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The role of innovative grid-impacting technologies towards the development of the future pan-European system: the GridTech project

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SUMMARY

For the achievement of the European Union's ambitious renewable energy targets for 2020 and beyond, extensive electricity system planning and investments are necessary. This covers electricity generation capacity, transmission networks, and supporting technologies and measures that will ensure clean, secure and efficient energy supply.
Within this framework, the European project GridTech mainly aims at conducting a fully integrated assessment of new grid-impacting technologies and their implementation into the European electricity system. This will allow comparing different technological options towards the exploitation of the full potential of future electricity production from renewable energy sources (RES), with the lowest possible total electricity system cost.
Within the 2020, 2030 and 2050 time horizons, the goal is to assess where, when, and to which extent innovative technologies could effectively contribute to the further development of the European transmission grid, fostering the integration of an ever-increasing penetration of RES generation and boosting the creation of a pan-European electricity market, while maintaining secure, competitive and sustainable electricity supply.
The present paper focuses on the ongoing activities and approach followed by the GridTech project: final results and recommendations are expected by beginning of 2015.

KEYWORDS

Cost-benefit analysis, DSM, FACTS, grid-impacting technologies, grid planning, HVDC, pan-European transmission system, RES integration, scenarios build-up, storage.

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1. INTRODUCTION: OVERVIEW OF GRIDTECH PROJECT

For the achievement of the European Union (EU)'s ambitious renewable energy targets for 2020 and beyond, extensive electricity system planning and investments are necessary. This covers electricity generation capacity, transmission and distribution networks, and supporting technologies and measures that are able to ensure a clean, secure and efficient energy supply. In particular, the development of adequate transmission infrastructures and grid-impacting technologies plays more and more a crucial role to foster the integration of renewable energy sources (RES), as also highlighted by different recent documents issued by the European Commission [1][17].

In this framework, the main objective of the European project named **GridTech** (*Innovative grid-impacting technologies enabling a clean, efficient and secure electricity system in Europe*) [2] is to conduct a fully integrated assessment of new grid-impacting technologies and their implementation into the European electricity system. This will allow comparing different technological options towards the exploitation of the full potential of future electricity production from RES, with the lowest possible total electricity system cost.

The GridTech project (running from May 2012 until April 2015) is co-funded by the European Commission under the Intelligent Energy Europe (IEE) Programme. The project consortium consists of fourteen European partners coming from eight Members States of the European Union (EU) under the coordination of EEG TU Wien. It directly includes four Transmission System Operators (TSOs), two utilities, and eight research institutes, universities and consultants. Two further TSOs are also involved in GridTech activities.

The present paper aims at providing an overview of the working activities of GridTech project, investigating the approach adopted, with details on the innovative technology screening, pan-European study and the regional case studies.

Figure 1 shows the basic architecture of GridTech project. The preliminary activities of the project include the investigation on the different types of non-technical barriers (such as social, environmental, regulatory issues) hindering transmission expansion nowadays in Europe and the analysis of market issues related to RES integration into the European system.

Then, the project focuses on the most promising and innovative technologies that directly or indirectly impact on the transmission system.

The specific focus is on the future integration of these technologies into the European power system and its behavioral characteristics, also in terms of improved flexibility and controllability[4].

Within the 2020, 2030 and 2050 time horizons, it is crucial to assess where, when, and to which extent innovative technologies could effectively contribute to the further development of the European transmission grid, also towards potential supergrid ("transmission highways") architectures, fostering the integration of an ever-increasing penetration of RES generation and boosting the creation of a pan-European electricity market, while maintaining secure, competitive and sustainable electricity supply.

Towards this aim, after the build-up of the 2020, 2030 and 2050 scenarios, the GridTech approach described in the paper features a cost-benefit analysis (CBA) of the implementation of the innovative technologies into the European electricity system. This requires the set-up of a consistent and tailor-made analysis methodology qualified to meet the objectives in the scenario analyses.

In detail, for each target year and scenario, the methodology is based on the evaluation of the different benefits to the European power system provided by the innovative technologies comparing the case implementing the assessed technology with respect to a base case without it ("with-and-without" evaluation). The verification of the CBA is based on technology cost calculation, on the one hand, and sophisticated European electricity system modeling (top-down level) as well as target country-specific case study analyses (bottom-up level), on the other hand.

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[4] The concept of controllability of a power system is here intended as its capability to flexibly react to rapid and large imbalances, such as unpredictable fluctuations in demand or in variable generation, by handling system variables in a way that keeps a reliable supply. It can be measured in terms of megawatts (MW) available for ramping up and down, over time [10]. On the other hand, the concept of flexibility in [7] is intended in terms of adaptability to scenario changes to assess whether an investment chosen under certain conditions can still be undertaken in presence of scenario variations.

It is important to note that both GridTech applications – top-down European and bottom-up target-country scenario analyses – are conducted consistently (taking into account several interdependencies and being accompanied by continuous data exchanges) and they are fully complementary in the sense that:

- the top-down European scenario analyses enable the investigation of electricity flows in the meshed pan-European transmission system, transregional transmission bottlenecks identification and possible relief actions carried out in a wider transnational context with the support of the implementation of different innovative technologies;
- the bottom-up target country-specific scenario analyses focus on the individual peculiarities of single electricity system regions, being different in terms of varying electricity system dynamics and transmission network configurations.

For the top-down level, a pan-European system analysis is carried out by modeling the whole European power system (EU30+ region) for the 2020, 2030 and 2050 time horizons. This is performed by a zonal approach, implementing the MTSIM tool, developed by RSE.

For the bottom-up level, taking some of the outcomes of the pan-European analysis into account as boundary conditions, for 2020, 2030 and 2050 scenario timeframes, GridTech also focuses on 7 target countries: Austria, Bulgaria, Germany, Ireland, Italy, Netherlands, Spain. The analyses on these countries are based on market and/or grid detailed approaches.

The 7 target countries, with their differences and strategies, can be representative of the existing and future European electricity systems. In fact, although large-scale RES integration significantly depends on the specific characteristics of the electricity system in each country (like mix and flexibility of power plant portfolio, transmission interconnection capacities to neighbouring market zones), the fundamental challenges are common to the other European countries.

The rationale for implementing also pan-European scenario studies in the context of large-scale RES integration in the GridTech project is to figure out how complementary electricity generation portfolios in different regions throughout Europe can be exploited in an economically convenient way. A consistent European planning, also possibly featuring the development of transmission highways in the long term, can emerge only if the EU30+ electricity system is considered in its entire extension. In addition, the local/regional usage of innovative technologies (e.g. bulk energy storage) to compensate high variable electricity flows, even if locally, is to be checked by considering also the full-scale European system and the electricity flows in it. By contrast, it is important to check to what extent the peculiarities of a local/regional electricity system can impact on the whole European electricity system. In this sense, both system boundaries are an essential part of GridTech scenario analyses.

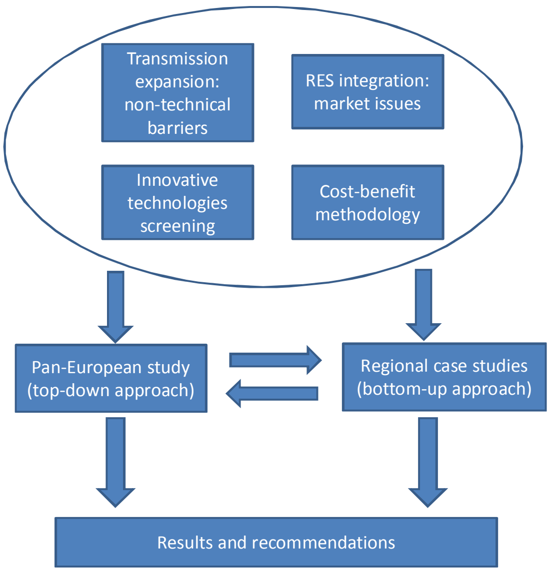

Figure 1: Basic architecture of GridTech activities

After achieving a common understanding on best practise criteria for the implementation of new technologies fostering large-scale RES integration, the final goal of GridTech project consists in

delivering tailor-made recommendations and action plans to the European policy community, taking into account the legal, regulatory, and market framework in Europe.
In the following, the present paper focuses on the ongoing project activities related to the innovative technologies screening in Europe (Section 2.), the cost-benefit methodology (Section 3.), the pan-European study (Section 4.) and the regional case studies (Section 5.).

