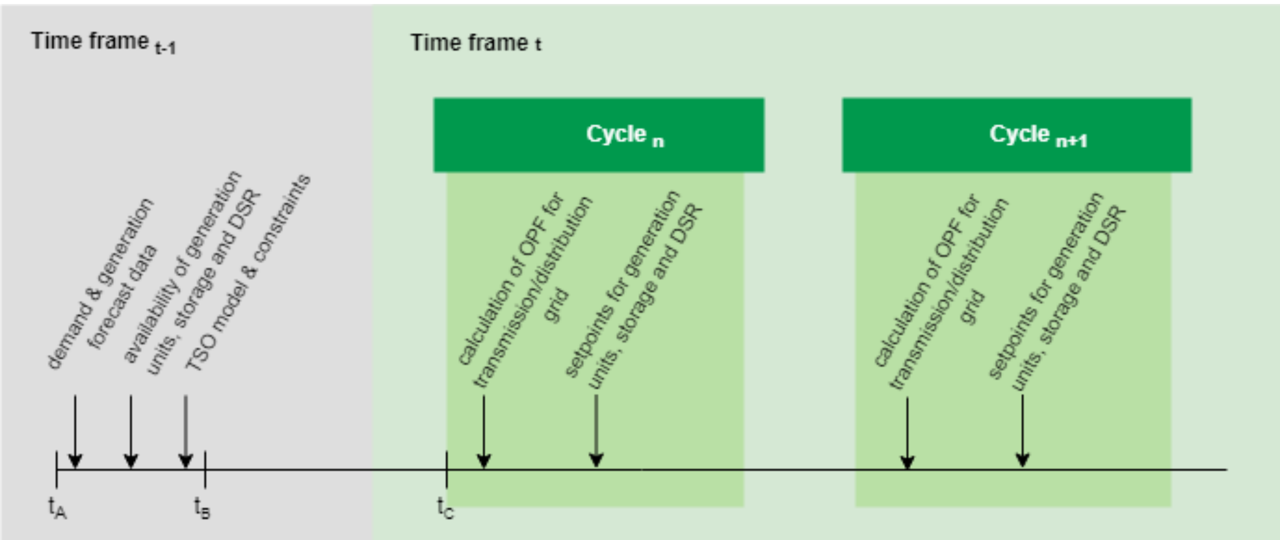


6.5.4.3 Timing diagram

Sub-use case 5.2



Sub-use case 5.3



6.5.5 Sequence of actions

Sequence of actions (based on sequence diagram) for sub use case number 5.2						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1	Demand & generation forecast data	Receiving demand & generation forecast data from specialised tools or services in a predefined format	Demand & generation forecast data	Forecast unit	OPF	IEX_01

2	Availability of generation units, storage and DSR	Receiving data on availability of generation units, storage and DSR	Availability of generation units, storage and DSR	Owner/ operator	OPF	IEX_02
3	Calculation of OPF for distribution grid	OPF for distribution grid is being calculated based on the received information about resources availability and informing TSO about the calculated balance of the distribution grid	Power flow at TSO/DSO interface	OPF	TSO	IEX_03
4	TSO confirmation	After receiving the information regarding the balance of the distribution grid the TSO is able to recalculate (if needed) the balancing needs for the whole grid under his supervision.	TSO answer	TSO	DSO	IEX_04
4	Calculation of OPF for distribution grid	Active power set points are sent to generation units, storage and DSR	Set points	DSO	Controllable generation units, storage, DSR	IEX_05

Sequence of actions (based on sequence diagram) for sub use case number 5.3						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1	Demand & generation forecast data	Receiving demand & generation forecast data from specialised tools or services in a predefined format	Demand & generation forecast data	Forecast units	OPF	IEX_01
2	Availability of generation units, storage and DSR	Receiving data on availability of generation units, storage and DSR	Availability of generation units, storage and DSR	Owner/ operator	OPF	IEX_02
3	TSO model & constraints	TSO enables a relevant part of the model of the transmission grid to the DSO for joint transmission-distribution grid OPF calculations (the two grids are coupled through the meshed structure of the 110	TSO model and constraints	TSO	DSO	IEX_03

		kV grid). Model equivalents can be used by the TSO where possible.				
4	Calculation of OPF for transmission/distribution grid	Calculation of OPF for transmission/distribution grid	Set points	DSO	Controllable generation units, storage, DSR	IEX_04

6.5.6 Other requirements (optional)

- In principle, in extreme cases, i.e. when the difference between the latest calculated value of the DSO grid balance and the grid balance planned beforehand (e.g. one day ahead, 48-hours ahead, etc.) is over certain agreed threshold, the TSO may require changes from the DSO in order make the DSO fulfil his obligations towards keeping balance as planned or may introduce the changes by himself in the resources operating in the transmission grid. The decision who will perform the change and which resources will be activated in this condition is subject to the proper statements to be introduced in the grid codes and/or regulations referring to its scope.

6.6 Use case 6: Inertia management

6.6.1 Description of the Use Case

6.6.1.1 Name of Use Case

Use case identification	
ID	Name
6	Inertia management

6.6.1.2 Goal, Objectives and Scope and of the use case

Goal, objectives and scope of use case	
Goal	The aim of this use case is to develop an approach for inertia management in systems with significant RES penetration resulting in low inertia.
Objectives	1. Limiting rate of change of frequency (RoCoF) and frequency max/min deviations 2. Maximizing DG/RES contribution to ancillary services 3. Maintaining frequency stability in reduced inertia systems
Scope	Inertia management in a power system where synthetic inertia and fast frequency response mechanisms are possible to utilize.

6.6.1.3 Narrative of Use Case

Narrative of the use case
Short description
With rising RES penetration, frequency stability issues appear and one of the main problems is decreasing system inertia. This use case addresses this issue and proposes a solution in the form of inertia management, where additional control (synthetic inertia and fast frequency response) is implemented.
Complete description
<u>Motivation and problem statement</u> Inertia is an inherent power system feature that opposes frequency deviations caused by power balance disturbance in a grid, and gives time for the primary control to start acting. In the past, inertia was not a concern, since rotating masses of synchronous generation were contributing to its high amount. However, as power systems evolve and synchronous units

are being replaced by converter connected RES, the problem arises since minimum system inertia in the system must be ensured for its secure and stable operation. In the future, this may lead to RES curtailments and mandatory operation of synchronous generation which might not be justified from market perspective. Solution Approach Introduction of new types of control to RES and storage systems as well as proper operation planning could minimize curtailments of converter interfaced units due to frequency stability issues and allow for maximizing share of this type of generation in power systems. Synthetic inertia allows converter connected generation to emulate inertial response of synchronous units through utilizing kinetic energy of wind turbines rotating masses and no curtailment is needed to provide frequency support. Fast frequency response (FFR) on the other hand, can either react proportionally to the deviation of frequency or inject power according to a pre-determined schedule (FFR approach can be used also for PV farms and storage systems). Addition of synthetic inertia and fast frequency control along with demand and weather forecasts as well as current system inertia estimation could be used for optimal inertia allocation with an objective to use renewable units' capabilities first.

6.6.1.4 **Key Performance Indicators**

Key performance indicators (KPIs)		
ID	Name	Addressed objectives
14	Level of DG / DRES utilization for ancillary services	2
20	Frequency nadir and zenith	1, 3
21	Rate of change of frequency	1, 3
25	Indication of stability	3
26	Oscillation damping	3

6.6.1.5 **Use case conditions**

Use case conditions
Assumptions
1. Synthetic inertia and fast frequency control are available 2. Necessary regulations and laws are enforced 3. Part of active power range from storage units can be used as ancillary service for frequency support 4. Appropriate amount of primary and secondary reserves are ensured 5. It is required (assumed) that the list of units that can provide synthetic or real inertia is available to the TSO and the selection methodology can be based on any of the following: bids for inertia service on ancillary services market, bilateral agreements, mandatory control mode enforced by the network codes to be optionally used by the TSO or other.
Prerequisite
1. Models of energy sources and storage enable simulation of emulation of inertia 2. Grid models for distribution and transmission levels are available 3. Forecast data for RES and demand is available

6.6.1.6 **General Remarks**

In this use case synthetic inertia and fast frequency control are used for the same purpose, i.e. limiting of RoCoF and, in turn, contributing to higher nadir. However, since the principle of the two control modes is different, also the results can be dissimilar and therefore two sub use cases are proposed to investigate the difference. From the perspective of sub use case description, these two

control modes are used interchangeably.

