Identifying Energy Efficiency improvements and saving potential in energy networks

Interim report

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Foreword

This interim report has been prepared for the European Commission by a consortium composed of Tractebel Engineering and Ecofys. The correspondence between the tasks in the terms of reference and the sections of the interim report are reported in the figure below:

	Electricity	Gas
TASK 1 – What is the **energy efficiency potential** in gas and electricity infrastructures?		
T 1.1 Literature Review (elec & gas) **T 1.2** Qualitative mapping of measures (elec & gas)	• **Section 2.1** Understanding energy losses in electricity network	**Section 5.1** Understanding energy losses in gas networks
T 1.3 Potential of EE measures (elec & gas)	• **Section 2.2** Energy efficiency measures in electricity networks: categorisation and potential • **Section 3** Potential of measures on operational efficiency in electricity grids	**Section 5.2** Energy efficiency measures in gas networks: categorisation and potential
TASK 2 – How to **select most cost-effective measures**?		
T 2.1 How to rank EE measures according to cost-effectiveness	• **Section 4.1** Methodology to assess the cost-effectiveness of energy efficiency measures in electricity grids • **Section 4.2** Synthesis of the cost effectiveness of the measures	**Section 6** Assessment of cost-effectiveness of selected energy efficiency measures - Gas
T 2.2 Cost-effectiveness ranking tool	• **Excel tool -** electricity grids	• **Excel tool -** gas grids

The second part of the assignment will focus on demand response. A final report will be delivered at the end of the assignment and will integrate this interim report.

The project has been led by Stéphane Rapoport (Tractebel Engineering). Task leader for task 1 has been Georgios Papaefthymiou (Ecofys) and task leader for task 2 has been Vincenzo Giordano (Tractebel Engineering). The core team has included Gregoire Lejeune (Tractebel), Farid Comaty (Ecofys) Amelie Bonard (CRIGEN) and Pascal Vercamer (CRIGEN).

In addition to the core team valuable contributions have been made by several of our colleagues at Tractebel Engineering and Ecofys.

The work has been followed by Mr Massimo Maraziti of the European Commission DG-Energy. During the study, a survey has been carried out among European DSOs, thanks to the facilitation role of European associations EURELECTRIC, CEDEC, GEODE, EDSO4SG.

All conclusions are the responsibility of the analysis team and do not necessarily reflect the views of the European Commission, or any of the consulted stakeholders.

We are very grateful for all the valuable comments and suggestions received from the DG Energy officers and the consulted organizations. Any remaining errors or omissions are the sole responsibility of the analysis team.

Executive Summary

Objective of the study

According to Article 15(2) of the Directive, Member States have to ensure, by the 30th June 2015, that:

- (a) an **assessment** is undertaken of the **Energy Efficiency potentials of their gas and electricity infrastructure**, in particular regarding transmission, distribution, load management and interoperability, and connection to energy generating installations, including access possibilities for micro energy generators;
- (b) **concrete measures and investments are identified** for the introduction of cost-effective Energy Efficiency improvements in the network infrastructure, with a **timetable for their introduction**.

According to collected information at the moment of finalization of the interim report, some Member States are finalising their assessment, while others presumably are not.

The main objective of this study is therefore to support Member States which have not yet carried out the assessment. The study also aims at defining common ground to carry out the review of the assessment reports that will be submitted by Member States to the EC.

Perimeter of the study

Energy savings/loss reduction. Loss reduction is an important aspect of efficiency in energy grids. To date, the electricity and gas consumption is responsible for 43% of the final energy consumption in the EU and their infrastructure losses account for 1,5% and 0.3% respectively . Losses levels vary among Members States. One key way to improve energy efficiency is to reduce energy wastage. In the electricity sector this wastage is referred to as losses and in the gas sector as shrinkage [2]. Energy efficiency potential therefore implies the minimisation of wastage in both gas and electricity transmission and distribution. The study will assess the potential of selected measures to meet this objective.

Planning/Operational Efficiency - The directive also considers that, in assessing grid energy efficiency measures, planning/operational efficiency should also be considered. This entails exploring opportunities to improve the efficient operation of available energy infrastructure and reduce the need for investing in new infrastructures[1].

[1] DG ENER guidance note http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52013SC0450&from=EN point 57 and 58, Chapter E

This study will particularly consider the planning/operational efficiency potential in electricity grids, where, thanks to new “Smart” measures allowing active grid management (Smart Grid assets; flexibility of distributed energy resources), a higher potential for operation efficiency is available.

In particular, detailed analysis of the impact of demand response on energy efficiency (taking a broad view on energy efficiency and encompassing losses, and planning/operational efficiency) will be carried out in the second part of this study.

Methodological approach

The assessment of the energy efficiency potential in electricity and gas grids has been carried out according to the following four-step approach:

1. Identification of key **measures improving the energy efficiency** of gas and electrical grids.
2. Identification and discussion of the potential of those measures in term of losses reduction, through the identification the **type of sources of losses** in electricity and gas grids and a mapping between the sources of losses and the **corresponding measures** that can mitigate those losses
3. Discussion of the **potential for planning/operational efficiency** of each measure, looking at aspects like investment deferral, RES hosting capacity, outage reduction, power quality
4. Identify the **factors that affect the potential** of each measure (e.g. load demand, pressure level etc.)

The analysis is supported by examples of the observed impacts of the measures based on literature review and a **data collection survey** carried out with **European system operators’ associations** (Eurelectric, EDSO, GEODE, CEDEC). Around 15 European distribution system operators have participated to the survey and shared their experiences and best practices (more details in ANNEX III and IV).

A key outcome of the study is the definition of **a step-by-step methodology** to guide Member States and system operators in the definition of energy efficiency measures **for electricity and gas grids**.
To this end an **ad-hoc decision support tool** has been set-up (ANNEX V).The goal of the tool is to help project promoters in selecting good candidate measures and refine their Energy Efficiency strategy before carrying out full detailed cost-benefit analyses.

Some of the key outcomes and insights are summarized here below.

Grid Energy Efficiency - State of play in Member States

- European associations report that most of their members have not yet been actively involved by Member States in addressing the provisions of article 15.2. The level of mobilization in EU Member States in the implementation of the provisions of article 15.2 (definition of investment plans to improve grid energy efficiency) appears to vary across Member States.
- Based on collected information, a number of Member States are working on the topic and would likely publish their official assessments in the period after the completion of this study.
- According to information available at the time of publication of this study, Member States seem mainly to consider loss reduction initiatives in their assessments.
- Starting conditions of grids (e.g. voltage level; number of transformers) and potentials for energy efficiency improvement vary widely. In particular, the level of losses varies significantly among Member States.
- Loss reduction is typically taken into account in grid investment decisions, however often it is not the main driver for ad-hoc investments.
- For electricity grids,
  - System operators generally opt for traditional investments (replacement of assets; reinforcements etc.) to improve grid energy efficiency (mainly targeting loss reduction)
  - Smart Grid-related EE measures (e.g. use of flexibility of DER) to pursue energy efficiency are less common; the existence of regulatory barriers hindering their viability.

Mapping of losses – electricity grids

- A detailed categorization of losses in electricity grids have been carried out to map out where and why losses occur in electricity grids.
- A list of factors that have a key impact on the level of losses in the system have been identified, including:
  - Loading (including peak demand)
  - Number of energized transformers
  - Lengths of the feeders
  - Level of power quality
  - Presence of distributed energy resources
- The main potential for reduction of electricity grids is at distribution level, where the majority of losses occur.
- The implementation of adequate metering systems at substations and at customers’ premises is an important first step to identify where losses are actually occurring in the distribution grid and to better target EE measures.

Mapping of losses – gas grids

- A detailed mapping of losses in gas grids and compression stations has been carried out. Over 15 sources of losses have been identified.
- A list of factors that have a key impact on the level of losses in the system have been identified and analysed, including:
  - Pressure level, volume of vented pipe
  - Length and age of the grid, pipes and joints materials
  - Number and efficiency of heaters, necessity of burners
  - Base or peak load compressor

Planning/Operational efficiency improvement potential

- The potential benefits of each measure in term of planning/operation efficiency have been analysed, particularly for electricity grids where a higher potential of improvement exist. The following dimensions of planning/operational efficiency have been considered:
  - Investment deferral
  - RES hosting capacity
  - Security of supply (reduction of outages)
  - Power quality
- The factors impacting the effectiveness of each measure and the potential cost ranges have also been analysed. The factors need to be tailored to specific grid conditions to assess the cost-effectiveness of individual measures in a given context.

Drivers and regulation

- Measures which require the exploitation of DER flexibility have still limited diffusion in many Member States, often just at pilot level. Their implementation would require the definition of new regulatory mechanisms over how DSOs can procure and activate DER flexibility. On this topic, a specific focus on Demand Response will be carried out in the second part of the study.
- Energy efficiency (and particularly loss reduction) is the main driver of investments when there is the need to comply with regulatory requirements and quality standards (e.g. EcoDesign directive). In general, loss reduction is considered as one of the variables of a larger investment optimization plan, but not the main driver for investmnts.
- The incentive to pursue specific investments for loss reduction is strictly related to the presence of regulatory incentives. A wide variety of regulatory frameworks are present in European Member States, which in some cases do not explicitly support loss reduction measures.

Catalogue of measures and decision-support tool

- A detailed catalogue of energy efficiency measures together with an assessment of their cost-effectiveness has been defined for electricity and gas grids.
- As the potential of these measures is very much related to the specific local grid conditions, the analysis has focused on the assessment of key factors affecting the benefits and the costs of selected measures. System operators then need to customize these factors to their specific local grid conditions.

- An excel tool has been set-up to guide project promoters in the assessment of the cost-effectiveness of different energy efficiency measures according to their local grid conditions. The tool highlights the main factors affecting the benefits and cost of each measure and provides examples for benchmark.