2. INNOVATIVE TECHNOLOGIES SCREENING IN EUROPE

In the European context, towards the achievement of EU climate change and energy policy targets for 2020 and beyond, a paradigm shift is ongoing: while in the past the generation was controllable and the load demand was mostly unpredictable due to its stochasticity, nowadays some of the generation units may have a stochastic behaviour due to variable RES, whereas some consumption may become controllable [5]. The integration of renewable and distributed energy resources can then present challenges for the dispatchability and controllability of variable RES and for the operation of the electricity system. Energy storage systems can alleviate such problems by decoupling the production and delivery of energy. Smart grids can help through automation of control of generation and demand (in addition to other forms of demand response) to ensure balancing of supply and demand.
To become smarter and stronger, current electricity grids are then requiring a progressive re-engineering, incorporating and utilising an increased amount of innovative technologies to keep the whole electric system reliable at affordable costs [16].
For the purpose of GridTech project, focus is on the innovative technologies that may impact on the transmission grid development and operation. For this, two general categories of technologies to be investigated can be distinguished [8]:
1st category -> technologies directly impacting on the transmission system
2nd category -> technologies indirectly impacting on the transmission system
The 1st category includes technologies which are generally planned/operated by TSOs: the use of these technologies is then in general in the hands of TSOs.
Transmission grid technologies (TGT) belong to the 1st category.
The 2nd category includes technologies which are generally not planned/operated by TSOs: the use of these technologies is in general not in the hands of TSOs.
Electricity generation technologies (EGT), energy storage technologies (EST), electricity demand technologies (EDT) (including demand side technologies, DST, and electric mobility technologies) belong to the 2nd category.
In the following, some preliminary GridTech outcomes and synthetic analyses, related to the screening of innovative grid-impacting technologies in Europe, are provided, with particular focus on TGT and EST but also EDT.

Transmission grid technologies (TGT)
In addition to conventional HVAC (High Voltage Alternating Current) technologies, like overhead lines (OHLs), substations, transformers, reactors, capacitors, protection etc., innovative TGT may include devices like:

- XLPE (Cross-Linked Polyethylene) underground/undersea HVAC cables;
- Gas Insulated Lines (GILs);
- High Temperature (HT)/High Temperature Low Sag (HTLS) Conductor-based OHLs;
- Innovative-design HVAC OHLs;
- EHVAC (Extra HVAC) OHLs;
- Fault Current Limiters (FCLs);
- High Temperature Superconducting Cables (HTSCs);
- Phase Shifting Transformers (PSTs);
- HVDC (High Voltage Direct Current) OHLs/cables/back-to-back devices;
- FACTS (Flexible Alternating Current Transmission System) devices;
- Wide Area Monitoring/Control/Protection Systems (WAMS/WACS/WAPS);
- DLR (Dynamic Line Rating)/RTTR (Real Time Thermal Rating)-controlled OHLs/cables.

The listed innovative TGT, most of which were investigated in [11][12][16][25], have been further analysed in [8], especially in terms of current, planned and potential developments and projects in

Europe in the short, mid and long term.
Concerning TGT, particular attention is paid to the most mature and promising TGT (starting from PSTs, HVDC, FACTS, WAMS, DLR/RTTR-devices) able to increase system controllability and flexibility towards RES integration: among these, HVDC is primarily emerging to play more and more a key role. This trend is expected to further continue over the coming years, also in the mid and long term, with a large boost especially for self-commutated VSC (Voltage Source Converter) - HVDC systems due to their well-known features, but also line-commutated CSC (Current Source Converter) - HVDC technologies will be further applied in Europe [8][15][25]. In fact, by analysing the ongoing transmission expansion and investment plans in Europe (see also [5][6][18][20][24]), several HVDC developments emerge, also towards rather new[5] applications of HVDC technologies in Europe. This is especially the case for: 1) HVDC links embedded into the HVAC synchronised system(s); 2) HVDC offshore connections; 3) HVDC long OHL corridors. For all these applications, VSC-HVDC is a very promising technology over the classic CSC-HVDC. Regarding application 1), different VSC-HVDC underground cable projects are ongoing across the ENTSO-E (European Network of Transmission System Operators for Electricity) system [30]. Concerning application 2), there is a very strong potential for VSC-HVDC offshore grids development in Europe, especially in the North Seas [15]. Several major issues and crucial challenges at different levels (technical and technological, economic and financial, regulatory and market) will have however to be addressed ahead of a North Seas DC[6] offshore grid development in the mid-to-long term [12][22][27]. Application 3) has been implemented so far in North and South America, in Africa, Asia (eg. China, India), Russia, but not in the European system [15]: the first projects are ongoing in Germany, where four VSC-HVDC[7] long OHL corridors (highways) are planned in the mid term to provide direct power feed-in from large production areas to load centres with high demand by north-south axes (see also Sections 4., 5.) [6][24].
All these emerging HVDC applications in Europe may contribute to set the first, essential building blocks of a potential HVAC/HVDC pan-European supergrid [15]. Such infrastructure can be also characterised by including a potential HVDC overlay grid, based on a HVDC backbone infrastructure interconnecting the North Sea countries, exploiting the different existing HVDC links and the north-south corridors in Germany transporting North Sea offshore energy to Central Europe, complemented by the storage infrastructure in the Alpine and Nordic regions [17][24].
Naturally, it has to be remarked that the realisation of a potential HVAC/HVDC pan-European supergrid is a complex process that can be put in place only in a long term perspective, as there are still several techno-economic, technological, regulatory, market and socio-environmental issues that will have to be properly handled and solved over the years [15]. Towards this goal, considering the needed re-engineering process and the relevant paradigm shift with respect to the traditional approach to transmission system development and operation adopted so far in Europe, different stages for an incremental evolution from the current European grid are to be foreseen. GridTech project aims to further contribute to this process by evaluating innovative technologies and measures for the mid-to-long term perspective (up to 2050) in the European context (see also Sections 3., 4., 5.) [8].
Table 1 provides an overview of current, planned and potential (preliminary) HVDC projects in Europe (as of 2013): these are generally categorised as CSC-HVDC and VSC-HVDC in terms of technology type, and then further distinguished as cables (underground or submarine), OHLs or back-to-back devices. It can be noted that many projects of (both CSC-HVDC and VSC-HVDC) undersea cables especially are planned or under study across Europe. Further implementations and projects towards the realisation of meshed HVDC systems will be developed upon the advent of commercial DC breakers [8].
Looking at other promising TGT (non HVDC), in the case of FACTS[8] devices these technologies can

[5] HVDC is currently used in the European system mainly for long submarine and/or asynchronous systems links.
[6] DC: Direct Current. AC: Alternating Current.
[7] It has to be noted that, while for underground and undersea cable applications VSC-HVDC offers several gains over CSC-HVDC, for OHL implementation VSC-HVDC is limited by its inability to suppress DC-side fault currents when they occur. To bypass the issue, different technological solutions are under development [15].
[8] SVC: Static VAR Compensator. STATCON: Static Condenser (known also as STATCOM: Static Synchronous Compensator). TCSC: Thyristor Controlled Series Capacitor. SSSC: Static Synchronous Series Compensator. TCPST: Thyristor Controlled Phase Shifting Transformer. IPFC: Interline Power Flow Controller. DFC: Dynamic Flow Controller. UPFC: Unified Power Flow Controller.

be further distinguished in shunt, series and combined FACTS elements. Among shunt controllers the main devices are the SVC and the STATCON. The series controllers category includes devices such as the TCSC and the SSSC. Devices such as the TCPST, the IPFC, the DFC and the UPFC belong to the category of combined FACTS controllers. Shunt devices present relevant features for reactive power compensation and voltage control, while series devices offer key advantages for active power flow control and transient stability enhancement [25].