6.6.2 Technical details

6.6.2.1 Systems and associated actors/tools

Systems and associated actors/tools			
Group	System	Actor/tool	Remarks
1	Transmission systems	Transmission System Operator (TSO)	-
2	Distribution systems	Distribution System Operator (DSO)	-
3	DG, RES, Synchronous Generator	Owner/operator	-
6	Storage	Owner/operator	-
7	RES	Forecast units	-
7	DG, RES, Synchronous Generator, storage	Controllers	-

6.6.2.2 Control variables

Control variables	
Control Variable	Corresponding actor / tool
Active power	RES, DG, Synchronous Generator, Storage
State of charge	Storage

6.6.2.3 Simulation environment:

- DigSilent Powerfactory
- Python

6.6.3 Sub-use cases

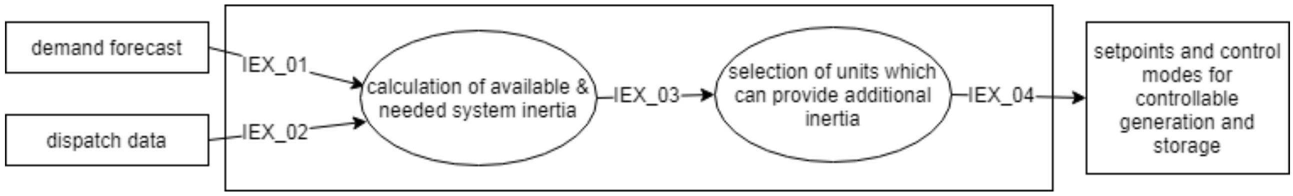
Sub-use cases	
Sub-use case number	Description
6.1	Base case - inertia only from spinning masses of generators
6.2	In this sub use case only synthetic inertia control is available
6.3	In this sub use case only fast frequency response is available
6.4	In this sub use case both synthetic inertia and fast frequency response are available

6.6.4 Diagrams of the use case

6.6.4.1 Context diagram

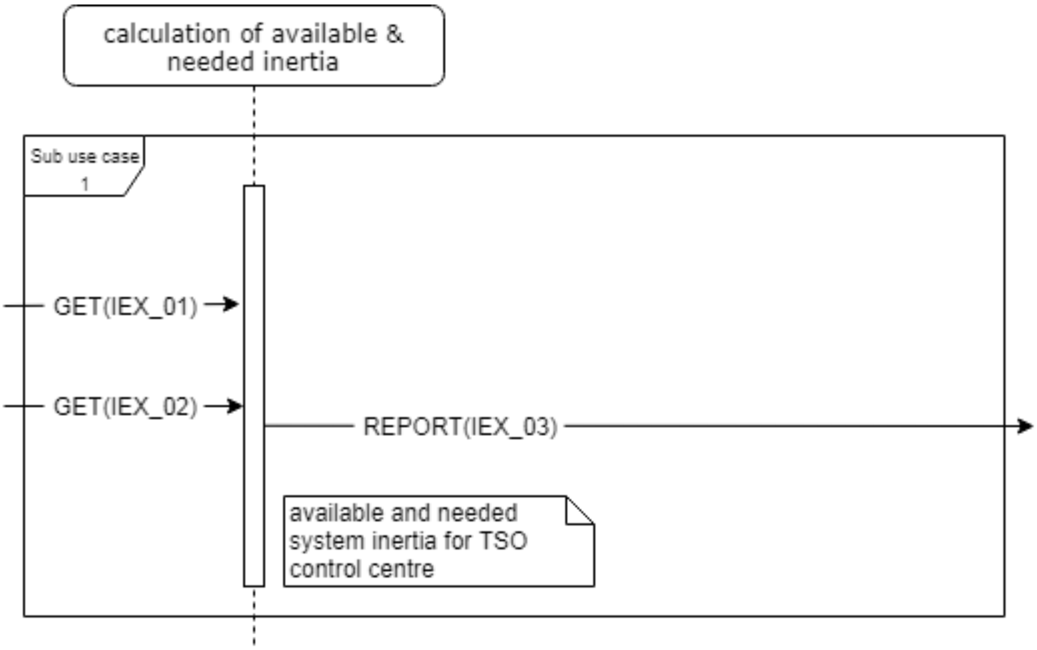
Sub-use case 6.1

Sub-use case 6.2, 6.3 and 6.4

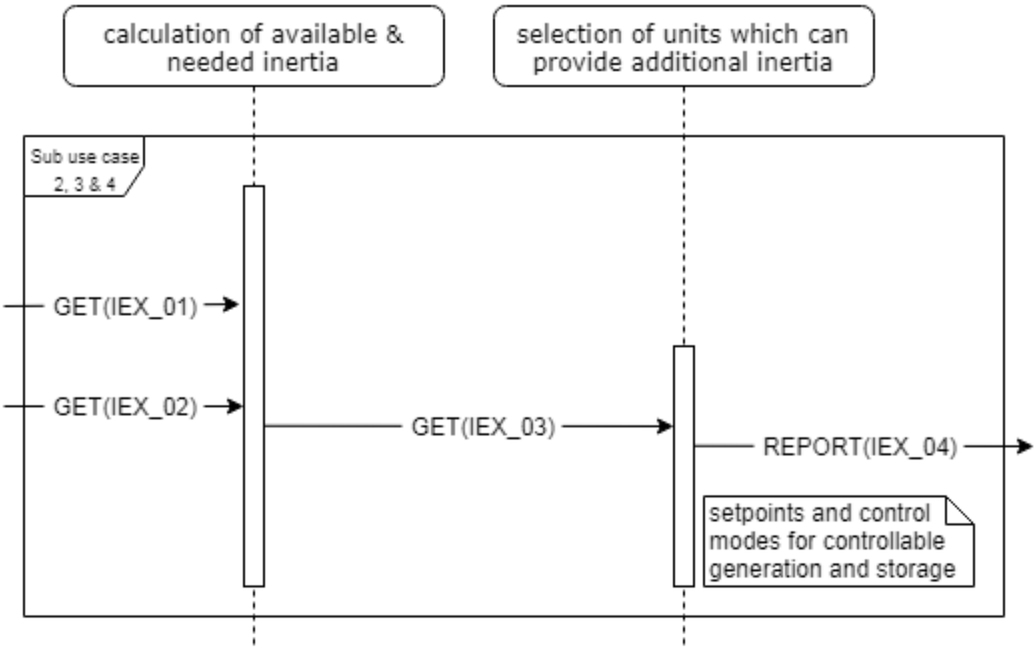


6.6.4.2 **Sequence diagram**

Sub-use case 6.1

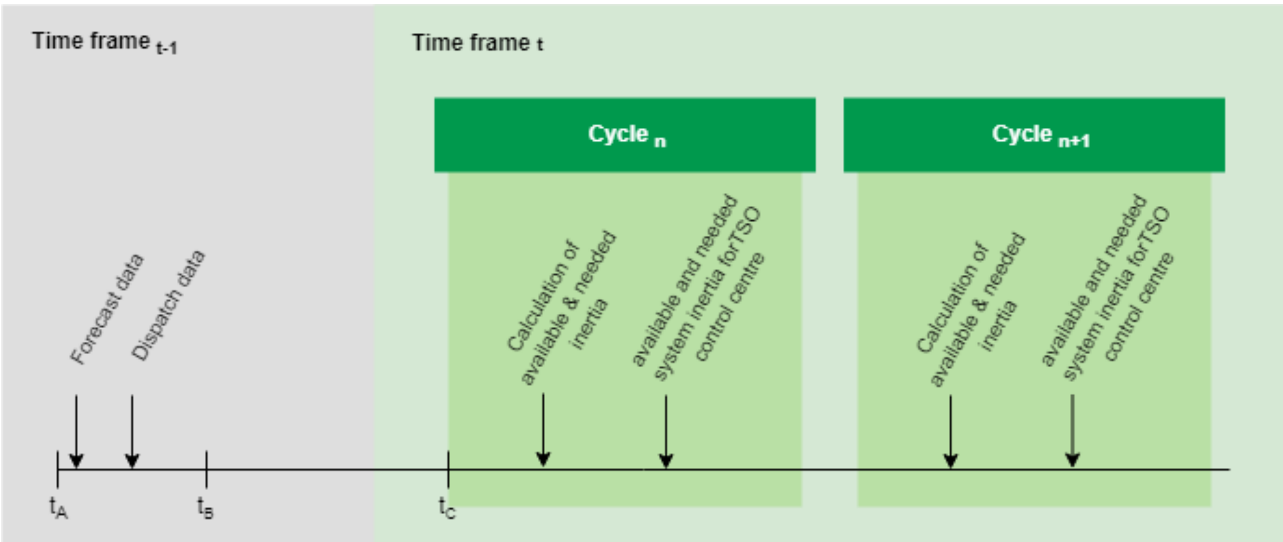


Sub-use case 6.2, 6.3 and 6.4

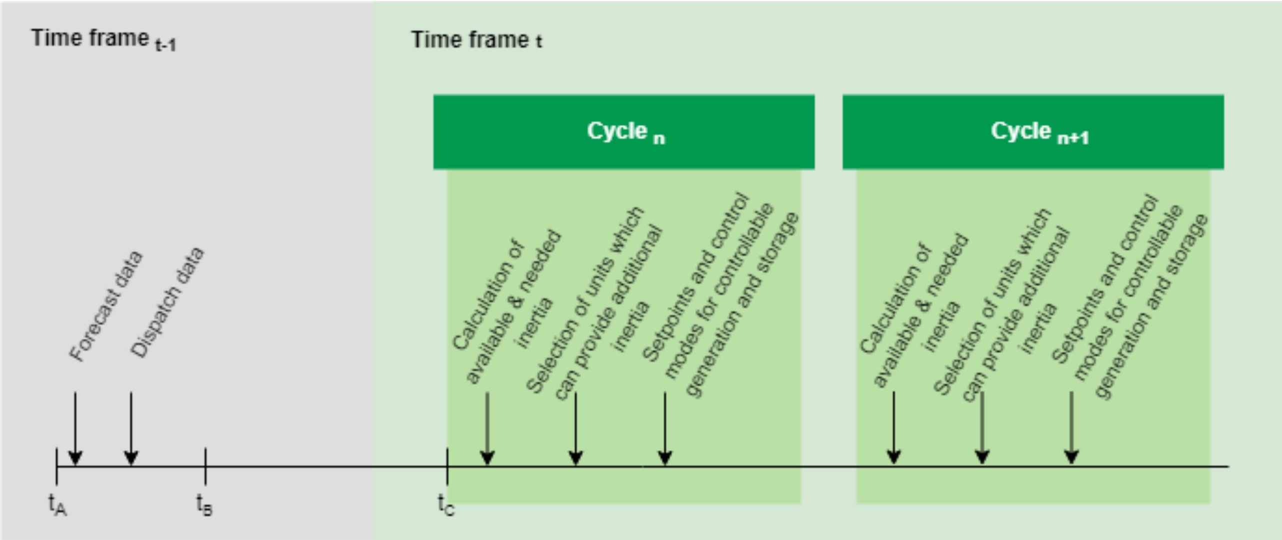


6.6.4.3 **Timing diagram**

<u>Sub-use case 6.1</u>



<u>Sub-use case 6.2, 6.3 and 6.4</u>



6.6.5 Sequence of actions

Sequence of actions (based on sequence diagram) for sub use case number 6.1						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1	Demand forecast	Receiving demand forecast	Demand forecast	Forecasting unit	TSO	IEX_01
2	Dispatch data	Receiving dispatch data including status and generation schedule of generating units, HVDC links and storage as well as their constraints regarding active power generation/transfer/consumption	Dispatch data	Owner/operator	TSO	IEX_02
3	Calculation of available & needed inertia	TSO calculates necessary system inertia based on the largest infeed or load and assumed criteria regarding RoCoF. Then it is compared to the inertia available from the scheduled generation.	Value of system inertia (for information purposes only)	TSO	TSO	IEX_03

Sequence of actions for sub use cases 6.2, 6.3 and 6.4 are the same. The only difference is in available controllers to which control modes are sent: synthetic inertia for sub use case 6.2, fast frequency response for sub use case 6.3 and both for sub use case 6.4.