Cost-effectiveness of energy efficiency measures

- A number of factors can greatly impact the cost-effectiveness of energy efficiency measures, such as:
    - Monetary value of losses, i.e. the average price of wholesale electricity (the higher, the more cost-effective are energy efficiency measures)
    - Loss reduction is in many cases a side-benefit of investments driven by other needs. The cost-effectiveness of energy efficiency improvements should thus be analysed within the context of a larger investment plan.
    - Parallel grid developments (e.g. roll-out of smart meters; built-in smart functionalities in DG converters etc.) make the enabling infrastructure for certain EE measures already available, reducing their implementation costs.
    - Energy efficiency measures could have conflicting objectives (e.g. loss reduction and hosting capacity when implementing DG voltage optimization).
    - External factors outside the control of system operators can also greatly impact the potential of EE measures: e.g. the development and location of DERs.

A system approach to energy efficiency

- A systemic approach should be adopted when assessing the impacts of the implementation of a portfolio of EE measures. This could include:
    - Synergies among EE measures, i.e. consider the whole EE program rather than individual EE measures. This includes the assessment of possible negative influence of parallel implementation of measures.
    - Synergies with on-going parallel investments in the energy system (e.g. installation of smart converters for DGs)
    - Synergies with replacement/investment programs already scheduled (e.g. oversizing new lines taking into account the loss reduction potential).

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ACRONYMS

Capital Expenditure	*CAPEX*
CHP	*Combined Heat and Power*
Prosumers	*Consumers with local generation*
DR	*Demand Response*
DER	*Distributed Energy Resources*
DG	*Distributed Generation*
DMS	*Distribution Management System*
DSO	*Distribution System Operator*
EE	*Energy Efficiency*
EV	*Electrical Vehicle*
NPV	*Net Present Value*
O&M	*Operation and maintenance costs*
OMS	*Outage Management System*
OPEX	*Operational Expenditure*
PV	*Photo voltaic electricity generation*
RES	*Renewable Energy Sources*
SAIDI	*System Average Interruption Duration Index*
SCADA	*Supervisory Control and Data Acquisition*
TSO	*Transmission System Operator*
VRES	*Variable Renewable Energy Sources*

1 INTRODUCTION

1.1 Objectives of this study

According to Article 15(2) of the Directive, Member States have to ensure, by the 30th June 2015, that:

- (a) an **assessment** is undertaken of the **Energy Efficiency potentials of their gas and electricity infrastructure**, in particular regarding transmission, distribution, load management and interoperability, and connection to energy generating installations, including access possibilities for micro energy generators;
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According to collected information at the moment of finalization of the interim report, some Member States are finalising their assessment, while others presumably are not.

The main objective of this study is therefore to support Member States which have not yet carried out the assessment. The study also aims at defining common ground to carry out the review of the assessment reports that will be submitted by Member States to the EC.

The analysis is supported by examples of the observed impacts of the measures based on literature review and a data collection survey carried out with European system operators' associations.

Finally the study aims at integrating the result of the analysis in an easy-to use decision support tool, to be used by system operators to screen most cost-effective energy efficiency investments.

1.2 The Energy Efficiency Directive

The 2012 Energy Efficiency Directive (EED) establishes a set of binding measures to help the EU reach its 20% energy efficiency target by 2020 [1]. The Directive states that 1.5% of the average final energy consumption in the period 2010-2012 needs to be saved annually from 2014 onwards till 2020. To achieve that, energy efficiency improvements throughout the whole value chain of the energy sector are required, that is from generation-transmission-distribution to consumption of any energy carrier to be delivered to the industry, building or transportation sector.

Article 15 of the EED targets specifically the transmission and distribution sector of electricity and gas and requires thus Member states to perform an assessment of the energy efficiency potential of their respective infrastructure.

Loss reduction is a key aspect of energy efficiency in energy grids. To date, the electricity and gas consumption is responsible for 43% of the final energy consumption in the EU and their infrastructure losses account for 1,5% and 0.3% respectively[2]. Losses levels vary among Members States. One key way to improve energy efficiency is to reduce energy wastage. In the electricity sector this wastage is referred to as losses and in the gas sector as shrinkage [2]. Energy efficiency potential therefore implies the minimisation of wastage in both gas and electricity transmission and distribution networks. Energy savings that can be provided by investing in measures aiming at reducing those grid losses can be significant, depending on the local situation.

Moreover, the directive also considers that grid energy efficiency measures should go beyond loss reduction and also take into account **planning/operational efficiency**. This entails exploring opportunities to improve the efficient operation of available energy infrastructure and reduce the need for investing in new infrastructures[3].

This study will particularly consider the planning/operational efficiency in electricity grids, where, thanks to new "Smart" measures allowing active grid management, a higher potential for improvement is available. In particular, a detailed analysis of the impact of demand response on operational efficiency will be carried out in the second part of this study.

1.3 Reading guide to this document

For sake of brevity and readability, the main text reports the key results and messages of the analysis.
A more detailed description of all the analysis that has been carried out is reported in the Annexes:

- ANNEX I reports detailed analysis of the parameters affecting the potential and the cost-effectiveness of EE measures.
- ANNEX II and III report the results and the questionnaire of the stakeholders' survey.
- ANNEX IV describes in detail the decision support tool (excel file) that synthetises the analysis in a step-by-step methodology.

The interim report is organized in two main parts. A first part analyses the potential and the cost-effectiveness of energy efficiency measures in electricity networks, whereas the second part carries out the same analysis for gas networks.

[2] Ecofys analysis from EuroStat database

[3] See DG ENER guidance note http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52013SC0450&from=EN point 57 an d 58, Chapter E

1.3.1 Energy efficiency measures for electricity grids

Energy efficiency measures for electricity grids are analysed in chapters 2 and 3. Chapter 4 provides a summary of the cost-effectiveness of the selected energy efficiency measures.
The study considers three categories of energy efficiency measures for electricity grids:

- Traditional ones (replacement/reinforcement)
- Network management (e.g. Smart Grid assets)
- Flexibility of distributed energy resources (Feed-in control).

Table 1-1 provides a mapping of the perimeter of the study for the energy efficiency measures in electricity grids.

The second part of the study carries out a dedicated focus on the feed-in control category, especially on demand response. In particular, the use of DR flexibility in planning and operation will be thoroughly explored.

EE Measures for electricity grids	Grid energy efficiency – electricity grids	
	Loss reduction	Planning/Operational efficiency
Traditional (replacement/reinforcements)	Chapter 2	Chapter 3
Smart Network Management	Chapter 2	Chapter 3
Feed-in control (flexibility of distributed energy resources)	Chapter 2	Chapter 3
	Specific focus on Demand Response in second part of the report	

Table 1-1 - Perimeter of the study for energy efficiency measures in electricity grids

1.3.2 Energy efficiency measures for gas grids

Energy efficiency measures for gas grids are analysed in chapters 5 and 6. Selected measures have been categorized as follows:

- Measures for transmission grids
- Measures for compression stations
- Measures for distribution grids

The analysis has mainly focused on the potential for reduction of gas shrinkage in the gas system.
Error! Reference source not found. reports the perimeter of the study for the energy efficiency measures in gas grids.

EE Measures for gas grids	Potential for reduction of gas shrinkage	Cost-effectiveness of measures
Transmission grids	Chapter 5	Chapter 6
Compression stations	Chapter 5	Chapter 6
Distribution grids	Chapter 5	Chapter 6

Table 1-2 - Perimeter of the study for energy efficiency measures in gas grids

2 POTENTIAL OF ENERGY EFFICIENCY MEASURES ON LOSS REDUCTION IN ELECTRICITY GRIDS

This chapter presents the qualitative and quantitative assessment of the energy efficiency potential in electricity infrastructure with particular reference to losses.

Section 2.1 presents the key factors that are central to the understanding of how losses are created in electricity networks. Based on this mapping, section 2.2 presents the key measures for increasing energy efficiency, and key context indicators on how to assess their energy efficiency potential. Figure 2-1 reports best estimations of the level of energy losses in electricity and gas grids in a number of European Member States. The figure shows that the level of losses varies significantly among Member States, hinting that potentials for energy efficiency improvement are different and depends on local conditions (e.g. starting conditions of grids -e.g. voltage level; number of transformers- and potentials for energy efficiency improvement are different).

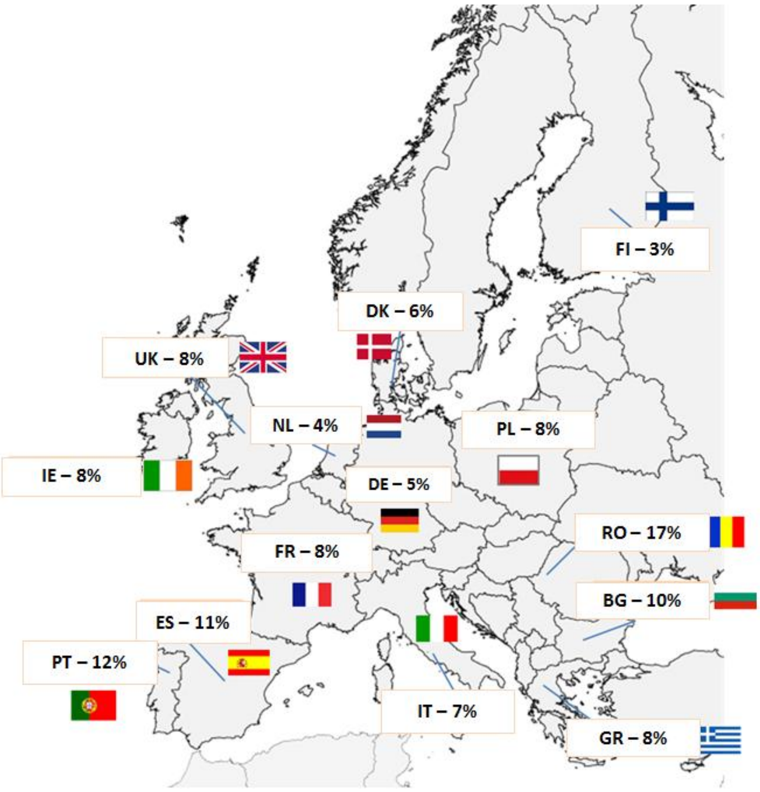


Figure 2-1 – Level of losses[4] in electricity grids in selected EU Member States

[4] Both technical and non-technical losses, based on the Ecofys analysis from EuroStat database

2.1 Understanding energy losses in electricity networks

Energy losses in electricity grids are created through a set of parallel mechanisms which affect the different network components. In order to analyse the impacts and potential of energy efficiency measures, one should understand how losses are created through these mechanisms and how losses are mapped in electricity grids.