TGT typology	TGT	Current implementation location	Planned implementation location	Potential implementation location	Commercial viability
HVDC cables	VSC-HVDC underground cables		Ireland Cross-border links: Belgium-Germany, France-Spain, Italy-France, Ireland-UK, Italy-Switzerland, Sweden-Norway	Cross-border links: Austria-Italy, Slovenia-Italy	● (Available)
HVDC cables	CSC-HVDC undersea cables	Spain (Iberian Peninsula-Majorca), UK (Northern Ireland-Scotland) Cross-border links: Denmark-Sweden, Denmark-Germany, Finland-Sweden, France-UK, Greece-Italy, Italy (Sardinia)-France (Corsica)/France (Corsica)-Italy (Italian Peninsula) (SA.CO.I. 2), Norway-Denmark, Norway-Netherlands, Sweden-Germany, Sweden-Poland, UK-Netherlands	UK (England-Scotland), UK (England-Wales) Cross-border links: Estonia-Finland, France-UK, Ireland-UK, Italy-Montenegro, Italy-Albania, Italy-Greece, Italy-Tunisia, Norway-Netherlands, Norway-Germany, Norway-UK, UK-Belgium	Greece Cross-border links: Cyprus-Israel, Cyprus-Greece, Cyprus-Turkey, Greece-Egypt, Iceland-UK, Iceland-Norway, Italy-Algeria, Italy-Libya, Russia (Kaliningrad)-Germany, Spain-Algeria, Spain-Morocco, Spain-UK	● (Available)
HVDC cables	VSC-HVDC undersea cables	Germany (offshore wind connections), Norway, Sweden Cross-border links: Estonia-Finland, Ireland-UK (Wales)	France, Germany (offshore wind connections), Sweden, UK Cross-border links: Denmark-Germany, Denmark-Netherlands, Ireland-UK (Wales), Italy (Sardinia)-France (Corsica)/France (Corsica)-Italy (Italian Peninsula) (SA.CO.I. 3), Norway-Denmark, Sweden-Lithuania, UK-France	Germany (offshore wind connections), Greece (Attica-Crete-Rhodes), UK (Northern Ireland-Scotland) Cross-border links: France-Spain, France-Ireland, France-UK, Ireland-UK, Italy-Croatia, Sweden-Latvia	● (Available)
HVDC OHLs	CSC-HVDC OHLs	France (Corsica, SA.CO.I. 2), Italy (Sardinia, SA.CO.I. 2) Cross-border link: Russia-Ukraine	Italy, Spain	Greece Cross-border links: Italy-Austria, Netherlands-Germany, Ukraine-Hungary, Ukraine-Poland	● (Available)
HVDC OHLs	VSC-HVDC OHLs		France (Corsica, SA.CO.I. 3), Germany (corridors A, B, C, D), Italy (Sardinia, SA.CO.I. 3), Sweden-Norway		● (To be further tested)
HVDC	CSC-HVDC back-to-back	Russia (cross-border tie with Finland)	Lithuania (cross-border tie with Poland), Georgia (cross-border ties with Turkey), Ukraine (cross-border ties with Poland and Romania), Russia (Kaliningrad) (cross-border tie with Poland)	Russia (cross-border ties with Estonia and Latvia), Belarus (cross-border ties with Poland and Lithuania)	● (Available)

● Available ● To be further tested

Table 1: Overview of current, planned and potential HVDC projects in Europe (as of 2013) [8]

Costs, complexity and reliability issues have represented so far the main barriers to a wider FACTS integration in the European system. Up to present, shunt devices (like the SVCs) have been the most widespread and mature FACTS technologies: different SVCs are presently installed in Europe (mostly in the UK, but also eg. in Norway, Finland, France) and further SVCs are planned (eg. in Germany), as also reported by Table 2, which provides an overview of current, planned/potential (preliminary) TGT (non HVDC) projects in Europe (as of 2013).

TGT typology	TGT	Current implementation location	Planned/potential implementation location	Commercial viability
XLPE HVAC cables	XLPE HVAC underground cables	Austria, Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Spain, Switzerland, Turkey, UK Cross-border links: Italy-Switzerland	Belgium, Denmark, France, Germany, Italy, Latvia, Luxembourg, Netherlands, Switzerland, UK Cross-border links: Belgium-Luxembourg	🟢
XLPE HVAC cables	XLPE HVAC undersea cables	Denmark, Ireland, Norway Cross-border links:	Belgium, Germany, Greece, Italy, Ireland, Latvia, Switzerland Cross-border link: Italy-Malta	🟢
GILs	GILs	Germany, Switzerland, UK	Cross-border link: Austria-Italy	🔴
HT/HTLS OHLs	HTLS OHLs	Belgium, France, Germany, Ireland, Spain	Austria, Belgium, Bulgaria, France, Germany, Italy, Netherlands, Poland, Romania, Spain, UK Cross-border links: France-Italy, Germany-Netherlands	🟢
HTSCs	AC HTSCs	Denmark, Russia (all at distribution level)	Germany, Netherlands, Russia, Spain (all at distribution level)	🟡
HTSCs	DC HTSCs	Russia (at distribution level)	Russia (at distribution level)	🟡
Innovative OHLs	Innovative-design HVAC OHLs	Italy, Netherlands	Italy, Netherlands	🟢
EHVAC OHLs	EHVAC OHLs (750 kV)	Belarus, Russia, Ukraine Cross-border links: Belarus-Lithuania, Russia-Belarus, Russia-Ukraine, Ukraine-Hungary	Russia, Ukraine Cross-border links: Ukraine-Poland (revamped), Ukraine-Romania (revamped)	🟢
FCLs	SFCLs	Germany, Italy, Spain (all at distribution level)	Germany, Italy, Slovakia, Spain (all at distribution level)	🟡
PSTs	PSTs	Austria, France, Ireland, Italy, UK Cross-border links: France-Spain, France-Belgium, Germany-Denmark, Italy-France, Italy-Austria, Italy-Slovenia, Netherlands-Belgium, Netherlands-Germany	Austria, France, Ireland, Italy, Romania, Spain Cross-border links: Austria-Italy, France-Spain, Germany-Poland, Germany-Czech Rep., Italy-Slovenia, Luxembourg-Belgium, Netherlands-Belgium, Romania-Bulgaria	🟢
FACTS	SSSCs		Spain	🟡
FACTS	SVCs	Finland, France, Norway, UK	France, Germany, Italy, Poland	🟢
FACTS	STATCONs	UK	Italy, UK	🟢
FACTS	TCSCs	Sweden		🟡
WAMS/WACS/WAPS	PMUs	Most countries	Most countries	🟢
DLR/RTTR	DLR-OHLs	Czech Rep., Germany, Spain	Austria, Germany, Italy, Netherlands, Spain	🟢
DLR/RTTR	RTTR-cables	Italy, Russia, Spain, UK	Italy, Spain	🟢

🟢 Available 🟡 Prototype 🔴 To be further developed

Table 2: Overview of current and planned/potential TGT (non HVDC) projects in Europe (as of 2013) [8]

Furthermore, a key FACTS project (SSSC installation in Spain, see also Table 2) may represent a milestone for fostering the penetration of FACTS series devices, which have been so far discarded by

European TSOs to achieve power flow controllability in favour of PSTs (generally simpler, more robust, and less costly solutions, but with limited dynamic capabilities). Further FACTS penetration will depend on the possibility to realise more standardization, interoperability and economies of scale at manufacturing level [8][14][16].
Table 2 also highlights that PSTs and HTLS Conductor-OHLs are currently the most widespread technologies among the innovative TGT (other than HVDC) for their reliable abilities to provide the transmission system with increased controllability and capacity [8].
In a mid term perspective, FACTS, HVDC (especially VSC-based), PST, DLR/RTTR-monitored technologies will be crucial for the future integration of RES into the European system, while delivering full benefits when subject to a coordinated control, in combination with WAMS [8][14].
In a long term perspective, superconducting technologies may also emerge for transmission level applications: to overcome current barriers especially related to complexity, further testing facilities and pilot projects will be needed. Superconducting technologies such as HTSCs can be of two main types, AC or DC; superconducting FCLs (SFCLs) represent also promising technologies.
In general, different innovative TGT need to be duly tested and carefully evaluated at technological, techno-economic and socio-environmental level [8].

In sum, concerning innovative TGT, given the current technology progress, in the short term (up to 2020) these TGT may definitely emerge: HVAC XLPE cables, VSC-HVDC cables/OHLs, FACTS (SVC and STATCON, also coupled with storage), HTLS Conductor-based OHLs, DLR/RTTR-monitored OHLs/cables, WAMS/PMU.
In the mid-to-long term (after 2020) these TGT may definitely emerge: multiterminal VSC-HVDC, VSC-HVDC OHLs, FACTS (SSSC, TCPST, UPFC), FCLs, GILs, HTSCs [8][26].