Sequence of actions (based on sequence diagram) for sub use case number 6.2, 6.3 & 6.4						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information	Information receiver	Information Exchanged

				producer (Actor/tool)	(Actor/tool)	IDs
1	Demand forecast	Receiving demand forecast	Demand forecast	Forecasting unit	TSO	IEX_01
2	Dispatch data	Receiving dispatch data including status and generation schedule of generating units, HVDC links and storage as well as their constraints regarding active power generation/transfer/consumption	Dispatch data	Owner/operator	TSO	IEX_02
3	Calculation of available & needed inertia	TSO calculates available and necessary system inertia using dispatch data and forecasted load. Based on the largest infeed or load and assumed criteria regarding RoCoF. Then it is compared to the inertia available from the scheduled generation. If the necessary inertia is higher than the available one then the process of identification of additional inertia resources is initiated.	Value of system inertia	TSO	TSO	IEX_03
4	Selection of units which can provide additional inertia	Units which will be used to provide additional inertia for the system are selected from the list of units that can provide this service. The TSO will optimise the process of selection of the units so that no surplus inertia is in operation.	Signal for activation of inertia control mode (SI, FFR or both) and respective set points for this control mode if necessary	TSO	Controllable units	IEX_04

6.7 Use case 7: Optimal generation scheduling and sizing of DER for energy interruption management

6.7.1 Description of the Use Case

6.7.1.1 Name of Use Case

Use case identification

ID	Name
7	Optimal generation scheduling and sizing of DER for energy interruption management

Goal, Objectives and Scope and of the use case

Goal, objectives and scope of use case	
Goal	Securing the continuity of supply to improve system reliability and minimizing energy interruptions for a given set of contingencies while maximizing the share of RES in the network.
Objectives	1. Minimizing the energy interrupted during a contingency event 2. Minimize the energy losses in the network 3. Minimize the costs of energy interruptions and energy losses 4. Maximize the share of RES 5. Increasing the network hosting capacity 6. Load shedding scheduling to maximize the reliability of the network
Scope	Scheduling of generation and interruptible loads when an unplanned contingency occurs in the network with the aim of minimizing the total energy interrupted.

6.7.1.2 **Narrative of Use Case**

Narrative of the use case
Short description
This use case is about TSO and/or DSO using a tool to mitigate energy interruption problems at both transmission and/or distribution levels. Under the operation planning phase, the tool evaluates the suitable flexibility in terms of energy interruption and perform optimal generation scheduling in order to re-dispatch the related active power flows for minimizing the energy interruptions in the presence of contingencies. The emphasis here is on the line outages. This tool aims to minimize energy interruptions, securing the continuity of supply and reducing the costs of service interruptions. This use case acts both on DSO and TSO levels, by operating on the available controllable resources (e.g. load shedding, DG, etc.) and performs the power flow re-dispatch as a grid operation task. One of the sub task is also to identify the hosting capacity for a given location of DGs in the network and related it to energy interrupted after a contingency
Complete description
<u>Motivation and problem statement</u> The increasing share of DG in the transmission and distribution rids have recently introduced number of challenges. The planning of the electric system with the presence of DGs requires the definition of several factors, such as: the technology in use, the number and the capacity of the units, the optimal locations, the type of network connection, etc. The impact of DG in system operation characteristics such as electric losses, voltage profile, stability and reliability needs to be appropriately evaluated. Due to distributed nature of generation there is a need of studies that explores the energy interruptions when an unplanned contingency occurs in the grid. DG units can have a positive impact on distribution system reliability if they are correctly coordinated with the rest of the network. DG can also operate as a generation backup, in which the unit operates in the case of main supply interruption. <u>Solution Approach</u> The solution approach is formulated as sub-use cases. Following steps are take in order to prepare the base case. • The load flow sensitivity analysis is performed on the given network to identify the contingency list. • The interruptible loads are defined by the network operator. • Location and sizing of DG is according to normal network operation.

Sub-Use Case 7.1

Objective
The objective of sub-use case is to minimize the total energy interrupted by optimally dispatching the generators and interruptible loads. The location and sizing of the DGs is the input of this sub-use case and is fixed.

Hypotheses:

- Optimal dispatch is the revised schedule for the generators that is optimal regarding energy interruption minimization;
- Contingency analysis will be considered for each point in time for a given load and generation in the network. Contingencies are defined based on 'safety net' minimum reliability standard of N-1 “The Grid shall continue to operate in the Normal State following the loss of one Generating Unit, transmission line, or transformer”. The focus of the use-case is explicitly on the line contingencies.
- Load shedding flexibility is defined by relevant TSO/DSO after performing reliability calculations in the post contingency state of the network.
- The location of DG is pre-specified and hosting capacity acts like a constraint of the generation schedule.
- Load shedding and generation re-dispatch are used as control variables to minimize the energy interruption.

The optimization problem minimizes the following objective function.

Objective Function:

For each contingency c, where $c = 1 \cdots C$

$$\text{Min } f_1 = \sum_{c=1}^{C} \sum_{i=1}^{N} LPENS_i \ ,$$

$$\text{such that } A_i \leq P_{L_i} \leq B_i \ \text{ and } \ P_{DG_i} = HC_i \ ,$$

while the power balance constraint formulated as,

$$\sum_{i=1}^{G} P_{DG_i} = P_D + P_{Loss} \ .$$

$LPENS_i$ =Load point energy not supplied, it is the function of power curtailed for i^{th} load

N = Total number of controllable loads in the network

G = Total number of DGs in the network.

P_D = Total demand in the network

P_{Loss} = Total losses in the network

A_i, B_i = Minimum and maximum load that can be shed

HC_i = Hosting capacity

P_{DG_i} = Power output of the DG

Sub Use Case 7.2

Objective:

The objective of sub-use case is to minimize the total energy interrupted and energy loss by optimally dispatching the generators and interruptible loads. The location and sizing of the RES is the

input of this sub-use case and is fixed.
This use case adds an objective function of loss minimization to the sub use case 7.1.

Objective Function

$$\text{Min } f_1 = \sum_{i=1}^{N} LPENS_i + P_{Loss}$$

Sub Use Case 7.3

Objective:

This sub-use case performs scenario based studies for different distribution of nominal power infeed from DGs in the network corresponding to same hosting capacity. It identifies the distribution that results in minimum energy interrupted for a contingency event.

Hypotheses:

- Hosting capacity here refers to the maximum share of renewable energy that can be integrated in the network for a given range of locations and distribution of DG.
- Study leads to optimal sizing of DGs.

The sub-use case 3 encapsulates the sub-use cases 7.1 and 7.2 by providing an additional level of flexibility in terms of nominal power a DG can infeed in the network.

Sub Use Case 7.4

Objective:

Perform energy interruption minimization as state in sub-use cases 1 and 2 while varying the load shedding strategies in order to find a good strategy that minimizes the energy interrupted for a range contingency events.

Hypotheses:

- Load shedding scheduling strategy defines the loads that can be turned off if generation is not sufficient.
- It defines the boundary conditions for the controllable loads and identifies the influence of load shedding strategies on the interruption management

Key performance indicators (KPIs)		
ID	Name	Addressed objectives
3	SAIDI (System Average Interruption Duration Index)	1,5
18	SAIFI (System Average Interruption Frequency Index)	1,5
7	Energy losses	2
8	AENS & ENS (Average Energy Not Supplied) &(Energy not Supplied)	1,5
9	IEAR (Interrupted Energy Assessment Rate)	1,5
28	Share of RES	4
4	Costs of service interruption	3

6.7.1.3 Use case conditions

Use case conditions
Assumptions

1. Availability of controllable active power devices in the grid model in the form of generators 2. The load shedding strategy is pre-defined by the system operator. 3. The locations of DGs are pre-defined
Prerequisite
1. A model of the grid is available both at TSO and DSO level 2. Exemplary load and generation profiles (including forecasted profiles) and characteristics are available for each bus 3. Reliability models of grid components including DGs are available 4. Load shedding information (shedding steps, number of customers, priority….) are available

6.7.2 Technical details

6.7.2.1 Systems and associated actors/tools

Systems and associated actors/tools			
Group	System(s)	Actor(s)/tool(s)	Remarks
1	Transmission System	Transmission System Operator (TSO)	Controlling the resources connected to the transmission grid
1	Distribution system	Distribution System Operator (DSO)	Controlling the resources connected to the distribution grid
4	Controllable load, DGs	Prosumer	Contribute to minimize energy interruptions
2	Synchronous generator	Traditional generators	Contribute to minimize energy interruptions
3	Flexible Loads	Consumer	Contribute to minimize energy interruptions
5, 6	Generation and load	Forecast unit	-