Figure 2-2 presents the key factors on the mapping of losses (to allow the quantification of where losses occur in the system), and further presents the key mechanisms for losses creation (for a better understanding of how measures could lead to losses reduction). In total there are 8 key dimensions to categorize energy losses in electricity networks, presented in the following sections.

Figure 2-2: Categorisation of losses in electricity networks: Mapping and key mechanisms [3], [2], [4]

2.1.1 Type: Technical/non-Technical and Variable/Fixed

Electrical losses can be divided into *technical losses*, which refer to energy transformed to heat and noise during the transmission and therefore physically lost, and *non-technical losses*, which refer to energy delivered and consumed, but for some reason not recorded as sales (such as theft). A general rule of thumb is that technical losses can rise up to 12%. When system losses exceed this limit, they are most probably due to increased non-technical losses [5]. In general technical losses can be split into [6]:

- **Variable losses** (also referred to as load or copper losses), occur due to the heating effect of energy passing through conductors in lines and cables and also in the copper in transformers. They vary in proportion to the square of the current and in proportion to the conductor resistance. In essence, measures to reduce variable losses can be understood under these two main influencing factors and how they apply in the global system: they either aim to reduce the system power flows or to reduce the resistance of the transportation paths. In general, variable losses contribute roughly to two thirds to three quarters of the total power system technical losses.
- **Fixed losses** (also referred to as non-load or iron losses), refer to energy needed for the energisation of transformers[5] or conductors. These losses are invariant with current and depend mainly on the number of energised components. In this respect, measures to reduce fixed losses mainly aim to

[5] This refers to the energy needed for the operation of the magnetic fields that enable the operation of transformers.

reduce the number of energised components or to increase their efficiency. In general they contribute to roughly one quarter to one third of the total network losses.[6]

2.1.2 Voltage level: transmission and distribution networks

Electrical losses are directly affected by the voltage level: increasing the voltage level leads to a reduction of system currents and therefore of the respective energy losses. A consultation on the treatment of losses by network operators was conducted by the European Regulators' Group for Electricity and Gas[7] for fourteen EU countries in 2008 and since, no update to the study has been completed[8]. Table 2-1 illustrates the percentage of losses per system level in selected EU countries from [7]. The average losses in transmission networks (TNs) in EU vary between 1-2.6% while for distribution networks (DNs) between 2.3-13.4% [7]. This variation has mainly to do with the historical development and current state of the grids in each country with regard to age, design etc. In general, distribution networks present the highest losses and the highest energy efficiency potential and therefore are the focus of this study.

Country	Average % of losses in TNs	Average % of losses in DNs
France	2.3%	5.0%
Austria	1.5%	4.5%
Czech Republic	1.5%	7%
Slovakia	1%	8.3%
Romania	2.6%	13.5%

Table 2-1: Percentage of losses in transmission and distribution networks in selected EU countries.

[6] Another source of fixed losses are corona losses, which occur in high voltage lines. They vary with the voltage level and the physical wire diameter and with weather conditions such as rain and fog and are generally a very small percentage of the overall system losses.

[7] Referred to today as the Council of European Energy Regulators

[8] Eurostat provides data on for total system losses for each EU country in 2014 but the breakdown of this data does not exist

2.1.3 Components: Lines and Transformers

Power lines and transformers are the primary components of the infrastructure in electricity networks. A key difference is that only variable losses occur in lines, while transformers are responsible for both fixed and variable losses. Figure 2-3 presents how losses are distributed between these two key categories of components for the different voltage levels and different EU countries. As can be seen, the majority of losses occur close to the customer, on low voltage (LV) networks followed by medium voltage (MV) grids. A high variation in energy losses in transformers can be observed, primarily due to the age of the assets.

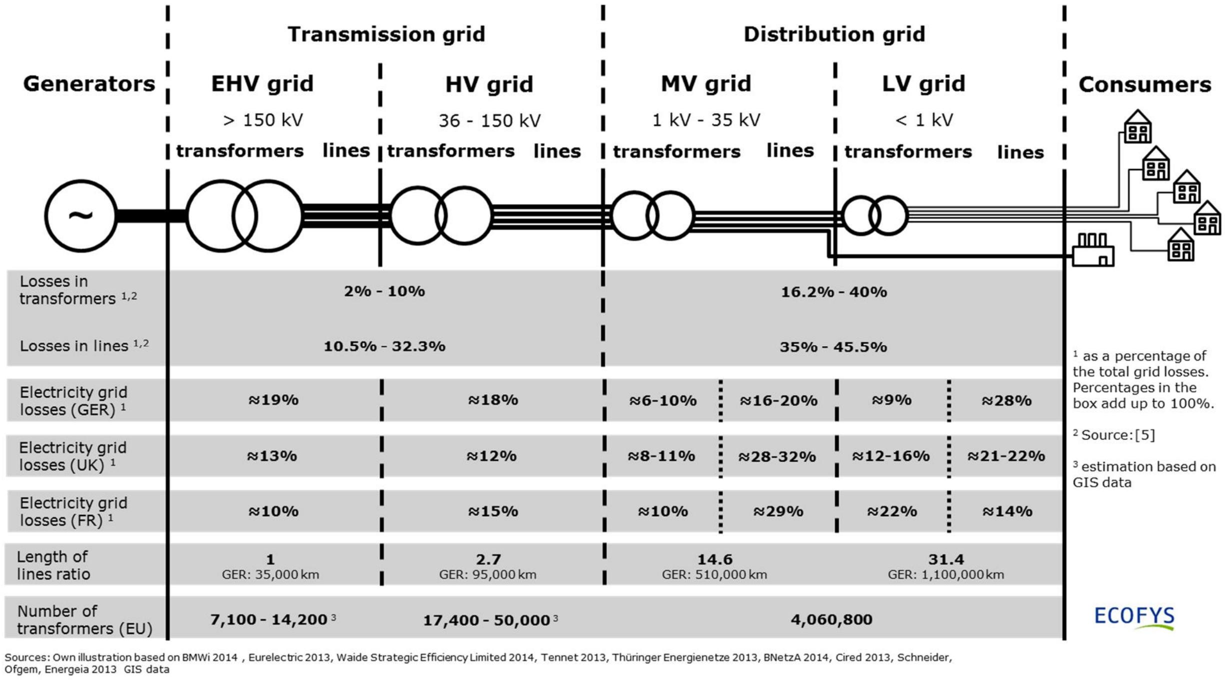


Figure 2-3: Mapping of losses based on voltage level and components for different EU countries (FR: [8], [9]; GER: [10], [11], [12], [13], [14]; UK: [2], [5], [15]; EU: [16], GIS Data)

In Figure 2-3, the sum of the losses of the EHV and HV grids in each country falls in the general range of transmission losses for transformers and lines expressed in the top row of the figure. For example, in Germany, transmission losses sum to 37% of the total grid losses which falls in the range of 13% and 42%. The transmission losses are specifically high in this country compared to France and the UK, both at 25%. This is due to high international transits and internal transits from north to south [17]. Similarly, the distribution of losses is not uniform across countries and depends on the specific grid conditions. For example, in France and UK line losses are higher in the MV grid compared to the LV grid, and in France, losses in LV transformers are higher than in LV lines, whereas in Germany losses are highest in LV lines. We discuss further the factors that affect the losses in each component.

Transformers are the system components presenting both fixed and variable losses. Typically a third of the total system technical losses occur in transformers while fixed losses account for about two thirds of total transformer losses. The operational efficiency of transformers depends on the loading. The peak efficiency of distribution transformers reaches 99.4% at approximately 40-50% of rated capacity [18]. In the EU the average loading of distribution transformers in electricity distribution companies is 18,9%, far below optimal, rendering their efficiency at 98.38% [18]. Since transformers run round the clock for more than 40 years, a 0.1% marginal increase in efficiency of a transformer population leads to significant loss reductions. [18] conducted a unique study in 2008 comparing the operating efficiency of newly purchased versus the existing fleet of distribution transformers in electricity distribution companies across the EU. Figure 2-4 illustrates the results. On average, the efficiency of distribution transformers in the E.U has the potential to increase by 0.35%.

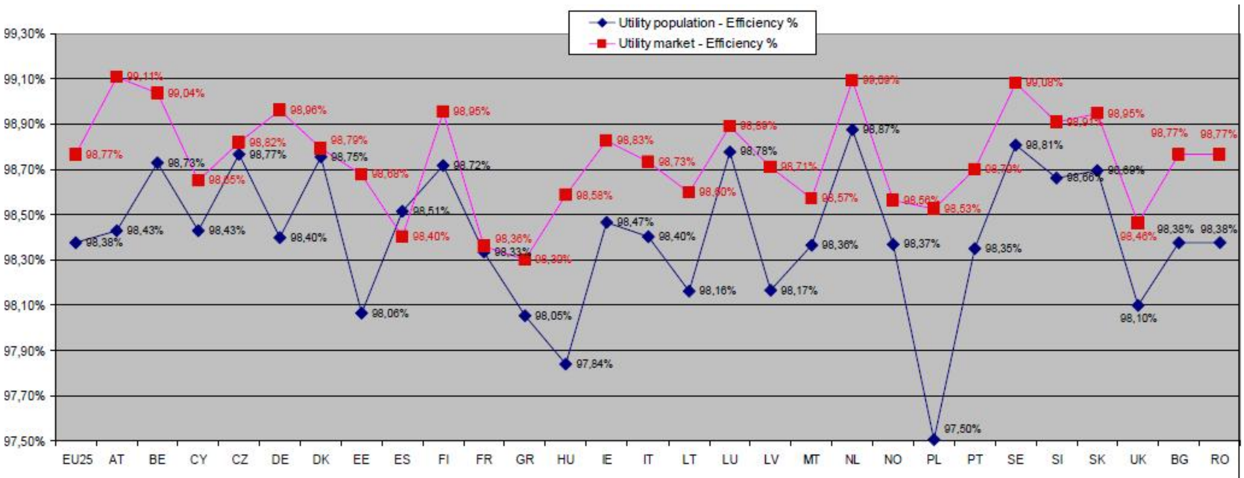


Figure 2-4 Efficiency of distribution sector transformer population and market [18]

Lines

Power lines are the primary source of losses as indicated in Figure 2-3. Power line losses can be considered almost entirely as variable losses and are proportional to the conductor resistance and to the square of the current. Resistance of the line is equal to $= \rho \cdot \frac{L}{A}$, where:

- L is the length of the line, thus long lines have a higher R and higher losses
- A is the cross sectional area , thus thicker lines lead to decreased line losses
- ρ the resistivity, which depends on the material of the line (copper or aluminium) and its temperature, hence a heated line leads to higher losses

The current represents the power flow fluctuation and has a quadratic effect which is discussed below.