Energy storage technologies (EST)
There exist different possible classifications of EST in available literature [8]. As the focus of the present analysis is on storage of energy for electricity scopes, thermal storage is here not considered. The EST for electricity have been classified following the approach used in [8] (see Figure 2). The different EST for electricity can be grouped in two main classes: direct storage technologies and indirect storage technologies. The first group includes those EST for electricity in which electrical energy is directly stored in the magnetic or electrical field of an inductor or a supercapacitor, respectively. The second group refers to those EST for electricity in which electrical energy is indirectly stored as mechanical or chemical energy, before conversion into electricity.

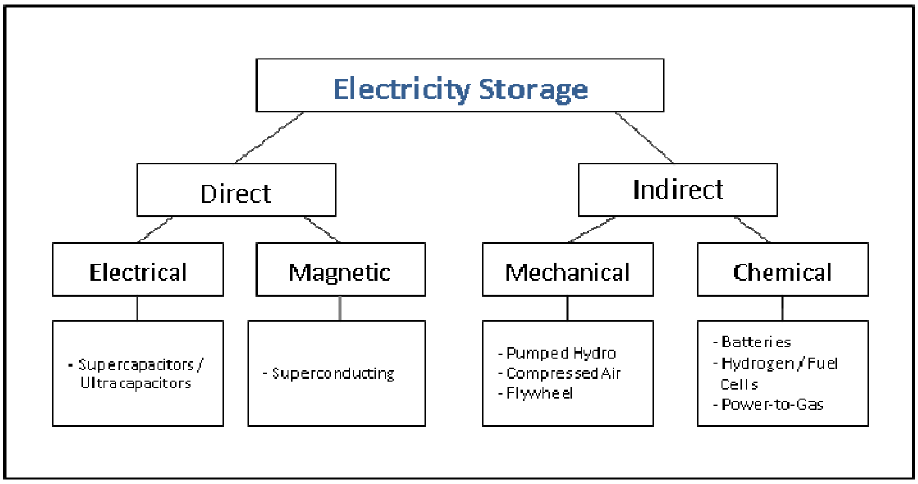

Figure 2: The classification of EST for electricity [8]

More in particular, the EST under analysis within GridTech include:

- Pumped Hydroelectric Energy Storage (PHES);

- Compressed Air Energy Storage (CAES);
- Power-to-Gas (P2G) Storage;
- Flywheel Energy Storage (FES);
- Superconducting Magnetic Energy Storage (SMES);
- Molten-salt Batteries Energy Storage;
- Flow Batteries Energy Storage;
- Supercapacitors / Ultracapacitors;
- Lithium (Li)-Ion Batteries Energy Storage;
- Hydrogen / Fuel Cell (HFC) Storage.

Preliminary activities on EST in GridTech have resulted in an overview of the state-of-the-art and the expected developments of EST that are currently, or in the future, potentially capable to effectively support the European power transmission system expansion and operation [8].

Attention has been then particularly paid to bulk EST such as PHES and CAES technologies, which are more suitable for transmission side applications nowadays. In this sense, several PHES projects across North-West Europe (Ireland, UK), North-East Europe (Estonia, Lithuania, Poland), Central Europe (Austria, Germany, Switzerland), South-West Europe (France, Portugal, Spain) and South-East Europe (Bulgaria, Greece) have been recorded for the short-to-mid term; furthermore, it has to be highlighted that for some of PHES projects (like the MAREX plant in Ireland) seawater will be used [8][18]. Concerning CAES, different projects are ongoing at various development stages in some countries like Germany, UK (Northern Ireland), Norway, Spain [18][28]. On the other hand, also P2G and all the other listed EST types, currently under development/use for small-scale applications, are duly analysed within GridTech, as they are emerging as promising technologies, potentially useful for future transmission side applications in Europe. In particular, in several European countries (especially in Southern Europe, but not only) pilot projects based on batteries storage are more and more taken in consideration at transmission level: in this sense, the case of Italy has to be highlighted, given its large programmes for installing batteries for RES integration (250 MW in total) and for security enhancement (40 MW in total) on different critical sections of the 150 kV grid. Concerning P2G penetration, in the mid term there are promising tendencies in countries like Germany, Denmark, Netherlands and Spain [8][18][28].

Energy storage technologies can be used for a number of applications on different time scales, which are not all directly related to the support of variable / intermittent RES generation. The main relevant clusters for TSO applications would be: RES management, area control & frequency, commodity storage, reserve provision, transmission system stability, voltage regulation, and reliability support [8][13].

RES management applications of EST can be described as output smoothing of variable RES generation on different time scales by controlling and synchronizing many individual RES generation units, so that they resemble conventional power plants in their ability to reduce or increase output on demand to the extent possible.

In the time interval of a few seconds to minutes, EST can deal with excessive power output which could not be absorbed by the network at that particular moment and discharge the power delayed when the network can accommodate it again, leading to a reduced curtailment of RES. For these applications, suitable EST are FES, batteries, PHES and CAES.

In longer time periods, EST enable firming up and backup of variable RES generation to allow for extended periods of low electricity generation which typically characterises patterns of wind and PV generation. For these applications, suitable EST are PHES, CAES, batteries and fuel cells.

Frequency control and reserve capacity provision can be divided into three sub-categories: a) primary, secondary and tertiary control, b) black-start capability, and c) load leveling or commodity storage.

For the provision of primary control, the applicable EST refer to those technologies that may be activated within seconds, like flywheels and batteries, and partially PHES (if spinning). On the contrary, for secondary control provision PHES can be considered as the most suitable EST. Applicable EST for tertiary control are PHES, CAES, batteries and fuel cells. For the provision of black-start capability suitable EST can be PHES and CAES, among others. PHES and CAES can be applicable also for load leveling and commodity storage.

For the **support of transmission system stability and voltage control** the applicable EST can be batteries, SMES and Supercapacitors [8].
Table 3 presents a summary of the technical characteristics of main storage technologies as well as their relevance for different applications (not only transmission-related).
Given the different EST applications and potential benefits, there also exist some barriers related to costs, constraints on sites, adequacy to the TSO needs. The challenges ahead of further EST penetration and more widespread application consist in: lowering technology costs; establishing industry standards and protocols for TSO planning and operation; addressing regulatory issues; minimising environmental impacts [8][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

Table 3: Technical characteristics and applications of storage technologies [8]

Electricity demand technologies (EDT)
The category of electricity demand technologies (EDT) groups together the different types of devices that are operated by and/or have an impact on the demand sector of the electricity system. This category then takes account of: demand-side management and demand response technologies, including smart metering devices and smart appliances for smart grids applications; electric mobility vehicles, including the different types of electric or hybrid cars. In the following, a general overview on demand-side management and demand response technologies as well as on electric mobility vehicles is provided.

Demand-Side Management and Demand Response
Actions related to demand-side participation aim at modifying and/or reducing energy consumption profiles in order to obtain technical and/or economic benefits. Demand-side participation involves two concepts developed over time: demand-side management (DSM) and demand response (DR) [8].
Traditionally, DSM has been used by the power industry over the last decades with the objective of reducing energy consumption and improving overall electricity usage efficiency through the implementation of policies and measures that control electricity demand. In the past, DSM was characterized by a top-down ("utility-driven") approach: electricity companies decided to implement measures on the demand side to increase the efficiency of the energy system, hence deferring investments in generation and network capacity. These measures included the use of high-efficiency generation units, peak-load shaving, and operating practices facilitating efficient usage of electricity. One example of "utility-driven" measure is the interruptibility service, through which the utility pays the interruptible customer for the demand-side management capacity made available under certain critical conditions, e.g. in presence of lack of sufficient generation capacity to cover the expected load demand: in fact, it is cheaper for the utility to cut some supply than to build new generation/transmission capacity. This approach is also referred to as load management [8].
On the other hand, DR, brought by the electricity sector liberalisation, is characterized by a bottom-up approach: measures are implemented to incentivize customers to become active in managing their consumption, obtaining in turn economic benefits. In this sense, DR can be defined as the action, in

terms of the changes in electricity consumption, by end-use customers in relation to their normal consumption patterns in response to changes in the price of electricity over time. DR also involves incentive payments designed to shift or reduce electricity consumption at times of high wholesale market prices or when system reliability is threatened. The final goal of DR programs is to reduce electricity consumption in times of high energy cost or network constraints by allowing customers to respond to price or quantity signals or by increasing consumers' awareness. DR programs can change customers' consumption indirectly, i.e. customers change their behaviour in response to price signals (or other types of incentives), or directly, i.e. consumption is shifted automatically through technical signals and based on pre-established agreements with the supplier.
From being "utility-driven" in the past, DSM is nowadays moving towards a "customer-driven" activity. In this sense, it can be considered that DSM comprises energy efficiency measures and DR actions (including load management). Within GridTech, after investigating the features of different EDT components and DR actions, particular attention has been paid to the analysis of the potentials in Europe for peak shaving and energy saving under different DR programs [8].