6.7.2.2 Control variables

Control variables	
Control Variable	Corresponding actor / tool
Output active power	Synchronous generators, DG, RES, controllable loads

6.7.2.3 Simulation environment:

- DigSilent Powerfactory
- Python

6.7.3 Sub-use cases

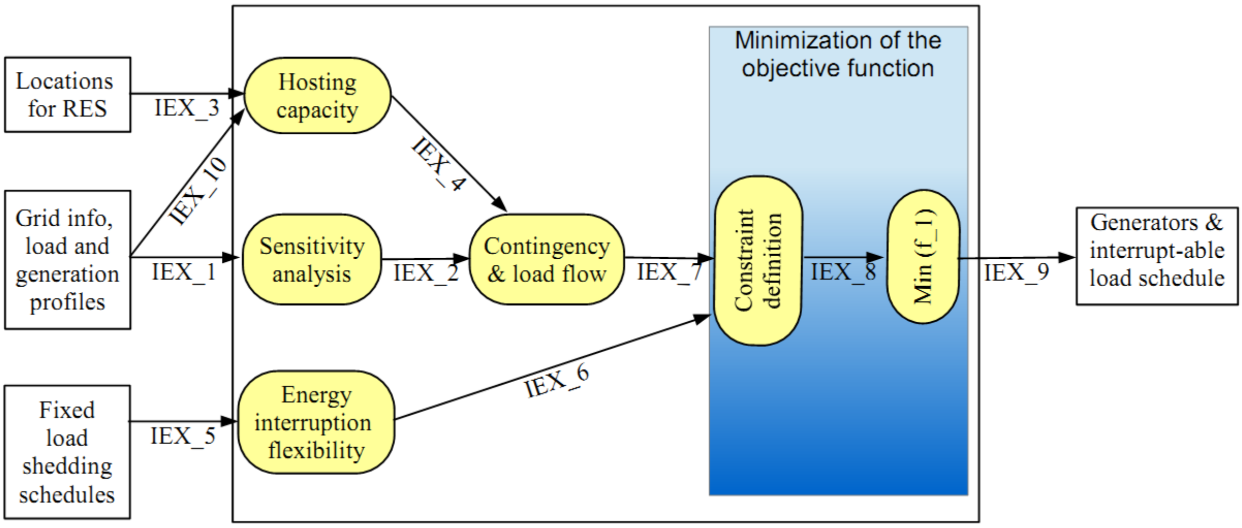
Sub-use cases	
Sub-use case number	Description
7.1	In this sub-use case, the tool is aimed to perform optimal interruption management to minimize the total energy interrupted in a contingency scenario. The flexibility provided by the interruptible loads and redispatch of generation is used to achieve this objective.
7.2	This sub-use case extends the use case 7.1 by introducing an additional objective of minimization of losses.
7.3	The sub-use case 7.3 encapsulates the sub-use cases 7.1 and 7.2 by providing an

	additional level of flexibility in terms of nominal power a DG can infeed in the network.
7.4	The sub-use case 7.4 aims to identify the best load shedding strategy among a set of possibilities that leads to minimum energy interrupted considering all the contingencies.