2.1.4 Marginal vs Average losses

The currents in a system vary based on the system loading. The variable losses are the sum of the losses for all operational instances, comprising of operational instances of high loading (marginal losses) and of normal loading (average losses). Average line losses are more often used when estimating power losses, due to the fact that they are measured by meters, while measuring marginal line losses requires advanced and expensive meters [19]. Since variable losses are proportional to the square of the current, marginal losses have a much higher contribution to the total sum. This is shown as an example in Figure 2-5 where the losses from 3 cases of system loading are presented. In all cases the same energy is transported, but the loading profiles present a different variability. Smoother loading profiles lead to significant losses reduction, up to 20% for a flat profile.

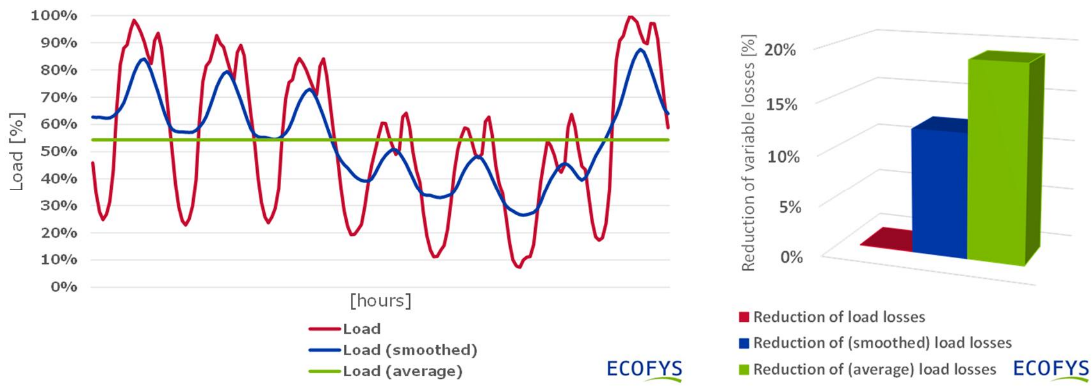


Figure 2-5 Impact of smoothing the system loading on the reduction of variable losses

Therefore, losses increase disproportionally when the system loading is higher, which is actually when they cost more, since normally these are the cases when power prices are higher. Furthermore they create an increase in the system loading exactly at the times when there are less available generation resources. In this respect, efficiency measures that help reduce the marginal loading of the system would have a higher contribution to the reduction of system losses [20].

2.1.5 Role of DG and grid management

In the latest years, distribution networks experience increasing penetration levels of distributed generation (DG), in the form of small-to-medium size generating units connected in medium and low voltage networks. A large share of these units consists of renewable generators, namely wind turbines, CHP or PV panels. The general expectation has been that locating generation closer to demand could reduce losses since the distance over which electricity is transported is shortened and the number of voltage transformation levels is reduced. [21] However, this is only true when the energy generated by DG and variable RES (VRES) units is consumed locally (synchronised to load, local balancing). [22] In reality, such local balancing does not occur, either due to lack of a proper operational market framework or due to the stochastic nature of the prime energy mover (in the case of VRES). This unbalanced operation can lead to increased network flows (and thus losses), often translated into reverse flows from distribution networks to transmission systems. Figure 2-6 presents the expected effect of increasing shares of non-synchronised DG to distribution network losses. In particular, losses are expected to decrease for low penetration levels, due to the fact that no significant reverse flows are expected but after a certain level they increase due to the increased power flows they incur to the system. For example, [23] shows a study case in a LV grid in Switzerland where grid losses reach a maximum reduction of 20% at 25% PV penetration. At a penetration level of 50%, they are equivalent to the case when there was no PV and further increase if more PV panels are installed.

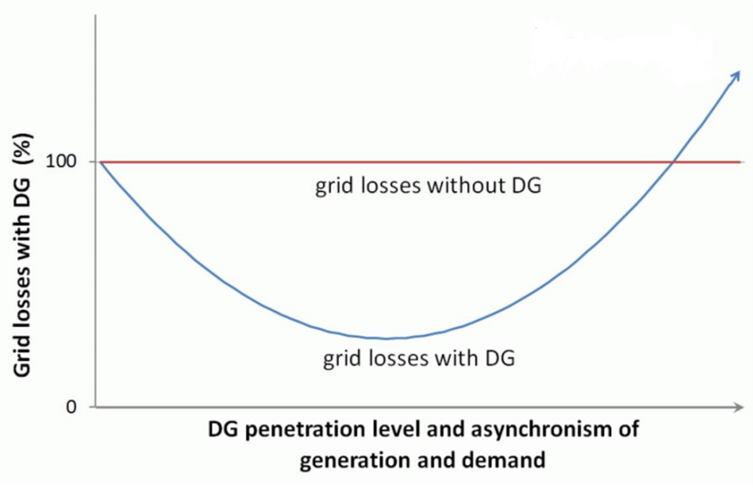


Figure 2-6: Impact of increasing DG penetration level and asynchronism of generation and demand to grid losses [12]

2.1.6 Reactive Losses

Currents in electricity systems comprise of the vector sum of two components, active (responsible for the transmission of active power) and reactive currents (responsible for the energy alternately stored and released by inductors and/or capacitors). Reactive losses are due to the circulation of reactive currents, which are increased when the power factor[9] is deviating from unity, and when voltage deviations are observed. Local voltage control actions (reactive power injection or absorption) are the most widely accepted means for supporting voltages and reducing reactive losses in distribution networks. In traditional distribution networks (comprising mainly of loads), the voltage drops at the end of the line due the consumption of reactive power by the line when it is highly loaded. The placement of capacitors for local injection of reactive power to compensate for those losses is the state of the art solution for voltage support. In [24] it is demonstrated that the use of such device reduce reactive losses by up to 45% compared to the case where reactive power is transmitted from an external grid to compensate for the voltage deviation. In distribution networks comprising of loads and DG, situations of over-voltages are observed if the DG output exceeds the load. In [25] a case study analyses the effect of DG on the voltage deviations of a 10 kV test distribution feeder with five equally distributed load of 0.5 MW each. Variable capacities of DG are connected to node 4.

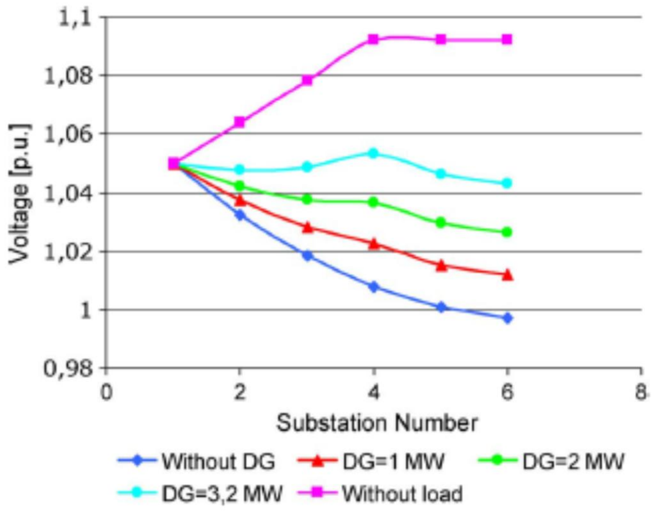


Figure 2-7: Voltage profile of the test feeder for different generating scenarios [25]

9 Power factor is a ratio between the real power and apparent power flowing through a conductor.

Figure 2-7 demonstrates that all possible load/DG scenarios need to be studied to assess the decrease of reactive losses in the system. In this specific case a 3.2 MW DG capacity synchronised with the load would lead to almost no voltage deviation, hence minimizing reactive losses. However, in reality, utilities do not have control on the allocation or the size of DG that will be installed in their distribution grid. Therefore different voltage support actions with different impacts are used. We discuss them in the next section on voltage optimisation.

2.1.7 Imbalances

Electricity networks comprise three phase systems which (especially in distribution grids) serve single or dual phase loads. Imbalances in the loading between the three phases lead unavoidably to increased currents in at least one phase, which increase marginal losses. Typically, imbalances occur on all parts of the low voltage network due to customers who use one or two phases with different load consumptions. In order to rebalance the network it is necessary to reconfigure phase loading to ensure that this captures the development of loads. This is normally done based on maximum customer load and cannot capture the fluctuations of load profiles over time. In this respect, some imbalance is unavoidable [3]

2.1.8 Life cycle assessment: impact of losses on investment decisions

Losses are one key contributor to operational expenditures in power networks. Typically, optimal investment decisions translate in finding the components configuration that minimise the sum of initial investments and lifetime costs (Lifecycle costing – LCC). Due to the long lifetime of the network assets, adopting a LCC approach that includes losses can steer decision making when included in investment analysis. In the case of transformers, LCC shows that the purchase of energy efficient equipment could be optimal decision regardless of the higher initial capital costs. [18] Similarly, in the case of lines, and due to the characteristics of variable losses, a LCC optimal decision leads to increased line capacities for reduction of losses. In distribution network design, the inclusion of the cost of losses leads to much lower utilisation rates of the assets (thus higher installed capacities) in contrast to the practice of using the assets as much as possible to increase capital efficiency. [26] Consequently, there is a trade-off between the cost of financing surplus capacity and the cost of losses.

2.2 Energy efficiency measures in electricity networks: categorisation and potential

Figure 2-8 presents the key energy efficiency measures and their categorisation in two main categories, a) the 'traditional' measures of component replacement, and b) measures that achieve a reduction of losses by an improved management of the power system, either by controlling the network infeeds (local balancing) or by grid management actions (such as network reconfiguration, voltage control, or elimination of imbalances).