Electric mobility vehicles
Electric mobility (E-mobility) is based on promising technologies, like electric cars, to provide sustainable mobility. There currently exist different types of electric cars, such as BEVs (Battery Electric Vehicles) or simply EVs (Electric Vehicles), PHEVs (Plug-in Hybrid Electric Vehicles), HEVs (Hybrid Electric Vehicles), FCEVs (Fuel Cell Electric Vehicles), EREVs (Extended-Range Electric Vehicles). Nowadays, about 900 million passenger cars are in operation worldwide, about 267 million of them are running in Europe (241 million ca. in the EU) [8]. Within the next decades a substantial part of today's cars based on internal combustion engine (ICE) could be replaced by the different types of electric cars, especially by those ones charged by the electric grid. Considering the technological progress over the years, nowadays improving performances offered by battery storage are expected to enable up-growing market penetration [8].
The development of the electric vehicle sector is driven by several factors. Electric cars may have substantial benefits by exploiting high efficiency of electricity storage and drive train and by enabling mobility based on renewable (eg. hydro, wind and solar) sources. It should be mentioned explicitly that, nowadays and in future time, the exploitation of electricity generation by RES shall be the key pillar for charging an electric automobile. Electric cars may then bring overall benefits to the system in terms of: CO_2 emissions reduction; reduced dependency on fossil fuel imports.
Moreover, electric cars can widely use existing infrastructure (no erection of an additional distribution system is required), however additional public and semi-public charging points are needed. Electricity charging needs also to be managed and controlled in order to smoothen load profiles.
Several studies and detailed scenarios for penetration of electric mobility vehicles in the European countries have been built up over the years and have been taken into due account as basis for the GridTech development of prospects for electric cars [8].
For the build-up of potentials and scenarios of electric mobility vehicles penetration, the influencing parameters for the calculation of the power and energy demand are the following: the structure of urban development; the specific type of car and battery; the users and their driving profiles; the possible charging strategies. The knowledge of all these parameters will enable the calculation of the load profiles and energy demand for electric cars.

3. COST-BENEFIT ANALYSIS METHODOLOGY

The techno-economic assessment of investments in new infrastructures (generally translated in cost-benefit analysis) represents a key stage of the transmission expansion planning process.
Within the cost-benefit analysis, it is then crucial to quantitatively assess the possible benefits provided by transmission expansion: this task, especially in a liberalized power system, generally represents a rather complex stage since the evaluation strongly depends on the viewpoint taken for each considered benefit. In particular, benefits evaluation has to consider the manifold aspects in which a new infrastructure can affect the system [3].
In general, transmission expansion benefits can be grouped in the following categories: system reliability improvement; quality and security increase; system losses reduction; market benefits;

avoidance/postponement of investments; more efficient reserve management and frequency regulation; environmental sustainability benefits; improved coordination of transmission and distribution grids [3]. The first benefit deriving from transmission expansion is represented by the increase of capacity. However, this additional capacity can be useful for the system only evaluating its impact in terms of an increase of the Social Welfare (SW) or, more simply, a reduction of dispatching costs, in case of inelastic load demand. Further key factors that shall be considered in a cost-benefit analysis (CBA) refer to benefits such as CO_2 emissions reduction, reliability increase (i.e. load shedding probability reduction), resilience improvement, RES curtailment (spillage) decrease, losses reduction.

In addition to these benefits, it is also important to assess further elements provided by innovative technologies: among these, the benefits related to higher system controllability[9], flexibility and observability[10] have to be taken into account.

Aspects related to social acceptance and environmental impact, especially derived by the implementation of TGT and EST, are also taken into account and quantified, but not in economic terms. In particular, aspects related to land occupation/footprint are considered: given that the routing and local details are needed for this analysis, the investigation of social-environmental aspects can be done at the level of grid-based investigation only. All these elements are duly taken into account within GridTech towards the set-up of a tailor-made methodology for managing a multi-criteria CBA to evaluate transmission expansion options: this methodology is being applied firstly in the pan-European ("top-down") zonal study, and then, upon opportune assumptions, it will be adapted for the target-country ("bottom-up") studies. In this way, aspects of both the "corridor-based" and the "grid-based" approaches can be taken into account, economically quantifying more factors than in [7].

Table 4 provides the list of benefits/aspects analysed within GridTech preliminary CBA, with the indication concerning the economic quantification of each corresponding benefit/aspect.

Benefit/aspect	Economic quantification	Non-economic quantification
Social Welfare	X	
Losses	X	
Reliability	X	
Resilience	X	
CO_2 Emissions	X	
RES spillage	X	
Controllability	X	
Flexibility	X	
Observability		X
Social-environmental impact		X

Table 4: Summary of benefits/aspects of the GridTech CBA approach (preliminary analysis)

4. PAN-EUROPEAN ZONAL STUDY

Towards the assessment of the investments in new infrastructure and innovative technologies for RES integration, scenario studies are conducted within GridTech for the entire European electricity system,

[9] Resources that contribute to system controllability may include dispatchable power plants, DSM/DR devices, EST, as well as TGT like FACTS, HVDC, DLR/RTTR, PSTs, PMUs/WAMS. The issue of controllability evaluation can be seen in different perspectives, depending on the timeframe considered and the corresponding task target (long term planning, operational planning, operation). Controllability can be taken into account by two parallel and independent ways. In the first approach, since controllability is connected to the capability of a wide set of facilities and/or TGT to cope with different operating conditions, the benefit that these devices may generate can be seen as a component of the total SW increase. In the second approach, controllability benefit can be considered in terms of savings derived to a TSO from a reduced reserve power acquisition in a balancing market. This benefit may be quite challenging to capture nowadays: advanced tools for balancing markets simulation in real-time would be needed. An approximation to evaluate this aspect could be based on the estimation of the avoided reserve power acquisition monetized at a possible standard/reference price.

[10] An estimation of observability benefit (provided by the use of WAMS/PMU) translated in terms of security increase may be performed by taking into account, if available, statistics of EENS (Expected Energy Not Supplied) variation with respect to PMU amount.

at both pan-European (top-down) and target country (bottom-up) level, with special consideration for the target years 2020, 2030 and 2050.
To do this, taking into account the technology evolutions in Europe, the first step consists in the build-up of scenarios: within GridTech three scenarios are considered for each target year (2020, 2030, 2050) subject of the analysis, that is S1, S2, S3.
The GridTech scenarios, S1, S2, S3, are built having as main drivers two (also interrelated) factors: RES penetration and technology progress. Energy efficiency improvement is taken implicitly into account within both drivers.
Each of the three scenarios is characterized by a mix of RES and innovative grid-impacting technologies of TGT, EST, EDT categories. S1 corresponds to a baseline scenario, while S2 and S3 present an increasing level of technology penetration.
At 2020, in particular, the baseline selected as reference for generation/load at 2020 is provided by the EU2020 scenario (complying with the 2020 RES targets) of ENTSO-E Scenario Outlook & Adequacy Forecast (SO&AF) 2013-2030 with opportune adaptations [9].
TGT and EST do not vary across scenarios at 2020, as the TGT and EST expansion plans are already set for 2020 (this will however change for 2030 and 2050). In this sense, the key reference duly taken into account for 2020 TGT evolutions scenario is given by the ENTSO-E Ten-Year Network Development Plan (TYNDP) [6], whose data on interconnections have been opportunely complemented by the ones of the European Commission's Projects of Common Interest (PCI) (see Figure 3, left) [17][18] and of the Projects of Energy Community Interest (PECI) (see Figure 3, right) [20]. For 2020 EST evolutions scenario, key data on storage projects in Europe are based on PCI documents [17][18] and on national plans [8].
At 2030 the reference scenario for generation/load is provided by the updated Vision 3 (V3) scenario of ENTSO-E SO&AF 2013-2030 [9], with opportune adaptations in line with the 2030 EU targets (and also to include electric vehicles).
The respective 2020 and 2030 scenarios feature a quite high penetration of RES in the different European countries: they have been then selected to investigate the role and the needs of new technologies in those contexts towards a techno-economically effective RES integration. In fact, starting from 2030 scenarios, several sensitivity analyses related to technology penetration are further carried out. The same applies for 2050 scenarios that are constructed following 2030 trends.
The technology mixes for 2050 will include variable levels of TGT (especially HVDC), EST and DST technologies for S1, S2, S3, with sensitivity analyses/subcases.