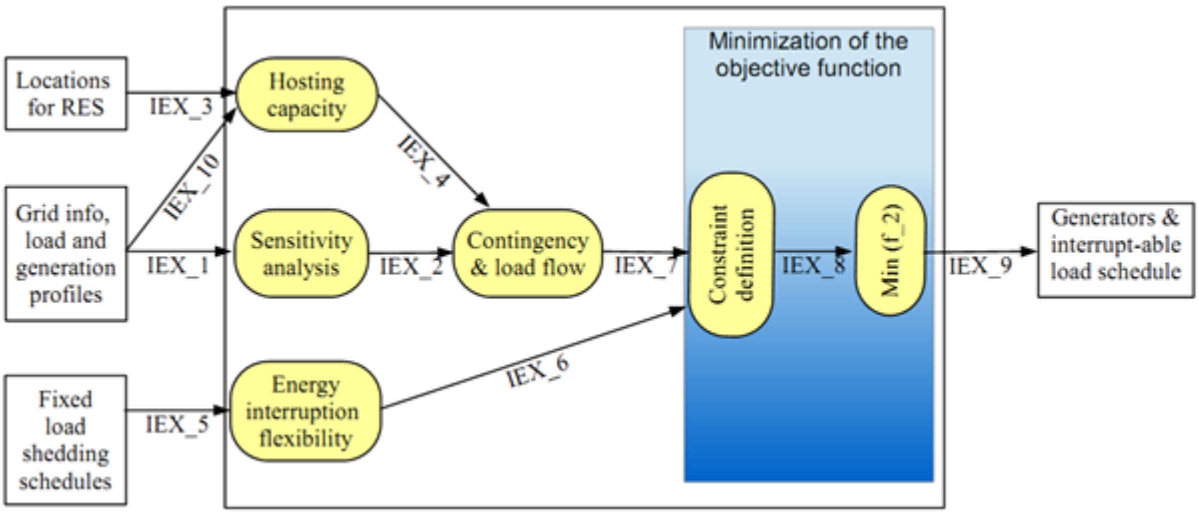
6.7.4 Diagrams of the use case

6.7.4.1 Context diagram

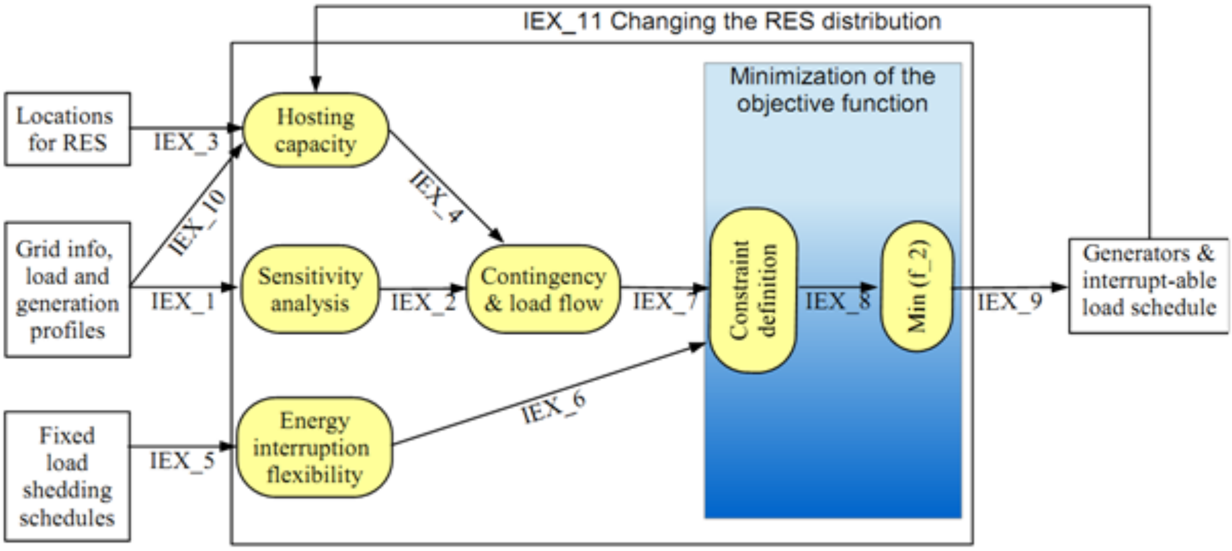
Sub-use case 7.1



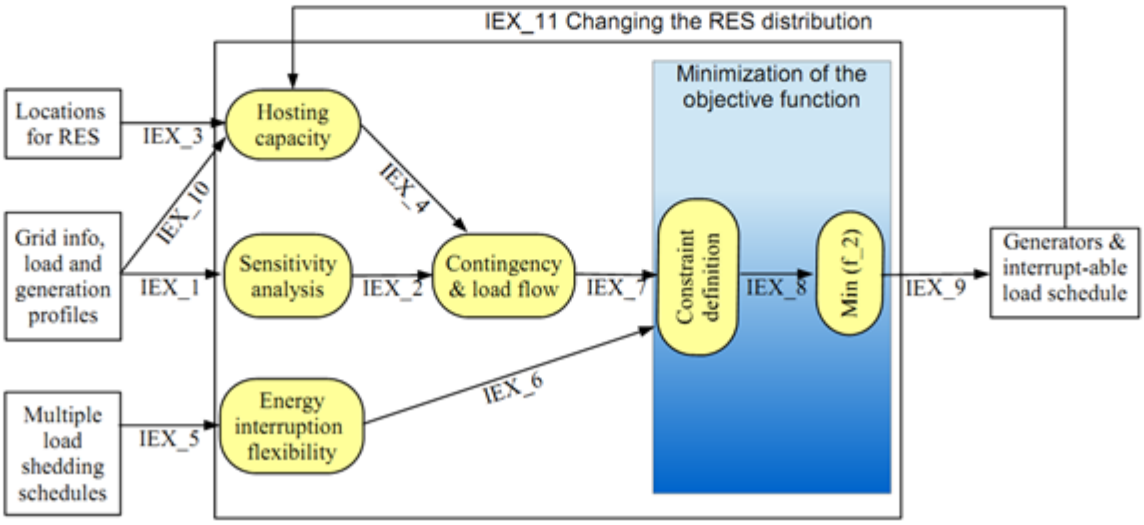
Sub-use case 7.2



Sub-use case 7.3

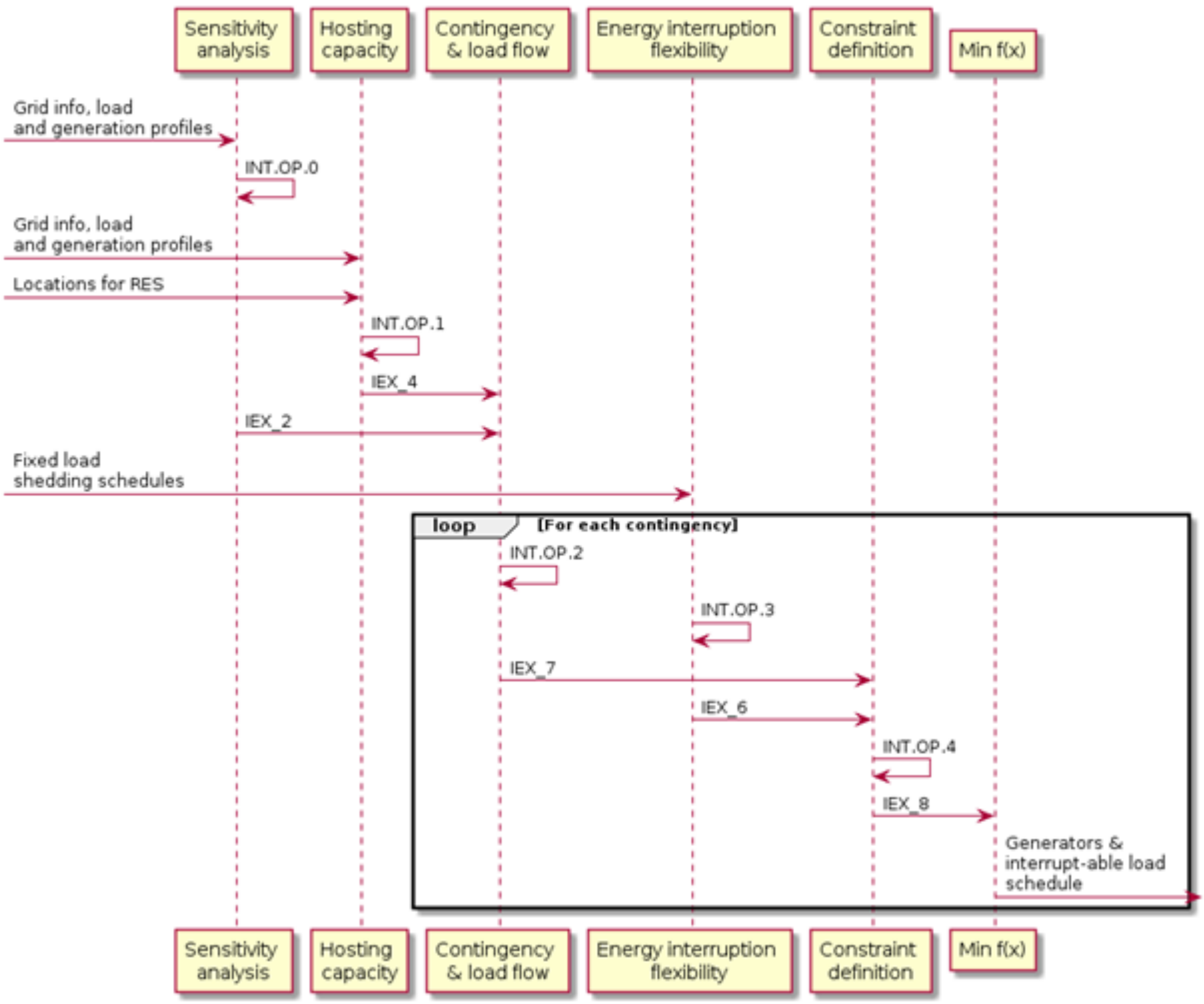


Sub-use case 7.4



6.7.4.2 Sequence diagram

Sub-use case 7.1 and Sub-use case 7.2



Operations definition:

INT.OP.0 = Based on the grid information, load and generation profiles, sensitivity analysis is performed. This identifies the lines that are most susceptible to loading. We can then identify the critical contingencies accordingly.

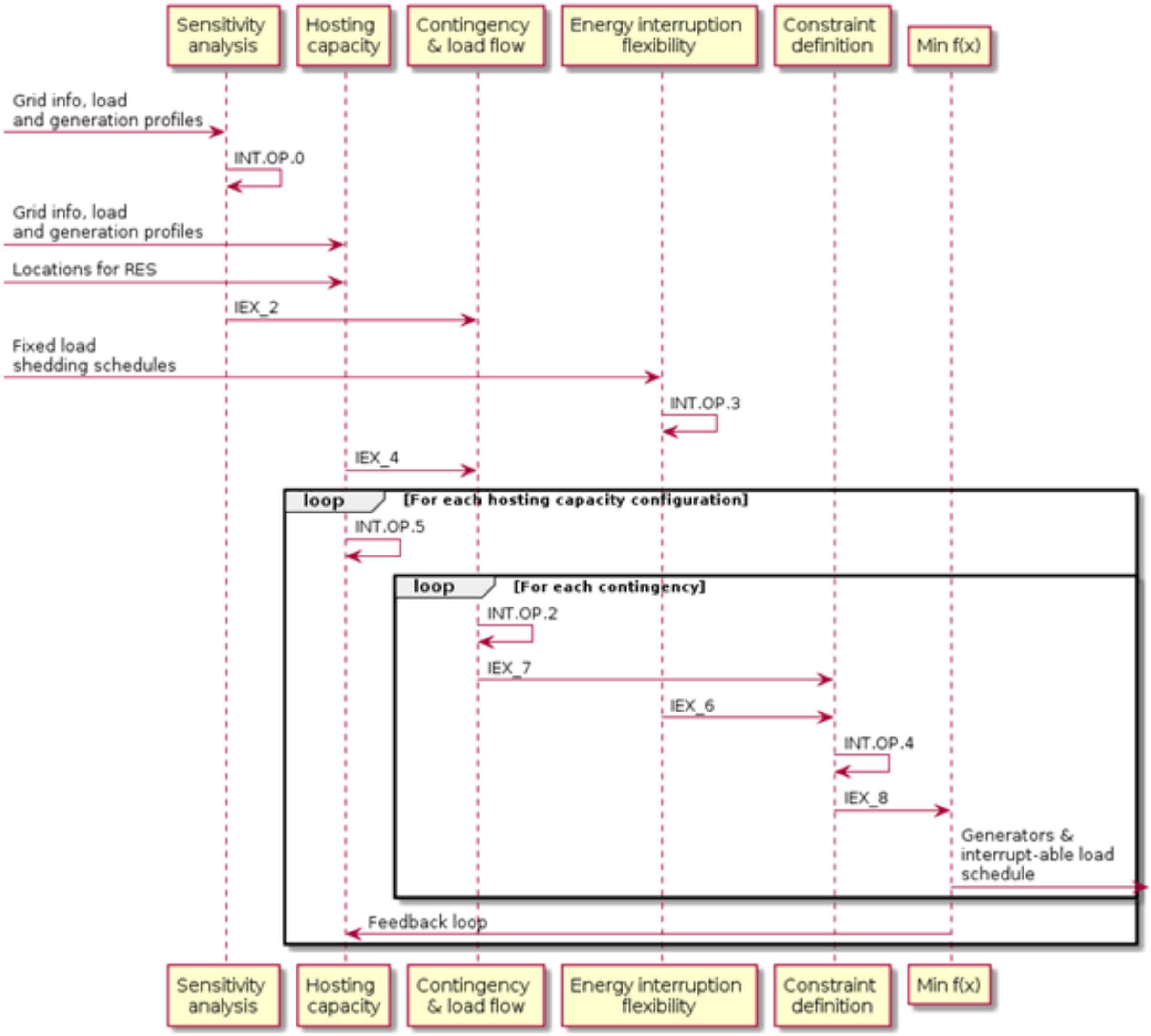
INT.OP.1 = The grid information and the location of RES in the network is used to run load flow-based analysis to identify the maximum share of RES that can be placed at the given locations. Repeated load flows are used to identify the hosting capacity.

INT.OP.2 = The peak level of RES is used to configure the network and the contingency is activated in the network. The load flow is performed, and result is communicated to the next stage.

INT.OP.3 = The load shedding schedules are defined as the back-up measure. The energy interruption flexibility transforms it as constraints in the PowerFactory.

INT.OP.4 = The matrix of constraints is formulated.