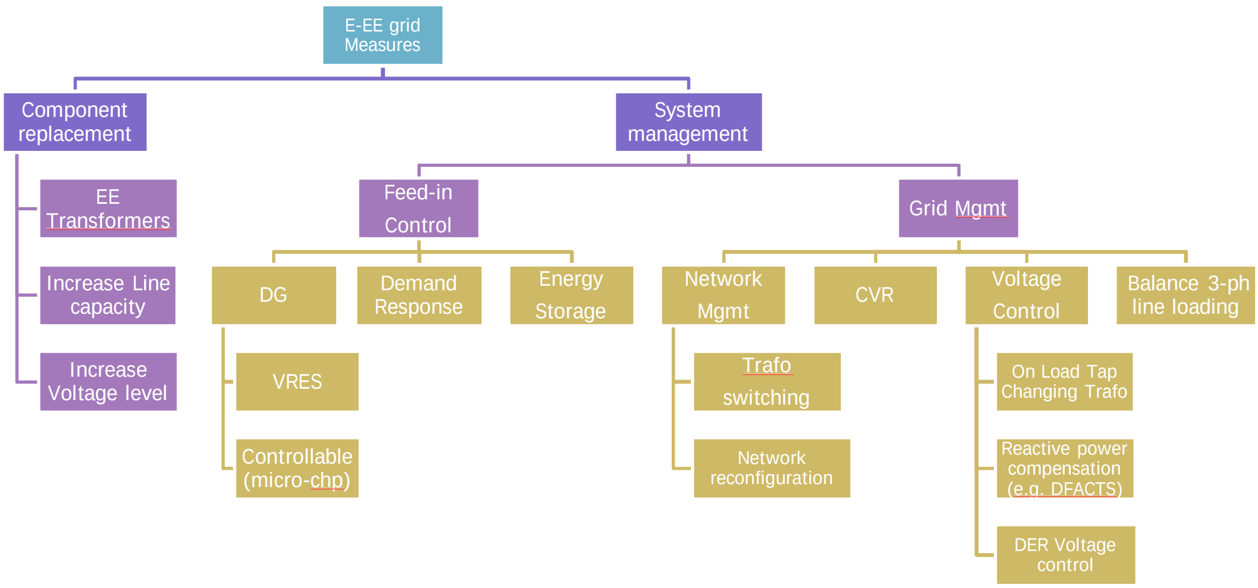


Figure 2-8: Categorisation of key energy efficiency measures in electricity networks

The loss reduction potential of each measure can be in principle analysed by the factors presented in the previous section. Table 2-2 presents a mapping of the energy efficiency potential of each measure with respect to the categorisation of losses presented in section 2.1 (table refers to distribution networks, as they present the highest share of losses in the electricity system). As can be seen, each measure affects a set of factors and therefore the potential of each measure will depend on how losses are mapped in the specific grid. The table presents two dimensions which together map the potential, firstly the applicability of each measure on different voltage levels and secondly the effectiveness for loss reduction when the measure is applied. The combination of the two dimensions allows the estimation of the potential, e.g. measures of high effectiveness but of poor applicability would rank low on potential.

Concerning variable losses, a key differentiator is the point where the measure is applied. System loading at each voltage level corresponds to the sum of the loadings from the networks in underlying voltage levels. Therefore, measures generally affect losses from the network level where applied and upwards, making energy efficiency measures that apply to lower voltage levels the most efficient. A typical example on this is demand response and demand flattening actions: applying such measure to LV networks will lead to a flattening of profiles to the higher system levels also, inducing a chain of loss reduction towards the upper levels. This also means that losses at the LV grid will only be influenced by measures at this voltage level, such as customer side demand response.

			Applicability		Effectiveness			
			Distribution Networks		Technical Losses			Non Technical Losses
					Variable		Fixed	
			LV	MV	Marginal	Reactive		
Component replacement	EE Transformers		+ + +	+ + +	+ +		+ + +	
Component replacement	Increase Line Cap.	Increase Diameter	+	+	+ + +	+ +		
Component replacement	Increase Line Cap.	HTS		+	+ + +	+ +		
Component replacement	Increase Voltage level			+	+ + +	+ + +		
Feed-in Control	DG	VRES	+ +	+ +	+			
Feed-in Control	DG	Contri. (m-chp)	+ +	+ +	+ +			
Feed-in Control	DR		+ + +	+ + +	+ + +			+ +
Feed-in Control	Energy Storage		+	+	+ + +			
Grid Management	Network Mgmt	Trafo Switching	+ +	+ +	+	+	+ + +	
Grid Management	Network Mgmt	Network reconf.		+ +	+ +	+ +		
Grid Management	CVR		+	+	+ +			
Grid Management	Voltage Optim.	Reactive comp. devices	+ +	+ +		+ +		
Grid Management	Voltage Optim.	Smart Trafos		+ +		+ + +		
Grid Management	Voltage Optim.	DER Volt. control	+ +	+ +		+ + +		
Grid Management	Balancing 3ph loading		+ + +		+ +			

Table 2-2: Mapping of the energy efficiency potential of each measure (focus on loss reduction in electrical distribution grids)

2.2.1 Energy Efficient transformers

The key mechanism is the replacement of transformers with energy efficient ones[10], which in most cases are larger and with higher capital cost. As transformers are responsible for both variable and fixed losses in the system and their replacement is easier than changing cables or lines, this option presents a good loss reduction potential, and affects almost all factors of losses, as shown in Table 2-2. As shown in Figure 2-3 most losses in transformers occur in distribution grids, therefore the potential of the measure in lower voltage levels is higher.

The asset replacement strategy depends on the state of the population, characterized by the age, size and type of transformers. For an optimal investment decision the cost of losses should be taken into account in a full LCC analysis. Such LCC estimation shows that efficient transformers have a payback period of 2-13 years compared to less-efficient models when the cost of the lost energy is included to the cost of purchase [5].

The lifetime of transformers is typically around 40 years. In many cases however, assets are still operational beyond this point, but with significantly lower efficiency levels. As shown in [18], 20% of the oldest distribution transformers (installed before 1974) are responsible for 35% of the fixed losses and 30% of the variable losses in the EU, approximately a total of 38 TWh of losses per year. Replacing them with energy efficient transformers can help reducing these losses by 80% [5], leading to an annual saving of 30TWh, equivalent to the annual electricity consumption of Denmark [27]. Furthermore, [28] quantified the impact of implementing the MEPS[11] of the Ecodesign Directive till 2025 and found that energy savings of 84 TWh could be achieved compared to a business as usual scenario.

Western Power Distribution (DSO in UK) conducted a cost and benefit analysis including the values of losses to know whether their transformers needs to be replaced. [3] The outcome of the study shows that it is only beneficial to oversize their smallest units (pole or ground mounted) and to replace earlier than planned all pre-1958 ground mounted distribution transformers. The expected savings per annum reaches 2.76 GWh, 97% coming from the replacement of the old transformers.

[1010] Energy efficient transformers have reduced variable and fixed losses. To reduce variable losses, the resistance of the wires needs to be decreased, which can be done by increasing the cross sectional area or by using materials with a lower resistance. To reduce fixed losses, one way is to use materials with better magnetic properties.

[11] This option of the Mandatory Energy Performance Standards requires newly installed transformers to follow Top Efficient level of EN 50464-1 for Tier 1 (2015) and Least Life Cycle Cost for Tier 2 (2020).

2.2.2 Increasing voltage level

Increasing voltage level reduces the currents required to distribute the same amount of electricity, increases current capacity of the grid and reduces substantially voltage drops and line losses. It presents further indirect benefits such as reduction of probability of short circuits, increase of quality of supply and it increases the DG hosting capacity. The measure typically applies to MV networks, where multiple voltage levels are possible (e.g. 10kV and 20kV). In cases where the insulation coordination allows both voltage levels, it can be applied by changing only the transformers. In most cases however this is not the case and a full renewal of all network components is necessary, which implies high costs. The measure is particularly interesting to aging MV networks as it comes at little extra cost to up-rate the voltage [5].

As shown in Table 2-2, the applicability of the measure is mainly on MV grids and is deemed rather low since only a limited number of networks will fulfil the respective conditions for applying this measure. On the other hand, the potential of the method on reducing variable losses is high, in the cases this solution is chosen.

The measure was applied in large scale in Ireland for upgrading the MV rural networks from 10kV to 20kV [28]. These networks were designed in the 50's for lower typical household consumptions and load densities, and were severely loaded and experiencing very poor voltage regulation. The costs of 20kV conversion were little more than those of rebuilding in 10kV, yet the voltage drop were halved, thermal capacity doubled and losses reduced by 75%.

2.2.3 Increasing line capacity

Increasing cross-sectional area of cables leads to reduction of variable losses. Typically, doubling cable rating leads to a reduction of losses by a factor of four. However, once a cable is installed, it becomes expensive to make alterations to the cable, since civil works cost element of replacing a cable outweighs any loss reduction benefits. The key opportunity to reduce losses therefore exists at the time that the cable is initially installed or replaced [3]. An alternative approach is to make use of high-temperature superconductors (HTS) which present no resistance when they are cooled down at -180°C and can carry five times the current of a conventional cable system with the same outer dimensions. The losses from this system are due to the energy needed to operate the cooling mechanism. [29]

As shown in Table 2-2, the applicability of cable up-rating is deemed medium, and the measure should be applied in cases on new line installations or replacements. Applicability of HTS is deemed rather low, mainly for cases of high currents that need to be transported over relatively short distances. Both measures have a high potential to reduce variable losses.