Figure 3: Map of PCI (left) [17][18] **and map of PECI** (right) [20]

The implementation of the different innovative technologies within the devised scenarios for the pan-European zonal study is carried out by the model of MTSIM (Medium Term SIMulator) tool [4][19].
MTSIM, developed by RSE, is a zonal electricity market tool able to simulate the behavior of the modeled European electricity system by a DC optimal power flow, having as objective function the minimization of the costs of the whole electricity exchanged (including load shedding and excess energy costs) and determining the hourly clearing of the market over an annual time horizon. The model takes into account the variable costs of thermal power plants (fuel, operation and maintenance, and CO_2 emission allowances), as well as the bidding strategies put in practice by producers, in terms of mark-ups over generation costs (within GridTech, however, no market power exercise will be simulated, given the different uncertainties, while focusing on the "natural" best response of the

system). By modelling active power flows, MTSIM can detect transmission congestion and the needs for network reinforcement can be quantified.
The main results provided by the simulator are: hourly marginal price for each market zone, hourly dispatch of all power plants, hourly inter-zonal power flows, fuel consumption and cost for each thermal power plant, as well as CO_2 emissions and related costs for emission allowances.
MTSIM is also able to take into account in its model innovative technologies such as HVDC links, PSTs, DSM, storage, whereas the meshed HVAC interconnected system is considered via the equivalent PTDF (Power Transfer Distribution Factor) matrix [4][19].
An important feature of the simulator is the network expansion planning modality: it can increase inter-zonal transmission capacities in case the annualized costs of such expansions are lower than the consequent reduction of costs due to a more efficient generation dispatch. This feature can support the determination of the optimal expansion of the European cross-border transmission system: this element is to be used within GridTech for some 2030 scenarios and especially for 2050 scenarios analyses, while for 2020 the interconnection development is practically already set, as above highlighted, based on available expansion plans [6][18][20].
For GridTech zonal (top-down) study, the pan-European (EU30+) power system has been then modeled with an equivalent representation where each country is taken into account by a node (i.e. market zone), interconnected with the other zones/countries via corridors characterized by an equivalent inter-zonal transmission capacity[11]. Figure 4 shows the current synchronous areas of the European power system, five of which are now part of the ENTSO-E association[12]. It is important to note that, even if BALTSO is now part of ENTSO-E system, it is still synchronously interconnected with the Russian IPS/UPS system.

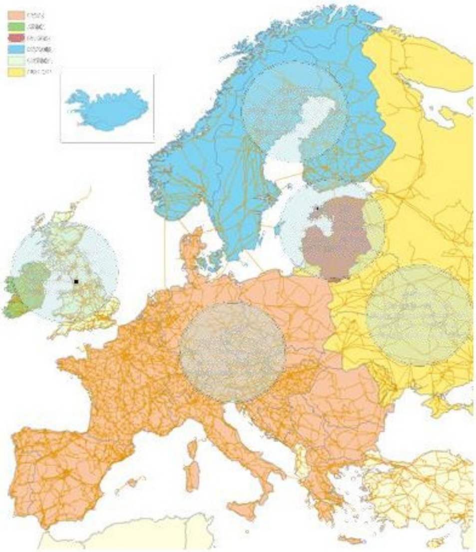

Figure 4: The European synchronous areas (2010) [15]

In the pan-European study the modelled EU30+ system takes fully into account endogenous countries such as the today's 28 Member States of the EU (EU28), the EU current and potential candidates (Albania, Bosnia-Herzegovina, FYR Macedonia, Iceland, Montenegro, Serbia, Turkey), and EFTA[13] countries (like Switzerland and Norway). Figure 5 and Figure 6 show the zonal scheme for the EU30+ system in GridTech 2020 and 2030 (preliminary) scenarios studies, respectively.
In Figure 5 and Figure 6 the endogenous zones, mostly interconnected via HVAC (in black) and/or HVDC (in blue) corridors, are represented in light grey, whereas the exogenous zones (external regions), with which the EU30+ system exchanges imports/exports (blue arrows), are highlighted in orange. Figure 6 takes also into account some of the further potential inter-zonal corridors, based on

[11] The concept of inter-zonal transmission capacity resembles the one of Net Transfer Capacity (NTC): within GridTech the corresponding highest values of NTC are taken at each interface in both flows directions [4].
[12] This refers namely to the systems of former UCTE (continental Europe), NORDEL (Nordic countries), BALTSO (Baltic countries), UKTSOA (United Kingdom), and ATSOI (Ireland).
[13] EFTA (European Free Trade Association) currently includes Iceland, Liechtenstein, Norway and Switzerland.

HVAC (dashed black) and/or in HVDC (dashed blue), that may be techno-economically convenient and deployed at 2030.

From Figure 5 and Figure 6 it can be seen that the actual number of endogenous systems at 2020 and 2030 totally amounts to 39, as Northern Ireland is treated separately and Germany has been split in two zones with the purpose to also highlight some of the internal north-south HVDC OHL-based corridors planned within German grid[14] [6][24]. On the contrary, Denmark is considered as a single zone, though Figure 5 and Figure 6 show both the western Denmark zone (DK_W) and the eastern Denmark zone (DK_E), interconnected through HVDC link, to highlight the respective inter-zonal (HVAC and HVDC) corridors with the neighboring countries. Endogenous countries like Cyprus and Iceland are isolated zones at 2020 (see Figure 5), but they may be potentially connected, via HVDC cable(s), to the rest of the pan-European system at 2030 (see Figure 6 for Cyprus [18]) and/or at 2050.

In the pan-European study, Turkey is considered as endogenous country, given the ongoing process of synchronisation of the Turkish system with the one of ENTSO-E Continental Europe [5][6]; the linked zones at the Turkish eastern edge have then to be considered for their exchanges with Turkey and they are treated as exogenous zones [21]. On the other hand, the systems of Ukraine and Moldova, that are interconnected (and partially synchronised[15]) with the one of ENTSO-E Continental Europe, are considered as external regions at 2020 and 2030. However, in the mid/long term (2030 and beyond) they may be fully integrated within the European electricity market and synchronously operated with the system of ENTSO-E Continental Europe [5][6]. For this reason, given the possibility to change status in 2030-2050, the zones of Ukraine and Moldova are depicted in light green in Figure 5 and Figure 6.

At 2020 the exogenous countries (external regions) for the EU30+ system are (see Figure 5): Morocco (MA), Russia (RU) and its Kaliningrad enclave (RU-KA), Belarus (BY), Ukraine (UA), Moldova (MD), Georgia (GE), Armenia (AM), Azerbaijan (AZ), Iran (IR), Iraq (IQ), Syria (SY). At 2030 the potential exogenous countries for the EU30+ system, in addition to the ones considered at 2020, may also include (see Figure 6): Algeria (DZ), Tunisia (TN), Israel (IL) [6][18].