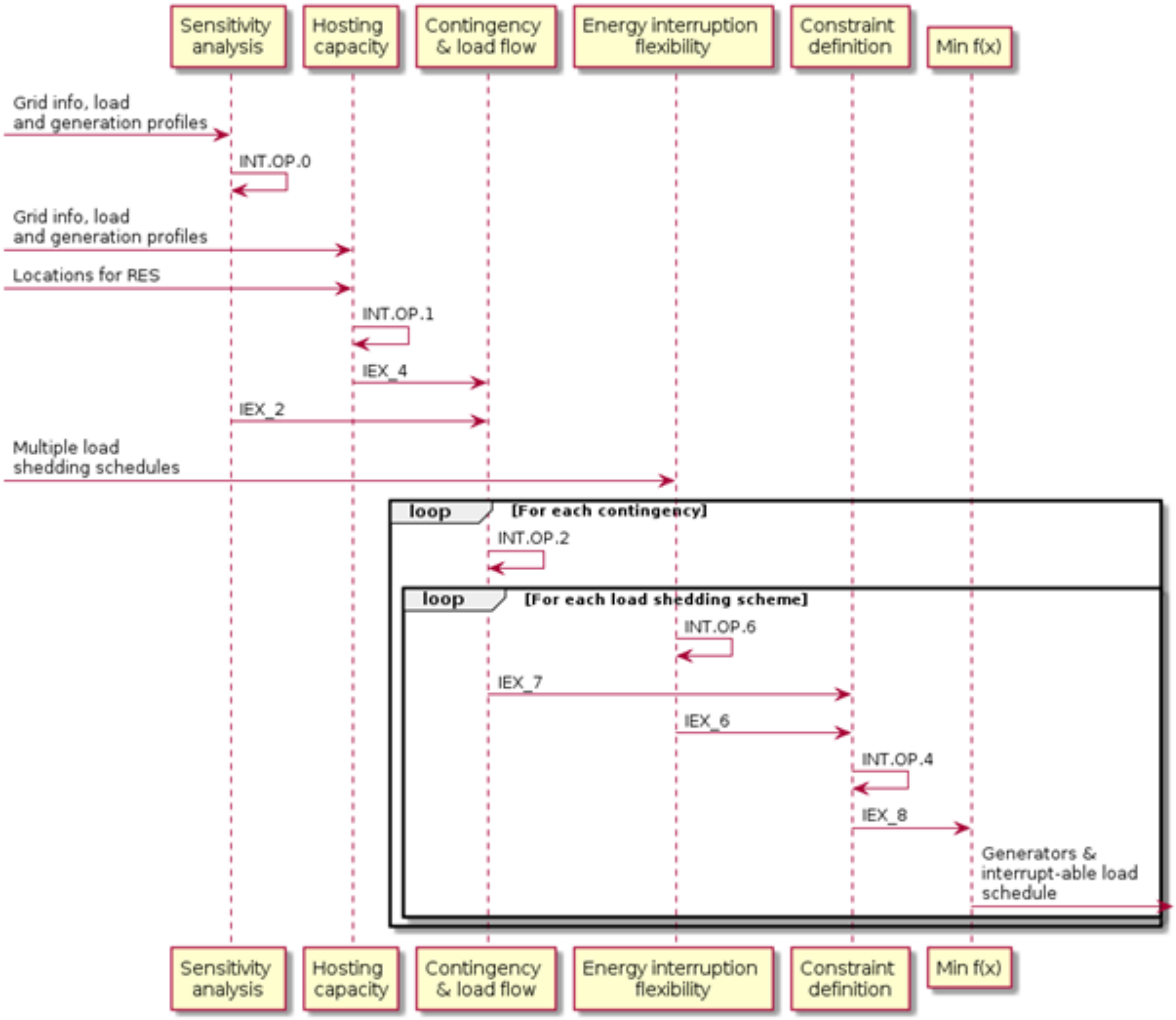
Sub-use case 7.3



Operations definition:

INT.OP.5 = The hosting capacity is updated by varying the distribution of the RES generation, for instance uniform, towards the feeder and end of the feeder. Each scenario gives a new set of operating points for RES at which the optimization of energy interruptions are performed.

Sub-use case 7.4

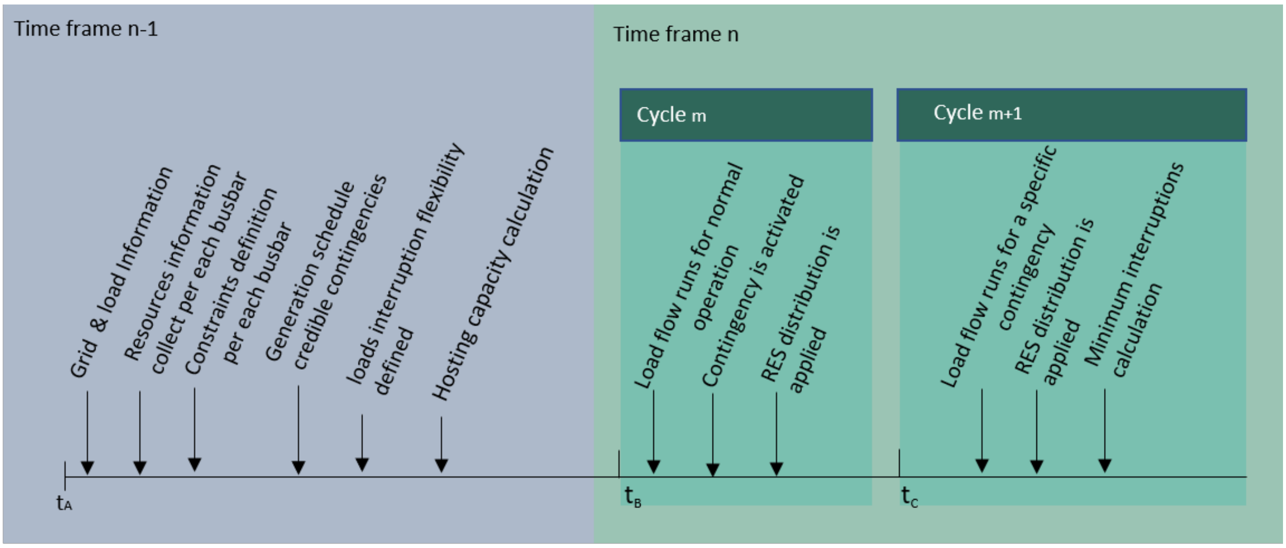


<u>Operations definition:</u>

INT.OP.6 = Several load shedding schemes can be defined by the TSO/DSO and the effectiveness of each is evaluated in a loop.

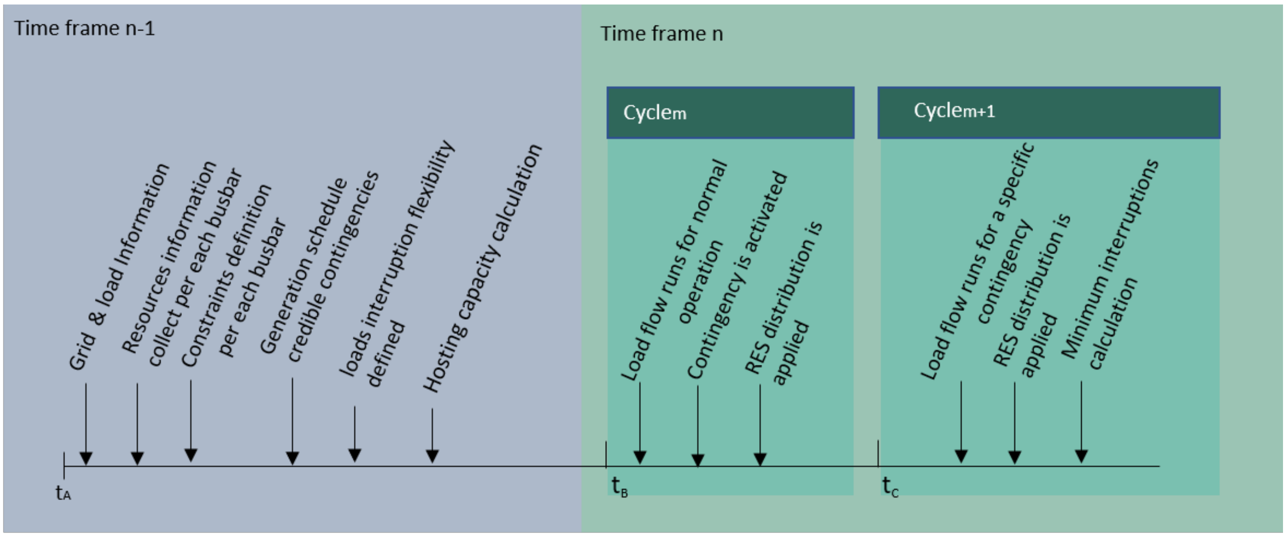
6.7.4.3 **Timing diagram**

<u>Sub-use case 7.1:</u>



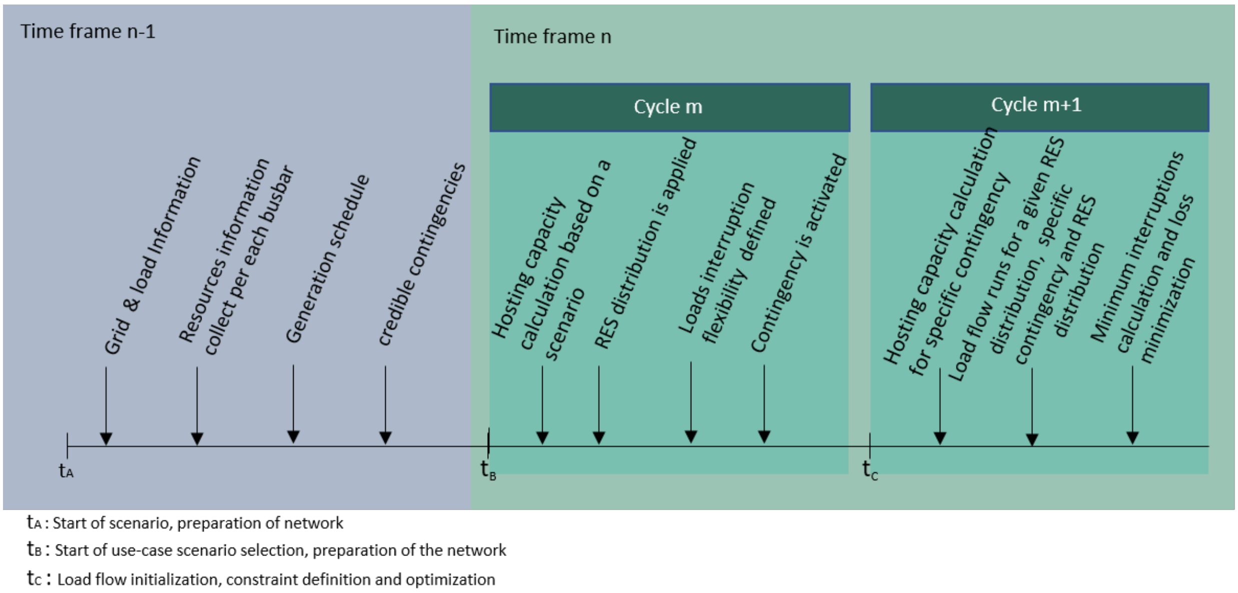
tA : Start of scenario, preparation of network
tB : Start of use-case scenario selection, preparation of the network
tC : Load flow initialization, constraint definition and optimization