A CBA conducted by Western Power Distribution showed that is beneficial to uprate all the existing MV underground cables from 6.6kV to 11 kV. The planning is to replace 700 km of cables per year and savings are estimated at 3GWh per year. The study also showed that it is not beneficial to uprate the 11kV network as these higher voltage network cables support adjacent networks in times of fault. [3]

A 1 km 10 kV HTS cable was installed in 2014 to replace several 110kV underground cables connecting two 10 kV substations in Essen Germany. The cost of the energy needed to cool the cable down to eliminate its resistance over its lifecycle is found to be 15% lower than the cost of compensating losses in conventional 110 kV cables. HTS are mentioned as the best technical and economically viable solution to avoid the necessary extension of the 110 kV grid in urban areas. [29]

2.2.4 Feed-in control

This measure refers to applying control actions for local balancing of demand and supply in distribution grids, which leads to reduction of variable losses due to two key factors, the reduction of energy transportation distance (energy is consumed locally) and the reduction of marginal losses (by a flattening of flow profiles). This local balancing can be performed by three options for control actions, of supply (DG), of demand (demand response actions) or of energy storage (can be considered as supply and demand)[12]. Under this measure the control of active power is considered. (Control of reactive power of DGs is analysed under the Voltage Optimisation section).

The potential of this measure depends on three key factors, namely the ability for spatial and temporal matching and the underlying technical limitations.

- **Spatial matching**: it relates to the system architecture, namely DG penetration levels and relative position of dispersed supply and demand; a general rule of thumb is that the measure is more effective when supply and demand are close and when it is of similar rating.
- **Temporal matching**: it refers to the operational framework that should coordinate local balancing; such a framework is most of the times non-existent. Network losses are generally reduced for low DG penetration levels, mainly due to the fact that independent of the coordination scheme generation does not exceed demand. For higher penetration levels however, this lack of coordination translates into reverse power flows and to a gradual increase of system losses (see Figure 2-6).
- **Technical limitations**: refer to the specific flexibility characteristics of the technology which reveal the degree of local coordination that can be achieved. Such limitations include DG controllability, demand elasticity and potential for peak shifting/clipping and the size and flexibility of the storage devices.

[12] New demand such as Electric Vehicles and Heat pumps are included in these categories, but with specific flexibility characteristics and limitations due to their primary operation.

As can be seen in Table 2-2, although VRES are generally present in MV and LV grids, their effectiveness to perform local balancing actions is deemed rather low, mainly due to the fact that such actions translate into reduction/curtailment of active power production. Controllable DG present a medium effectiveness, since although they are technically capable, they cannot perform such actions due to lack of enabling operational framework. Demand response presents a high applicability and high effectiveness on reduction of technical losses, which however depends on the technical potential of demand (peak shifting/clipping potential). This option presents also a medium potential for reduction of non-technical losses, since they are most of the time combined to smart metering infrastructure that enables better monitoring of the creation of non-technical losses. Finally, energy storage presents a high effectiveness on local balancing but a rather low applicability due to the low implementation of storage in distribution grids.

This impact is discussed in [30], where the potential of demand response from residential customers in reducing marginal losses of a Swedish distribution network is investigated. Results show that this reduction varies from 4%, (if 10% of the peak load is shifted) to a maximum of 18%, if the load profile is flattened. The Model City Mannheim project proved effectively after having developed, installed and tested smart control systems in 1000 households that the price elasticity of customers to variable tariffs was 10% [31], which means that 10% of the demand could be shifted when the price of electricity increased by 10%. In other terms, the 4% reduction of marginal losses mentioned in [30] is feasible. This translates into annual savings of 350 MWh, equivalent to the electricity consumption of 55 households in Sweden [32].

The IMPROGRESS project analysed the impact of distributed generation on three distribution network in Germany, Spain and Netherlands [33]. The different characteristics of each area were taken account: medium and low voltage networks, urban and semi-urban areas, number of customer, shares of wind and PV and CHP and a forecast for load demand and DG penetration till 2020 was applied. The areas studied are Aranjuez in Spain (industrial, wind and CHP), Mannheim in Germany (residential, lots of PV roof and micro-CHP) and Kop van Noord (lots of wind and CHP) in the Netherlands. The feed-in control action consisted on one hand of curtailing VRES or storing the excess power in an electric heat boiler and on the other shifting the demand from periods with low DG penetration to those where most CHP units were running. The study showed that if feed-in control is practiced instead of expanding the LV grid to cope with the forecast growth of DG until 2020, 97 €/kW_{DG} in Netherlands can be saved, 77 €/kW_{DG} in Germany and 73 €/kW_{DG} in Spain. The potential savings calculation includes the Net Present Value of the electrical losses that would have been caused by the increasing penetration levels of DG in each distribution grids.

In [34], energy storage is used to shift load from peak to off-peak period and the impact on reducing transmission and distribution losses is analysed. The authors developed a set of normalized charts to quantify the saved T&D losses as a function of the size of the energy storage device, its efficiency and the load shifting potential (i.e the ratio of the off-peak to peak load). Based on an existing 1 MW battery storage system installed for shifting a peak load from 20 MW to 6 MW in a 12 kV distribution feeder in Virginia USA, the authors estimate that 1 to 3% of T&D losses could be saved which translates in 180 to 330 MWh year of energy saved including the storage losses. The authors demonstrate that it is more beneficial to distribute small size storages at different locations rather than using a big size at a single site to maximize the reduction of T&D losses.

Within [14] the German Federal Ministry of Economics (BMWi) examines various measures to improve the integration of VRES into the distribution grids. One of the key findings is that the curtailment of 1% of the annual feed-in of VRES reduces the necessary grid extensions by 30%. A curtailment of 3% of the energy annually produced by VRES would be sufficient to avoid 40% of the required grid extensions. The effectiveness of curtailment measures rapidly decreases if more than 3% of the annual feed-in of VRES is curtailed.

2.2.5 Transformers switching

Fixed losses can be reduced without replacing equipment by reducing the number of energised transformers in the system. This can be achieved by eliminating transformation steps or by switching off transformers. Elimination of transformation steps could be achieved by direct coupling of higher voltage levels to lower ones without the use of intermediate transformers (use of a single transformation step). Alternatively, switching off transformers could be possible in periods of low demand for configurations where multiple transformers are required in a substation to meet peak load or for redundancy. This can be achieved via an 'Auto Stop Start' System that allows to periodically de-energise redundant transformers in substations.

As shown in Table 2-2, the potential of the measure is high on reduction of fixed losses. In addition to reducing the fixed losses, this measure also reduces the variable (and marginal) losses by improving of the loading of the energised transformers. The effectiveness of the measure in different voltage levels depends on the redundancy configurations used. In this respect, the measure is especially effective in MV or LV networks where redundant transformers are often in use.

Case studies show a 75% loss reduction in MV networks, equivalent to the loss reduction achieved by upgrading the 11kV network to 20 kV, however at about 1% of the upgrade cost. The project is in execution phase led by the Scottish and Southern Electric Power Distribution and will end in 2018 to validate the scale of loss reductions (640 MWh/year) and to confirm that repeated switching did not impact the asset lives and the supply security. [35].

2.2.6 Network reconfiguration

The measure involves changing network topology at the distribution level dynamically by using automated switching actions. Typical implementations are Smart Feeder Switching (SFS) and Advanced Distribution Management Systems (ADMS). The configuration of the network has an effect on losses in terms of the distance the electricity is transported. MV networks are typically configured as open loops and are controlled in order to be able to isolate faults and restore power. As the demand changes spatially and in time, it is often the case that the configuration of a network is not the optimal one for the specific demand situation. There might therefore be some scope for reducing losses by reconfiguring the network, to provide shorter, more direct paths to where highest demand is situated. SFS and ADMS are typical implementation for performing automated switching actions on distribution feeder systems enabling a reduction of distribution system losses [36], [15], [37].

As shown in Table 2-2, the measure involves reduction of variable losses mainly in MV networks, where such configurations are employed and its potential is defined as medium. The potential depends on the reconfiguration frequency and the spatial and temporal variations of power demand. A limitation may be if the switch-disconnector equipment is designed for a limited number of operations per lifetime (e.g. 1.000) [15], which limits the applicability of control actions. Typically, for systems with high penetration levels of intermittent DG (especially wind generators), which experience higher and random spatial and temporal demand variations, higher switching frequencies are necessary.

Results from field pilot projects reported in [15] show that network reconfiguration may lead to a theoretical reduction of losses of 40% for an hourly reconfiguration (which however cannot be applied due to limitations of the switching equipment), and up to 20%, 10%, 4% if the reconfiguration is made on a weekly, seasonal or yearly basis respectively.

2.2.7 Conservation voltage reduction

Conservation Voltage Reduction (CVR) is a reduction of active power delivered to demand resulting from a reduction of feeder voltage within the operational ranges. CVR schemes typically contain two fundamental components: a) reactive power compensation, achieved through the operation of shunt capacitors in order to maintain the power factor at the substation transformer within a prescribed band, and b) voltage optimization, achieved through the operation of substation voltage regulators in order to regulate the voltage at specific end of line points within a prescribed range. In this way the peak load and the annual energy consumption are reduced. [9] When applied on LV networks, the measure can be applied by changing settings at the primary substation [3].

The applicability of the method depends on the type of load in the system. The method typically applies well to 'voltage dependent' loads such as filament lamps and resistive heating[13]. However, increasingly more load is 'voltage independent', as it is fed via a switched mode power supply, which effectively changes its impedance based on voltage (such as HF fluorescent, LED, PCs VFD fed motors). Therefore lowering voltage may not, in all circumstances, lead to the demand savings as desired and could actually increase losses. [2] Therefore, the measure is considered of low applicability and medium effectiveness, as presented in Table 2-2.

According to [38], utilities applying CVR may expect to see 1% reductions in electricity consumption for every 1% reduction in voltage. Detailed analysis of CVR schemes in US show that they can lead to peak demand reduction of 1 to 2.5% [38] and annual energy reduction of 4% [9] Western Power Distribution is planning a voltage reduction trial in the South Wales area on their MV networks from 11.4kV to 11.3kV and anticipates reduction of 95MWh which will reduce the customer bills by a calculated €13M each year and carbon emissions by 41 000 tonnes a year. [39]

2.2.8 Voltage optimisation

Voltage optimisation refers to reduction of reactive losses by the application of local voltage control actions (reactive power injection or absorption) aiming at local correction of the power factor. The placement of capacitors for local injection of reactive power is the state of the art solution for voltage support for passive networks (networks including mainly loads). In distribution networks comprising of loads and DGs, the fluctuating generation profiles lead to situation of over-voltages (when local generation exceeds demand) or under-voltages (in situations of high demand and no DG production). Voltage support actions should therefore be performed dynamically and react to the conditions in each operational instance in order to optimise the feeder voltage profiles.