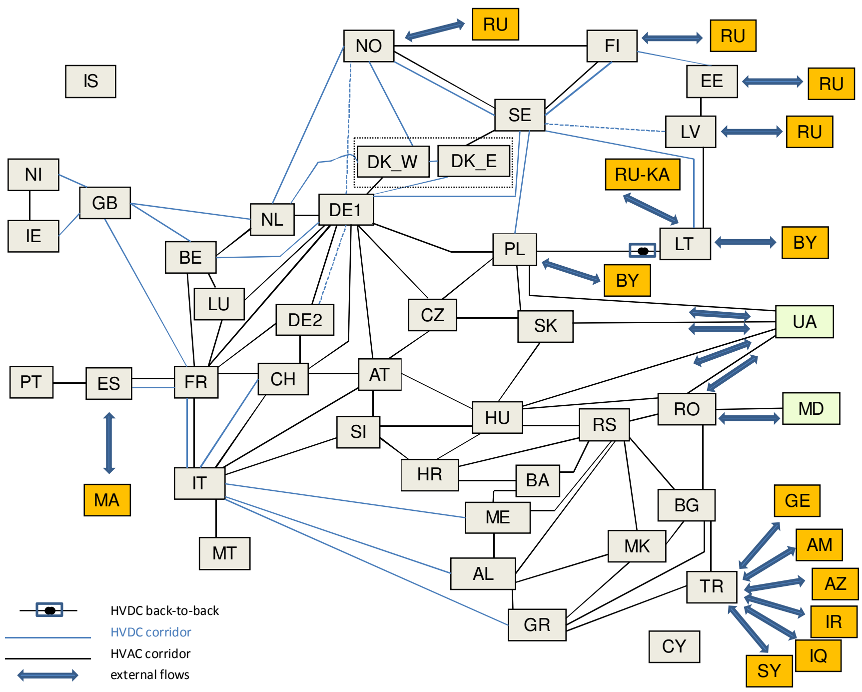

Figure 5: Zonal scheme of the pan-European system at 2020

[14] DE2 represents the south-western part of the German system, operated by TransnetBW, whereas DE1 takes account of the rest of German system, operated by the other three German TSOs (see also Section 5.).

[15] The network of the Western Ukraine region (so-called Burshtyn Island), currently disconnected from the rest of Ukrainian system, is synchronously operated with the ENTSO-E Continental Europe grid through its links with Slovakia, Hungary and Romania. Moldovan grid has several cross-border ties with Romanian system, but these are operated in radial mode for direct exchange or for serving passive islands.

Figure 5 and Figure 6 also highlight the installation of HVDC back-to-back (BTB) devices within the EU30+ system: these technologies are utilised to interconnect asynchronous systems. Currently, there exists only one HVDC BTB device installed in Europe, namely in the Russian grid, part of the IPS/UPS system, at the interface with the network of Finland belonging to the ENTSO-E Nordic system. Being this HVDC BTB device installed outside the EU30+ system, it is not represented in Figure 5 and Figure 6, however its effects are taken into account by the external flows exchanged with the exogenous zone of Russia. On the other hand, Figure 5 includes the HVDC BTB devices in the Lithuanian system at the cross-border interface with the grid of Poland as they are planned to be in operation by 2020 (then, the respective ENTSO-E Continental Europe and ENTSO-E Baltic systems will not be synchronously operated by 2020, but they shall be by 2030 [6][18]): the 2030 synchronous operation is taken into account by Figure 6. Further HVDC BTB devices are planned by 2020 at the interface between the networks of Turkey and Georgia [21]. At 2030 there are different options for more HVDC BTB devices to be installed at the eastern edges of the EU30+ system, namely at the borders with Ukraine (see Figure 6), Russia and Kaliningrad region, and Belarus (see also Table 1). The effects of all the HVDC BTB devices located outside the EU30+ system will be taken into account by the external flows exchanged with the respective exogenous zone [6][18].

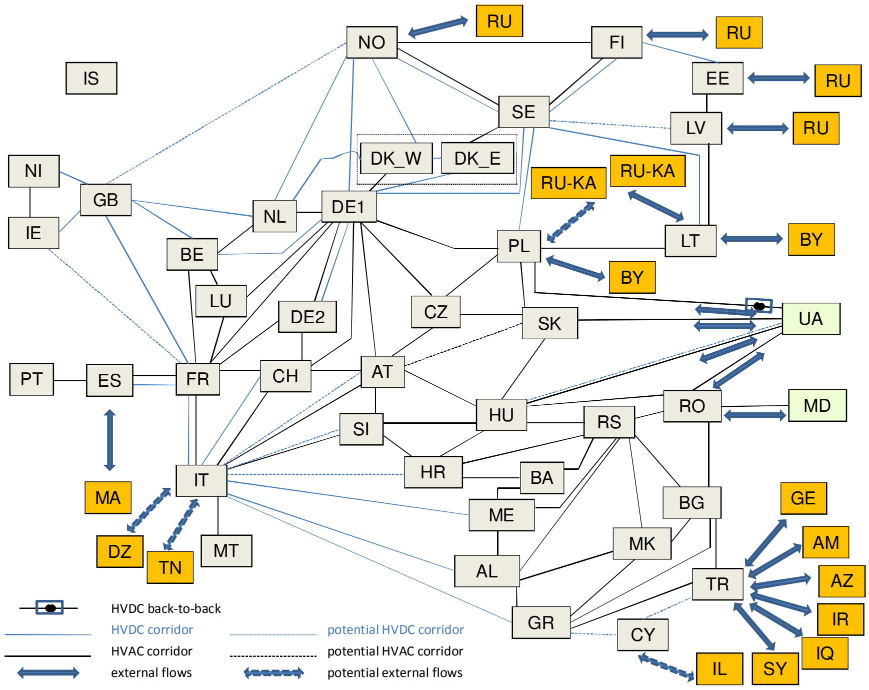

Figure 6: Zonal scheme of the pan-European system at 2030 (preliminary analysis)

In the long term (2030-2050), in order to take into account the developments related to the potential realisation of an offshore grid in the North Seas, additional endogenous offshore zones may be also considered in the EU30+ system.
Upon MTSIM model runs, for the different scenarios at each target year the results of the cases "with" and "without" the technology investment(s) under scrutiny are compared and the electricity system benefits can be calculated. Subsequently, by applying the methodology developed for the CBA, the electricity system benefits are balanced by the relevant technology costs and the different CBA indicators can be determined. Further sensitivity analyses are conducted within scenario studies.

5. REGIONAL CASE STUDIES

Taking some of the outcomes of the pan-European analysis into account as boundary conditions for 2020, 2030 and 2050 scenario timeframes, GridTech focuses further on 7 target countries: Austria, Bulgaria, Germany, Ireland, Italy, Netherlands, Spain. The analyses on these countries are based on market and/or grid detailed approaches.
In the following, an overview of the 7 regional case studies is provided.

Austria

At present, the Austrian electricity production is dominated by run-of-river power plants (38.5%) and PHES (18.9%). Remaining generation is covered by thermal power plants and other RES (mainly wind and increasingly photovoltaic, PV) generation. Besides PHES, also wind and PV capacities are denoted to increase significantly in the future. Furthermore, the Austrian electricity system cannot be treated and analysed isolated; due to the high share of PHES in Austria there have existed a strong cooperation with Germany since decades. Moreover, the further significant increase of variable RES installations (onshore wind, offshore wind, and PV) in the neighbouring countries (notably Germany and Italy) requires even better interconnections to the Austrian electricity system. The state-of-the-art of transmission interconnections from/to Austria is as follows: on the one hand, there are less congested transmission lines at the Austrian interfaces with Germany, Czech Republic, Hungary and Slovenia; on the other hand, there exists significant and frequent congestion on the interconnections at the Austrian interfaces with Italy and Switzerland. There is currently no link directly interconnecting Austria and Slovakia.

The Austrian case study analyses within GridTech are performed by investigations on the target years 2020, 2030 and 2050. For 2020 scenarios, focus is on the following specific measures and technology developments: completing 2 major 380 kV HVAC OHLs projects to close the so-called "380 kV HVAC transmission ring"; increasing/upgrading PHES capacities to support balancing of the neighbouring countries; studying the impact of further increase of wind (eastern part of the country) and notably PV (across the country) penetration. For 2030 scenarios, attention is paid to the following specific issues, measures and technology developments: studying the growing load flows from north to south, also including the possibility of a future HVDC link on the axis Germany-Austria-Italy (through the "Brenner base tunnel"); applying HTLS conductors on selected internal and cross-border HVAC OHLs; evaluating the impact of increasing implementation of DSM, DR and smart grids measures; implementing FACTS and DLR-based OHLs by sensitivity analyses. For 2050 scenarios, further in-depth studies are to be conducted, considering up-scaling of 2030 measures.

To perform these analyses, an optimisation model developed, specifically adapted, will be applied.