<u>Sub-use case 7.2:</u>

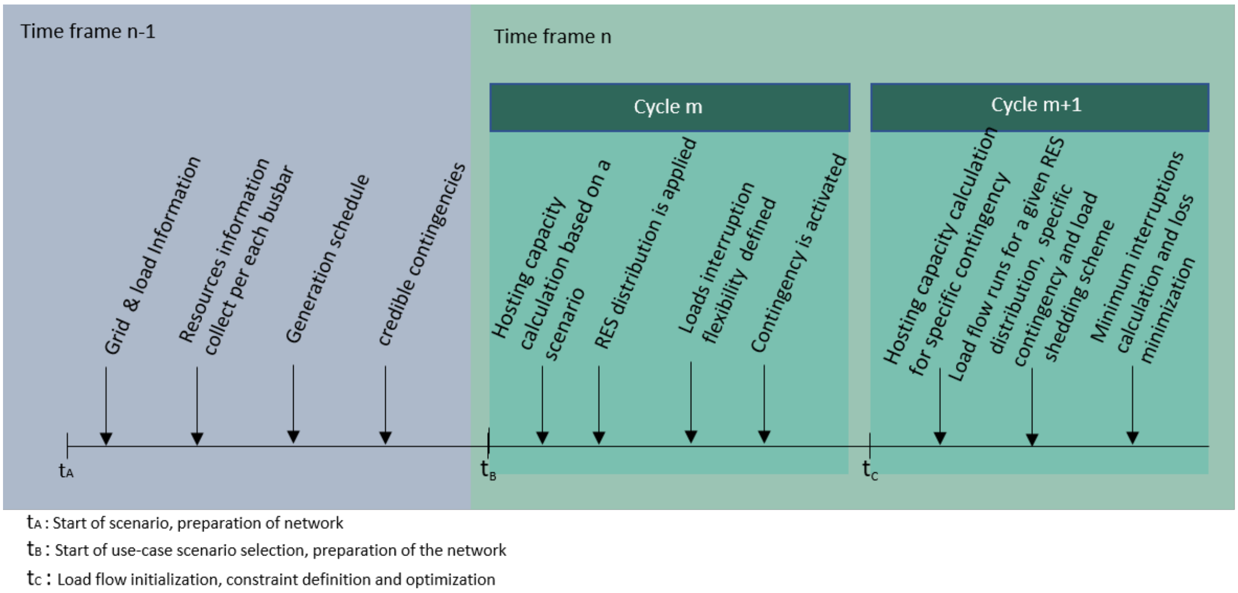


tA : Start of scenario, preparation of network
tB : Start of use-case scenario selection, preparation of the network
tC : Load flow initialization, constraint definition and optimization

<u>Sub-use case 7.3:</u>



Sub-use case 7.4:



6.7.5 Sequence of actions

Sequence of actions (based on sequence diagram) for sub use case number 7.1 and 7.2						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Infor-mation producer (Ac-tor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs

1	Load flow calculation	This first step is necessary to collect all power (Pmin, Pmax, Power reserves, etc) information per each resource in the grid	(Pmin, Pmax, Power reserves, etc) information per each resource in the grid	TSO/DSO providing grid information, loadn and generation profiles	Grid simulation tool	IEX_1, IEX_10
2	Load Flow Sensitivities	The LFS is performed to calculate the sensitivities coefficients for each line	Sensitivity coefficients per each line	Grid simulation tool	Contingency and load flow	IEX_2
3	Hosting capacity	This function calculates the maximum level of RES that can be integrated at the given locations in the grid	Maximum level of RES that can be integrated at the given locations in the grid	TSO/DSO load flow informationand location of DGs	Grid simulation tool	IEX_3, IEX_4
4	Energy interruption flexibility	Here, the loads interruption flexibility is defined in terms of the level and related cost	Interruption flexibility in terms of the level and related cost	Fixed load shedding schedule by TSO/DSO	Grid simulation tool (optimization)	IEX_5, IEX_6
5	Constraint definition	Based on the “contingency and load flow” and “energy interruption flexibility”, the constraints for the optimization problem are defined	Constraints for the optimization problem	Grid simulation tool (Constraints definition function)	Optimizer	IEX_6, IEX_7, IEX_8
6	Minimization of the objective function	This minimizes the objective function defined in the Solution Approach for Sub Use Case 1 and 2	Perform deterministic optimization	Minimization of the objective function for Sub Use Case 7.1 and 7.2	Grid simulation tool	IEX_8, IEX_9

7	generation dispatch and interruptable load schedule	New state of the system is achieved based on the dispatch schedule of the controllable DGs and interruptable loads in order to handle the contingency event.	new set of distribution schedule	Grid simulation tool	TSO/DSO	IEX_9

Sequence of actions (based on sequence diagram) for sub use case number 7.3						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs
1	Load flow calculation	This first step is necessary to collect all power (Pmin, Pmax, Power reserves, etc) information per each resource in the grid	(Pmin, Pmax, Power reserves, etc) information per each resource in the grid	TSO/DSO providing grid information, loadn and generation profiles	Grid simulation tool	IEX_1, IEX_10
2	Load Flow Sensitivities	The LFS is performed to calculate the sensitivities coefficients for each line	Sensitivity coefficients per each line	Grid simulation tool	Contingency and load flow	IEX_2
3	Hosting capacity	This function calculates the maximum level of RES that can be integrated at the given locations in the grid	Maximum level of RES that can be integrated at the given locations in the grid	TSO/DSO load flow informationand location of DGs	Grid simulation tool	IEX_3, IEX_4
4	Energy interruption flexibility	Here, the loads interruption flexibility is defined in terms of the level and related cost	Interruption flexibility in terms of the level and related cost	Fixed load shedding schedule by TSO/DSO	Grid simulation tool (optimization)	IEX_5, IEX_6
5	Constraint definition	Based on the “contingency and load flow” and “energy interruption flexibility”, the constraints	Constraints for the optimization problem	Grid simulation tool (Constraints	Optimizer	IEX_6, IEX_7, IEX_8

		for the optimization problem are defined		definition function)		
6	Minimization of the objective function	This minimizes the objective function defined in the Solution Approach for Sub Use Case 1 and 2	Perform deterministic optimization	Minimization of the objective function for Sub Use Case 7.1 and 7.2	Grid simulation tool	IEX_8, IEX_9
7	generation dispatch and interruptable load schedule	New state of the system is achieved based on the dispatch schedule of the controllable DGs and interruptable loads in order to handle the contingency event.	new set of distribution schedule	Grid simulation tool	TSO/DSO	IEX_9
8	Changing of the DG nominal power distribution	Varying the distribution of the DG nominal power for a given hosting capacity	Nominal power of generators as a boundary condition	Grid simulation tool output	Grid simulation tool (hosting capacity calculation)	IEX_11
9	Generation dispatch and interruptible load schedule	New state of the system is achieved based on the dispatch schedule of the controllable DGs and interruptible loads in order to handle the contingency event.	New set of distribution schedule	Grid simulation tool	TSO/DSO	IEX_9

Sequence of actions (based on sequence diagram) for sub use case number 7.4						
Step no.	Event name	Event description	Information Exchange (if any)			
			Content	Information producer (Actor/tool)	Information receiver (Actor/tool)	Information Exchanged IDs

1	Load flow calculation	This first step is necessary to collect all power (Pmin, Pmax, Power reserves, etc) information per each resource in the grid	(Pmin, Pmax, Power reserves, etc) information per each resource in the grid	TSO/DSO providing grid information, loadn and generation profiles	Grid simulation tool	IEX_1, IEX_10
2	Load Flow Sensitivities	The LFS is performed to calculate the sensitivities coefficients for each line	Sensitivity coefficients per each line	Grid simulation tool	Contingency and load flow	IEX_2
3	Load schedule	Different load shedding scenario are evaluated	New set of load schedule	TSO/DSO	Grid simulation tool	IEX_5
4	Hosting capacity	This function calculates the maximum level of RES that can be integrated at the given locations in the grid	Maximum level of RES that can be integrated at the given locations in the grid	TSO/DSO load flow informationand location of DGs	Grid simulation tool	IEX_3, IEX_4
5	Energy interruption flexibility	Here, the loads interruption flexibility is defined in terms of the level and related cost	Interruption flexibility in terms of the level and related cost	Fixed load shedding schedule by TSO/DSO	Grid simulation tool (optimization)	IEX_5, IEX_6
6	Constraint definition	Based on the "contingency and load flow" and "energy interruption flexibility", the constraints for the optimization problem are defined	Constraints for the optimization problem	Grid simulation tool (Constraints definition function)	Optimizer	IEX_6, IEX_7, IEX_8
7	Minimization of the objective function	This minimizes the objective function defined in the Solution Approach for Sub Use Case 1 and 2	Perform deterministic optimization	Minimization of the objective function for Sub Use Case 7.1 and 7.2	Grid simulation tool	IEX_8, IEX_9

8	Changing of the DG nominal power distribution	Varying the distribution of the DG nominal power for a given hosting capacity	Nominal power of generators as a boundary condition	Grid simulation tool output	Grid simulation tool (hosting capacity calculation)	IEX_11
9	Generation dispatch and interruptable load schedule	New state of the system is achieved based on the dispatch schedule of the controllable DGs and interruptable loads in order to handle the contingency event.	New set of distribution schedule	Grid simulation tool	TSO/DSO	IEX_9

7 Summary and outlook

INTERPLAN identified suitable scenarios where the future challenges of the Pan-European network and rising technologies are depicted and addressed in order to meet the 2050 goals of the European Union. It is challenging to bring different developed and presented scenarios from different institutions in a common ground. However, INTERPLAN came up with 4 different scenarios for the future electricity grid, with time horizons to 2030 and 2050, in which includes the different perspectives of development, from small-scale to large-scale, from centralized to decentralized, from conventional generation to renewables, from weak policies to strong policies, inter alia. INTERPLAN scenarios present in a descriptive and quantitative manner each of the 4 scenarios with detailed focus on shares of Generation and Load, Active Demand Side Management, trend of network topologies and interconnections, amount of vehicles and demand according to estimated driven kilometres, storage technologies, and fuel and CO2 prices.