This is made possible through recent improvements in sensors, communications, control algorithms, and information processing technologies that allow to monitor voltage levels throughout the distribution system. This information is sent to devices that can adjust voltage regulating equipment and capacitor banks on distribution feeders in near-real time enabling quick adjustments in response to constantly changing load and voltage conditions. Options to perform such actions are installing smart reactive power compensation devices (e.g. D-FACTS, see [40]), using on-load tap changing (OLTC) voltage control actions at the distribution transformers [41], or by using the capabilities of converters for power factor correction [12] in the case of converter-connected DG[14].

[13] As the resistance of these devices is largely fixed, applying a lower voltage reduces the current drawn, less power is transferred and hence overall load is reduced.

[14] Typically converters can adjust the power factor at the point of connection, by changing the injection or consumption of reactive power.

As shown in Table 2-2, there are difference between the applicability and effectiveness of the options. Smart reactive power compensation devices are applied mainly on MV grids but their applicability is considered medium mainly due to cost limitations. Their effectiveness is high, since they can be applied to specific grid points. The applicability of OLTC is considered medium and their effectiveness is also deemed medium, since their operation can be limited in cases when multiple feeders are connected to the transformer (voltage control actions from OLTC affect all feeders at the same time and this may lead to conflicts). [25] DER voltage control is considered as a highly effective option with medium applicability mainly due to the fact that DER should be converter connected and because the effectiveness of controlling voltage profiles by controlling reactive power from DG is best applied to feeders with low resistance to reactance (R/X) ratio [23]. As shown in [23] reactive power control from PV panels in a LV grid (<1kV) in Switzerland would not be effective if the line diameters connecting the panels to the feeder were not larger than 50 mm^2, i.e. the R/X ratio lower than 5.

In [38], the results from 26 voltage optimisation programs are reported. The voltage optimisation analysis focused on CVR and on reduction of energy losses along feeders, by automated switching of capacitor banks. Results reported that for the 31 feeders under investigation half of witnessed line loss reductions in the range of 0% to 5%, and 5 feeders experienced loss reductions greater than 5%. Feeders with the worst baseline power factors (i.e., those with the highest amount of inductive loads) showed the greatest reductions in line losses. Overcompensation was observed in some feeders, which resulted in line loss increases.

In [12] a study case is presented, investigating the role of reactive power compensation coming from DG on decreasing grid losses in the North of Germany. The analysis involves two MV grid areas of similar size in load and number of connected customers but with different DG penetration levels with respect to load demand (Area 1 with 45% and Area 2 with 146%). The DG mix analysed consisted of 90% wind power plants and 10% biomass plants. The results shows that grid losses would decrease by 15% in Area 1 if DG plants were adapting their power factor between a ±0,05 window but would increase by 3% in Area 2. The results confirm that the effectiveness of reactive power provision from DG plants is dependent on the grid topology and DG penetration level.

In [41] a study case is presented, investigating the role of dynamically controlled OLTC on decreasing grid losses. Six additional wind generation sites of 14 MW are connected to a generic MV radial distribution system in the UK which needs to supply an annual energy demand of 215 GWh and a peak load of 38MW. If the wind generation sites are operating at a fixed unit power factor, the OLTC helps reduce grid losses annually from 2,8% to 2.3%, saving 1 GWh per year, equivalent to the average annual consumption of 240 houses in the UK [42]. [14] states that a full penetration of OLTC in Germany would reduce the average yearly grid expansion costs by 10%.

2.2.9 Balancing loading of lines

As mentioned, imbalances are a common phenomenon in LV networks where single- or double-phase customers are connected to the three-phase system. These imbalances lead to having one phase carrying higher currents, giving rise to variable losses. The measure is to statically or dynamically transfer loads from one feeder to another to balance the total load across multiple feeders and transformers. As the demand changes in time, optimally balancing should be performed in short time periods and reacting to demand changes. [2]

The applicability of the measure is considered high and is limited to LV networks, as presented in Table 2-2. Its effectiveness is considered medium, depending on the frequency of balancing that can be achieved.

As discussed in [3], imbalances in the LV network can lead to neutral currents of around 35% of the phase current. The annual potential savings from imbalance correction in this respect are in the order of €70 to €110 per kilometre of LV network. An analysis of the effect of load balancing on the reduction of power losses in 12 feeders of a LV distribution power network in Russia is presented in [43]. The results show that the reduction of technical power losses after load balancing varies from 0% to 16% depending on each feeder configuration. A total of 13 MWh could be saved per year equivalent on average to the annual consumption of 100 customers. It is important to note that this specific regional power network already experienced high distribution losses of 18% in 2007. Reference [44] suggests the use of three-phase balancing PV units that are able to inject more power in one phase than in the other phases compared to single-phase PV units that inject only in one phase. The case study of typical Belgian LV network proves that the three phase balancing PV units could help decrease grid losses by 30% saving 7 GWh per year.

2.3 Regulatory regimes to promote loss reduction in electricity grids

2.3.1 Regulatory incentives: basic options

Various regulatory incentives exist to motivate network operators in investing in energy efficiency (particularly loss reduction) in their networks. Some key options are reported below.

TECHNICAL STANDARDS FOR CONDUCTORS AND TRANSFORMERS

A very effective measure that leads to an overall improvement in efficiency is setting mandatory standards on a European level. In such cases, the national regulatory design should allow a higher CAPEX allowance to grid operators as savings in OPEX will over-compensate them in the long run. Based on the EU Ecodesign Regulation, new power transformers installed after July 2015 need to meet a minimum energy efficiency standard.

FINANCIAL INCENTIVES

In general financial incentives to increase efficiency can be of various forms, e.g. grants, loans or tax breaks. They can also be set via lower interest rates for energy-efficient investments. To further motivate and simplify investments, specific energy-efficiency budgets can be set up. Given that the transmission and distribution networks are regulated industries, the most appropriate way to deliver financial incentives would seem to be via the existing regulations.

Another option regulators can use is setting individual targets for network losses for grid operators which can be a mechanism that financially penalises or rewards deviations from the target. This can be a strong incentive for grid operators to improve in operational performance while leaving them free space to decide on the most effective measure.

OBLIGATION OR CERTIFICATE SCHEMES

With obligations or certificates for energy efficiency and energy savings, grid operators are given specific shares of losses (and savings) that they have to meet, just like the option of financial incentives. In many schemes, there is also the option to trade certificates to meet the obligation. In case of not conforming to the obligation, penalties (financial or not) can be set to promote actions to meet the obligation which is a key difference to financial incentives.

VOLUNTARY AGREEMENTS

Regulators can start by setting voluntary agreements with grid operators which would comprise non-binding guidelines e.g. for a maximum share of grid losses in power transmission and distribution. It can acquire the market participants’ attention on the issue and provide alignments on grid operation.

INFORMATION CAMPAIGNS TO OVERCOME LACK OF MOTIVATION

There are two potential areas where lack of information might influence: with the regulators not understanding completely the case for energy efficiency and not setting the proper regulatory framework and with grid operators not having all the information for a business decision. An information campaign about best practices set up by the regulator can overcome such barriers.

2.3.2 State of play of regulatory mechanisms targeting loss reduction

The following key insights regarding regulatory mechanisms to support grid energy efficiency measures (particularly regarding loss reduction) have been derived from the survey with European system operators carried out within this study (see ANNEX II):

- The incentive to pursue specific investments for loss reduction is strictly related to the presence of regulatory incentives. A wide variety of regulatory frameworks are present in European Member States, which in some cases do not explicitly support energy efficiency measures.
- Energy efficiency (and particularly loss reduction) is the main driver of investments when there is the need to comply with regulatory requirements and quality standards (e.g. EcoDesign directive). In general, loss reduction is considered as one of the variables of a larger investment optimization plan.
- Energy Efficiency measures which require the exploitation of DER flexibility have still limited diffusion in many Member States, often just at pilot level. Their implementation would require the definition of new regulatory mechanisms over how DSOs can procure and activate DER flexibility.

Table 2-3 presents a synthesis of the different mechanisms in force among the respondents.

Bonus/malus following the level of losses	DSOs from the **Slovak Republic**, **Sweden** (for 2016), the **UK** and Portugal report that they have specific incentives that directly target loss reduction, in form of bonuses or penalties depending on the perfomances.
Cost reduction (Revenue cap regulation)	DSOs from **Bulgaria** and The **Netherlands** report that they are incentivised to perform losses reductions since it is part of their costs, and since the regulation targets a general reduction of the cost. Loss reduction is therefore not a first driver if other cost reduction opportunities are found.
Maximum loss threshold	DSOs from **Bulgaria**, **Czech Republic**, **France** and **Germany** report that they have an obligation to respect a given loss threshold, overpassing them leading to audit or non-recognition of the costs. However, this gives no incentives to go further if their current loss level is under the limit.
Benchmark among other DSOs	DSOs from **Spain** report that loss reduction is addressed by a benchmarking of all Spanish DSOs on their performance to reduce losses.

Table 2-3 - Regulatory incentives for energy efficiency measures highlighted by survey respondents

More generally, it is clear that proper regulatory incentives are necessary to stimulate loss reduction investments. Absence of such regulation often brings the opposite effect, and acts as disincentive for network operators. There are two main elements in the tariff regulations which may act as an incentive or disincentive to invest in energy efficiency measures of the grid:

a. the way the tariff is calculated, which determines the amount that can be charged to the consumer; and
b. Whether there is an incentive regulation for minimising operational costs.

Tariffs are usually calculated on the basis of all relevant operational costs of transmission and distribution of electricity. In this respect, grid operators can transfer the costs for purchasing energy to make up for losses directly to the consumers. A clear disincentive to invest in loss reduction measures is typically the case when the regulatory framework does not introduce a cap to the amount of losses that can be transferred to the customer, combined to financial penalties for trespassing the limit. In such cases, infrastructure investment decisions are based on the minimisation of capital costs only, without including of the operational life cycle costs. Hence low cost, and subsequently non-energy efficient equipment is chosen over advanced efficient equipment.

3 POTENTIAL OF MEASURES ON PLANNING/OPERATIONAL EFFICIENCY IN ELECTRICITY GRIDS

In this chapter we analyse the impact of measures proposed in chapter 2 on the broader aspects of efficiency in infrastructure design and operation.