Bulgaria

The applied feed-in tariffs support scheme in Bulgaria led to a huge amount of installed RES generation capacity (1013 MW of PV and 677 MW of onshore wind) versus average hourly gross load (4270 MW) for 2012. The direction towards RES generation, which gave rise to massive construction of wind parks, imposes on the system a new development process, mainly in the region of North-East Bulgaria. In addition, during the spring of 2013, the Bulgarian TSO ESO applied in some cases curtailment of RES production due to the impossibility to manage balance between generation and consumption with available reserve/storage capacities. Within GridTech Bulgarian case study, settling the above mentioned problems and facilitating further penetration of RES represent key goals, to be realized by a set of measures applied for each case study target year 2020, 2030, 2050. For 2020 scenarios, focus is on the following specific measures and technology developments: uprating transmission capacity of selected HVAC OHLs by applying HTLS conductors; increasing the capacity of PHES plant in Yadenitsa.

For 2030 scenarios, focus is on the following specific measures and technology developments: applying HTLS conductors to further increase transmission capacity of key HVAC OHLs; studying the effects of new PHES plant project in Gorna Adra; analysing the impact of 2% penetration level of electric cars out of the total amount of vehicles in Bulgaria; implementing DSM with range of load variation from 20 MW to 100 MW; incorporating 0.5% battery storage penetration level out of total demand on distribution grid.

For 2050 scenarios, focus is on the following specific measures and technology developments: analysing the impact of 10% penetration level of electric cars out of the total amount of vehicles in Bulgaria; implementing DSM with range of load variation from 120 MW to 225 MW; incorporating 2% battery storage penetration level out of total demand on distribution grid.

To perform these analyses a grid-based tool will be mainly applied.

Germany

High feed-in tariffs in Germany in recent years led to a huge amount of installed decentralized RES capacities. By end of 2012, 32.9 GW of PV and 31.1 GW of onshore wind capacity had been installed, mainly in the distribution grid. The four German TSOs (50HertzT, Amprion, TenneT TSO GmbH and TransnetBW) have the common task governed by the German Energy Industry Act of producing a grid development plan (GDP) for the expansion of the transmission networks for the coming ten years [24]. The two core elements of German GDP developments can be simply represented by a virtual wind power "busbar" in northern Germany and the integration of solar energy in southern Germany by regional grid reinforcement in a virtual solar "busbar".

Integrating these two power busbars and connecting generation and load demand by up to four HVDC OHLs, in accordance with German GDP, are the main challenges behind the underlying scenarios (partly) for 2020 and (fully) for 2030 and 2050 target years of German case study within GridTech. For 2020 scenarios, focus is also on DLR for HVAC OHLs.

For 2050 scenarios, DSM and storage options mainly will be further considered and analysed. Confidentiality reasons limit the area of analysis to the south-west of Germany (transmission system zone operated by TSO TransnetBW): German case study analyses in GridTech refer then to a German system split into two regions (see also Section 4). In addition, this will allow the investigation on the effects of some of the planned HVDC corridors, directly connected to the TransnetBW zone, which is also currently highly affected by the north-south power flows, with respect to the rest of Germany and neighboring countries. This represents a key aspect to be analysed within GridTech.

To perform these analyses a grid-based tool will be mainly applied.

Ireland

The Isle of Ireland has large potential of RES, such as wind, wave, tidal sources; notwithstanding this, its geographical position challenges the country on the size of RES deployment. In fact, a limited RES exploitation may be sufficient to cope with EU 2020/2030 targets in the mid-to-long term; however, a further RES exploitation may give the possibility to export premium energy to be sold in the European electricity market.

Large investments in transmission are required, both to connect the RES to the existing grid and to better integrate the Irish Island into European system. Therefore, the objective is to find a techno-economic break-even between operation and investment costs, which depend on the type of TGT applied, the amount and locations of RES, the market arrangement, the penetration of DR technologies and regulation policies in the framework of the smart grid initiatives. This multi-faced analysis will be also considering the penetration of multiple sea storage plants.

The Irish case study scenarios within GridTech will be developed in a long term horizon with intermediate steps, with particular focus for the target years 2020, 2030, 2050. The study analyses aim at investigating the effects of different RES/DR penetrations as well as EDT, EST and TGT; by using sensitivity analysis a matrix of worth of deployments in different conditions will be singled out. On the other hand, it will be possible to provide a relationship between transmission investment and flexibility/controllability of the grid.

A grid expansion planning tool, developed with RSE [29], will be used to single out future reinforcements, TGT and grid architectures for each sensitivity analysis, followed up by an AC study.

Italy

Over the past five years (from 2009 to 2013) in Italy, due to a particularly favourable incentive system, the installed capacity of RES plants (mainly wind and especially PV) has impressively increased by more than 15 GW (by a huge boost of +1500% for PV and +70% for wind capacity, respectively).

While the PV penetration is mostly affecting the low and medium voltage grid (but being also progressively connected to the high voltage network), the wind farms mainly impact directly on the high voltage transmission grid: the fact that these are mostly concentrated in the South of Italy away from large loads, generally located in central and northern Italy, has led to grid congestion on the local network and curtailment of RES production. In addition, the geographical location of Italy naturally predisposes it to be an electricity hub in the Mediterranean Sea, acting as a "transit country" for the expected power flows from North Africa and from South-East Europe.

Within GridTech, separate analyses for the Italian case study will be performed for the target years, 2020, 2030 and 2050, in the short, medium and long term, respectively. The preliminary results, obtained by a market simulation tool, will be further complemented by network studies and evaluated via cost-benefit analyses. The technology focus will consider for each target year: in 2020 scenarios, HVDC interconnections, HTLS conductors for HVAC OHLs and EST will be implemented; in 2030 and 2050 scenarios, HVDC technologies will be further considered, including AC / DC conversion of HVAC OHLs towards the potential development of a HVDC overlay grid; moreover, smart grid technologies and DSM will be added, too.

Netherlands

A country as the Netherlands has large potentials for onshore and offshore wind generation and plays a relevant role in the design of the future potential offshore grid in the North Sea. It may become a major transit country crossed by large power flows coming from the North Sea and supplying load in Continental Europe.

The present HVAC network in the Netherlands, after the completion of the so-called "large projects", is almost at the limit of the extension possibilities, on the one hand due to spatial planning and social acceptance issues and on the other hand due to technical limits. For further extension of the transmission capacity and for the transfer of large power flows, new technology architectures and options should be explored. One of the promising options consists in the application of a HVDC overlay grid, which may not only reduce the loading of the HVAC network, but it can also be more controllable than traditional grids.

One of the key goals of the Dutch case study within GridTech is then related to the determination of the most favourable topology of a potential HVDC overlay grid and its connection points to the HVAC network. If applicable, the overlay grid may be extended to be connected to large load centres in Germany.

Considering the target years 2020, 2030 and 2050, the analysis will focus on the mid-to-long term effects that the implementation of a HVDC overlay grid may have on the electricity systems of the Netherlands. Attention will in particular be paid to: the effects that transmission grid congestion and its relief through changes in the network structure will have on the level of integration of variable RES generation; the impact of the use of new technology options, compared to conventional ones (e.g. AC vs. DC). Further technologies, like DSM and battery storage, will be also considered and compared to HVDC. To perform these analyses, market-based and grid-based tools will be applied.

Spain

Spain has one of the largest penetration levels of wind generation in Europe and a great potential for solar power. Furthermore, it may become an important transit country for RES electricity if large amounts of solar generation are deployed in North Africa and exported to Europe (via the Morocco-Spain link). As a consequence of this significant penetration of renewable generation, the curtailment of RES production in Spain may be more and more required, not only due to network constraints, but also due to excess of generation, in case of no action.

Within GridTech, separate analyses for the Spanish case study will be performed for the target years, 2020, 2030 and 2050, in the short and mid-to-long term, respectively. The technology focus of each target year depends on the main challenges faced to integrate renewable generation into the grid and technology developments expected by those years.

For 2020 scenarios, the short term analysis focuses on the deployment of FACTS and DLR for HVAC OHLs to increase the internal existing grid capacity by alleviating transmission grid congestions due to higher RES-generated power flows.

In the longer term (2030-2050), it is expected that the Spanish system will not be able to absorb all the renewable energy produced in the Iberian Peninsula, especially if renewable generation is imported from North Africa. The analysis for the target year 2030 focuses on DR, which is expected to be highly deployed by that year, and storage (PHES and CAES). In 2050 the focus is put mainly on HVDC (by further expanding interconnection capacity with France) and storage options.

For 2020 and 2030-2050 analyses, adequate tools incorporating technologies modelling for grid-based and zonal-based studies, also duly including the effects of flows from North Africa, are to be respectively used.

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