INTERPLAN consortium has selected and described seven use cases for the INTERPLAN network models (TSO, DSO, TSO-DSO interface), grid equivalent models and the network operation planning tool. The definition and analysis of the use cases were based on the regulatory framework and grid code analysis performed in WP2. Besides, the consortium consulted with the advisory board and stakeholder groups to verify the alignments taken.

In defining use cases, the shortcoming identified in the analysis of regulatory framework and current practices at consortium countries for operation of future EU grid (INTERPALN D2.1 [1]) was taken into consideration. The defined use cases look beyond the current regulation and grid codes and propose solutions in order to face the challenges that high share of technologies like RES, storage and EVs will cause for operation planning of the grid and the current grid codes and practices are not able to address them. In case the proposed solutions are evaluated positively in the simulations planned in the later stages of the project, they will be recommended for possible amendments to grid codes and implications on European regulations. This will be reported in a future deliverable (INTERPLAN D2.4: "Grid code recommendations").

The seven INTERPLAN use cases are as following:

- UC1: Coordinated voltage/reactive power control
- UC2: Grid congestion management
- UC3: Frequency tertiary control based on optimal power flow calculations
- UC4: Fast Frequency Restoration Control
- UC5: Power balancing at DSO level
- UC6: Inertia management
- UC7: Optimal generation scheduling and sizing of DER for energy interruption management

Besides, the report presents the key performance indicators, which will be used for evaluating the use case implementation in the planned simulations.

In the further stages of the project, based on the defined use cases and identified EU grid scenarios, a series of showcases as well as required grid equivalent models will be developed for each use. Then, as set of dynamic and semi-dynamic simulations for each showcase will be performed, and the possible criticalities as well as the possible solutions will be identified.

8 References

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[5] ENTSO-e/g, „TYNDP 2018 Scenario Report,“ ENTSO-e/g, 2018.

[6] e-Highway2050 Project, „e-Highway2050 Project results: Europe’s future secure and sustainable electricity infrastructure,“ European Union, 2015.

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[8] Gridtech Project, „D4.1 - Description of the GridTech Scenarios for the Development of the European Electricity System up to 2050,“ 2012.

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9 Annex

9.1 List of Figures

9.2 List of Tables

9.3 Glossary of terms and definitions

9.3.1 Definition of project general terms

Term	Definition
Use Case	The specification of a set of actions performed by a system, which yields an observable result that is, typically, of value for one or more actors or other stakeholders of the system.
Sub Use Case	Description of a specific situation a use case is applied to. A Sub Use Case is always attributed to one (main) use case, but one use-case may have multiple sub use cases which detail the main use case in at least one aspect.
Showcase	Presentation of use case(s) in the frame of chosen scenario, simulation type, test model, time-series data and planning criteria
Scenario	Definition of a future situation applying to a well-defined time (most often year). A scenario can be fictional or predicted from the present situation. In INTERPLAN, scenarios describe the future situation of the European electric network, typically including grid topology, generation mix, loads and diffusion of EV, RES and storages.

Dynamic Simulation	A simulation experiment which considers the time dependent behaviour of a physical system, looking at events occurring in real-time operation, with a frequency of occurrence of less than one second of real time. The simulation may run faster or slower than real time, and may, despite the fast event frequency, span a total time interval of several hours real-time.
Semi-Dynamic Simulation (also: Quasi-Dynamic Simulation)	A medium- to long-term simulation experiment based on steady-state analysis, considering the state of a physical system at discrete steps of real time through user-defined time step sizes. The real time between the steps is at least one minute.
Grid Cluster	A a group of grids and parts of grids with similar characteristics
Grid Equivalent	A simplified network model, which approximately behaves like an associated complex physical network or a group of physical networks. The grid equivalent thus is a representation of the physical network(s), which is typically used for a simulation experiment.
Controller	A device, which implements an algorithm or methodology that is used for real-time grid operation. A controller may influence the operation state of distributed generators, loads or grid assets (e.g. tap changer, power switch, FACTS) based on information from different sources.
Interface	A means of transmitting information between two or more controllers or actors. It usually includes a specification about which information is to be transmitted, how this information is represented by data elements, and defines a physical means for transmission of those data elements.
Cluster Controller	A controller having the aggregated behavior of individual controller characteristic in a larger grid.
Interface Controller	A controller, which is intended to be installed in a specific "home" cluster, and uses information received through an interface from at least one other cluster data source outside the home cluster. This data source could e.g. be another cluster, but also e.g. an external weather forecast provider using an interface
Local Controller	A controller which is associated with a single specific generator, load or grid asset and which operation does not rely on remotely received information originating from any remote source. i.e. the operation only relies on information available within the local area network of the local controller's installation site.
Co-simulation	A simulation which consists of different parts that form a coupled problem and are modelled and simulated in a distributed manner (cp. Wikipedia). The parts are called "Co-simulation subsystems" and are exchanging data during the simulation. Different models and simulation means can be used in different subsystems. The Co-simulation (in the ideal case) is carried out by running the subsystems, which were individually tested and validated beforehand, in a black-box manner. In INTERPLAN, the data exchange between subsystems is done by the OpSim platform.
Co-simulation subsystem / Co-simulation subcomponents	A part of a Co-simulation which is developed, modelled and validated individually, while at the same time able to be integrated into the Co-simulation platform. In INTERPLAN, a subsystem might represent e.g. a DSO or TSO operation centre, a controller, or even the real physical network model.
Data model	An abstract model that represents a real-world entity, and defines, organizes and standardizes the description of the data elements related with that entity. Since real-world entities are typically consisting of other entities (e.g. an electric grid consists of lines, transformers etc.), a data model typically is hierarchically structured and also allows to define interrelations between entities.

V2G and G2V	Vehicle-to-grid (V2G) describes a system in which plug-in electric vehicles communicate with the power grid to sell demand response services by either returning electricity to the grid or by throttling their charging rate. When an EV is being charged, it's called G2V (Grid to Vehicle).
Allocation	With reference to the grid operation planning phase, it is the process deciding, which are the most suitable resources to commit and dispatch among *n* operating resources for a specific objective and under specific constraints.
Placement and sizing	With reference to the grid planning, it is the process deciding the most proper location (bus) and the size of a resource (active power) for a specific objective and under specific constraints.
Energy Not Supplied	Energy Not Supplied is defined as the amount of energy that would have been supplied to the customer if there had been no interruption.
Energy spillage	Energy spillage is the production (from Solar and Wind) that is unable to be accommodated due to demand being lower than production.

9.3.2 Definition of actors

Term	Definition
TSO - Transmission System Operator	Natural or legal person responsible for operating, ensuring the maintenance of the transmission system and, if necessary, developing the transmission 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 transmission of electricity. The term 'transmission' means the transport of electricity on the extra high-voltage and high-voltage interconnected system with a view to its delivery to final customers or to distributors, but does not include supply.
DSO - Distribution System Operator	A natural or legal person 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. The term 'distribution' means the transport of electricity on high-voltage, medium-voltage and low-voltage distribution systems with a view to its delivery to customers, but does not include supply.
ESCO	Electricity supply company (sometimes also: Electricity service company). General term for a company which supplies end users with electric energy. An ESCO may offer additional services, e.g. electricity generation, metering or supply with non-electric energy.
Prosumer	Active energy consumer who consumes and produces electricity. Various types of prosumers exist: residential prosumers who produce electricity at home – mainly through rooftop PV, citizen-led energy cooperatives, commercial prosumers whose main business activity is not electricity production, and public institutions.
Generator	A device which produces electricity.
Load	A device which consumes electricity.
Producer	A natural or legal person generating electricity.
Consumer	A natural or legal person consuming electricity.
Distributed Energy Resource (DER)	A source or sink of electric power that is located on the distribution system, any subsystem thereof, or behind a customer meter. DER may include distributed generation, electric storage, electric vehicles and demand response.
Aggregator	Company who grouping distinct agents in a power system (i.e. consumers, producers, prosumers, or any mix thereof) to act as a single entity when engaging in power system markets (both wholesale and retail) or selling services to the system operator(s).

Distributed generation (DG) unit	Any source of electric power of limited capacity, directly connected to the power system distribution network. DG can be powered by photovoltaic system, micro-turbines, combustion engines, fuel cells, wind turbines, geothermal, etc.
Flexible Loads	A load which consumption can be influenced in terms of power, time, or total energy consumed while still serving its intended purpose. The influence may be exerted by manual means (e.g. switching the load on or off at arbitrary times) or automatic means (e.g. external control signal).