In particular we consider planning/operational efficiency in terms of:

Optimization of investment planning - Traditionally, new capacity investments (grid reinforcement or expansion) have been directly related to the increase of demand. With the growing penetration of distributed generation, increasing the hosting capacity of DG is also becoming an important driver of grid planning decisions.

In this respect, the new options offered by active grid management hold a significant potential in optimizing the long term planning process. In particular, the use of flexibility of distributed energy resources is currently being explored as an alternative to traditional grid reinforcements[15] [16]. A specific focus on the use of demand flexibility to optimize grid planning decisions will be carried out in the second part of this study.

Investments in assets replacements could also be optimized. Measures presented in chapter 2 can in fact contribute to decrease stressful conditions in the grid that could lead to faults of components and a reduction of their useful life.

Optimization of grid operation - The reduction of losses is one important aspect of the optimization of grid operation. It has been extensively analysed in chapter 2 and will not be taken into account in this chapter. Other value streams for optimization of grid operation (OPEX reduction) iInclude:

- Reduction of outage times (e.g. via implementation of network automation)
- Improvement of quality of supply and reduction of customer complaints
- Reduction of maintenance costs (e.g. by minimizing stressful operating conditions for grid assets)
- …

[15] Regulatory Recommendations for the Deployment of Flexibility, EC Smart Grid Task Force Expert Group 3, January 2015

[16] Study on the effective integration of Distributed Energy Resources for providing flexibility to the electricity system, Report to The European Commission, April 2015 https://ec.europa.eu/energy/sites/ener/files/documents/5469759000%20Effective%20integration%20of%20DER%20Final%20ver%202_6%20April%202015.pdf

In the following sections, we analyze in detail the factors affecting the cost-effectiveness of each of the proposed measures considering key aspects of planning/operational efficiency.

Implementation examples and best practices collected in the stakeholder survey (ANNEX III) and in related literature are used for illustration.

3.1 Impact of selected energy efficiency measures on operational efficiency

3.1.1 High efficiency transformers

Planning/Operational efficiency		Assets to deploy		
Investment planning	Grid operation	Hardware	Software	Communication
Technology standardization **Lighter weight**	**Technology standardisation** **Reduced fault rate**	High efficiency Transformers		

Possible benefits on planning/operational efficiency

Benefits on investment planning

Some benefits could be achieved in term of investment optimization. Indeed, limiting the number of technologies present on the grid may lead to stronger purchasing positions in the market, depending of the local market organisation, and may also lead to O&M cost reduction (less various types of operation).

In case of pole-mounted transformers, lighter transformers might also reduce the need for investments in pole replacements.

Enexis (The Netherlands) is replacing older MV/LV transformers with existing but more recent transformers (left over from other regular replacements, such as capacity increase). 150 transformers have been already replaced out of their 53000 MV/LV transformers, at an average cost of 5300 €/transformers. 0.1% of loss reduction is estimated to results from those replacements, which shows a significant potential since only 0.3% of the assets have been replaced.

Benefits on grid operations

Aging transformers might present a higher fault rate than up-to-date transformers. Replacing most problematic assets will save O&M cost. According to the economic assessment carried out by the Asia-Pacific Economic Cooperation [46], replacing transformers in order to comply with current performance standards leads to long-term savings, including additional operation cost saving (in each of the 20 studied countries, positive net present values were observed in their 2016-2030 plans).

Assets to deploy - Investments costs

The costs of a transformer have a wide range of variability depending on the power rating**.** In [45],a study from the Indian government, it was showed that cost differences are high between their “1 star” and the “5 star” transformers of small power rating (50% of difference for a 25 kVA transformer) but those difference get smaller at higher power (27% for a 200 kVA transformers, for a cost estimated at 3390 €[17] for 5 star transformer). However, according to a study carried out in the Asia Pacific Economic Copperaiton [46], it appears that, installed capacity being equal, the cost-effectiveness of switching to higher standard is higher when replacing small transformers. Cost-effectiveness can be maximized if the measure is implemented within a planned asset replacement campaign. For instance, when replacing transformers at the end of their useful life, CEZ (DSO in Czech Republic), has found it economically convenient to opt for upper class transformers despite a 20% higher price, thanks to energy efficiency improvements.

3.1.2 Expanding line capacity

Planning/Operational efficiency		Assets to deploy		
Investment planning	Grid operation	Hardware	Software	Communication
Standardization	**Reduced SAIDI** **Improve voltage quality**	Cables	None	None

Possible benefits on planning/operational efficiency

Benefits on investment planning

Some optimization of investment planning can be achieved via the limitation of the number of the cables sizes in use. In fact this can lead to standardization of equipment on the network, and thus to an average purchase price reduction.

[17] Change rate $ to €: 1$ = 0.894 € (11/05/2015)

Benefits on grid operations

Oversizing the conductors decreases the impedance of the line, resulting in lower voltage drop. Therefore, a positive impact on voltage quality of the grid should be obtained.

A limitation of the current flowing through the line could reduce the probability of default (and the aging of the line). Moreover, by standardizing the line type, higher standardization of field works could be achieved, reducing the overall O&M costs.

Assets to deploy - Investments costs

It is difficult to give an accurate cost for such a measure, since it strictly depends on the implementation conditions (overhead lines or underground cables, size, voltage level, type of conductors, etc.). However, the cost of oversizing line sections can be relatively small in the case of installation works (particularly in case of cables) which are already planned. Western Power Distribution (see [3]) decided to size up their current standard LV cables to discontinue their smallest-size MV cables. The study shows that sizing up 95mm² cables to 185mm² adds a cost of 14€/m[18], while excavation costs range between 70€/m and 140€/m.

Východoslovenská distribučná (DSO from Slovak republic) has increased the maximal conductor section of their LV network from 70mm² to 150mm². While the first driver of this measure was to reach higher voltage quality, they expect a nominal losses reduction of up to 20% at peak load, and 5% on average (depending on the intensity of operation). The increase in investment was minimized and managed by process changes in the procurement procedure. The asset costs represent up to 10% of the project costs. However, a full roll-out was deemed to be too costly, due to costs of other grid elements such as poles.

[18] Change rate £ to €: 1£=1.3793 € (11/05/2015)

3.1.3 Increasing voltage level

Planning/Operational efficiency		Assets to deploy		
Investment planning	Grid operation	Hardware	Software	Communication
Deferred capacity investment **Life time extension** **Technology standardisation** **Increase DG hosting capacity**	**Improvement of voltage quality** **Reduction of DG curtailment** **Improvement of continuity of supply**	Fitted lines cables HV/MV substations: • *Transformers* • *MV cells (protections, switches…)* • *Rails* MV/LV substations: • *MV cells (protections, switches…)* Transformers	None	None

Possible benefits on planning/operational efficiency

Benefits on investment planning

Since increasing the voltage level reduces the current flowing through the conductors to meet the same power, networks reinforcement can be deferred. This is particularly true if only a limited number of assets need to be replaced. In their plan (see in [47]) to convert their rural 10kV network to 20kV, the Irish DSO operator ESB Networks aims to double their thermal capacity while reducing peak losses. Future investments to expand the grid could also be reduced thanks to an optimization of the number of substations.

As shown in [48], power line aging is mainly due to its temperature profiles along its lifetime. This temperature profile depends on the ambient air, the weather, type of soil, etc. but also the temperature generated by the carried current. Generally, less heavily utilized assets present lower risks of overheating. This could extend their lifetime.

A higher voltage level might also increase DG Hosting capacity.

Vattenfal (Sweden) is carrying out an optimisation of voltages levels in their regional grids. The analysis is performed area per area, taking into account the network topology and the load level. 5 to 15% of loss reduction has been observed in areas where voltage increase has been adopted.

Finally, reducing the number of voltage levels across the grid allows stronger standardization of network technologies. As discussed in the previous section, this can lead to benefits both in terms of CAPEX and OPEX.

Benefits on grid operations

A higher voltage level typically leads to better voltage quality (less significant voltage drop along the lines - for example [47] reports that a 10kV to 20kV conversion can halve the voltage drop/rise for a given power withdrawn/injected).

According to [49], a decentralized grid (more small transformers closer to the consumer), beside leading to high loss reduction (47% in reported case studies), also improves the reliability of the system (failure hours/years 4-5 times lower).

Assets to deploy - Investments costs

The cost of this measure strictly depends on the specific implementation scenario. A detailed study must be carried out to estimate the full cost of such a measure (e.g. assessment of which additional assets need to be replaced to sustain the new voltage level etc.).

A plan for voltage level increase can also be pursued by targeting a progressive increase of the share of the HV/MV grid with respect to the LV grid when undertaking new grid investments. In their replies to the survey, the system operators HEDNO (Greece) and EDP (Portugal) indicate that their plan of loss reduction foresees a progressive increase of the number of MV/LV substations.

3.1.4 Demand response

Planning/Operational efficiency		Assets to deploy		
Investment planning	Grid operation	Hardware	Software	Communication
Line extended lifetime **Deferred capacity investment** **DG hosting capacity increase**	**SAIDI reduction** **Lower DG curtailment**	Smart Meter Sensors for feeders monitoring Ripple control injector		Radio Optic fibre PLC GSM

Possible benefits on planning/operational efficiency

Benefits on investment planning

The implementation of demand response allows shaving peak loads, reducing the need of grid capacity increase and possibly extending the lifetime of the assets (by reducing their utilisation). Demand response could also increase the DG hosting capacity of the grid, by allowing local balancing of DG units injection. Grid reinforcements might therefore be deferred/avoided.

Detailed analysis of the impact of demand response on grid planning will be carried out in the second part of this study.

Benefits on grid operations

Demand response can be used to prevent loads in feeders or other assets to reach critical values that might determine asset faults. In this way, the average SAIDI can be reduced. Moreover, flexible load control synchronized with local DG units could reduce to a reduction of DG energy curtailment due to over/under voltage or to line overloading.

Assets to deploy - Investments costs

The on-going implementation of smart metering infrastructure in most European Member States is providing the enabling infrastructure to carry out demand response activation, increasing the cost-effectiveness of this measure for energy efficiency.

Other necessary assets to deploy include grid sensors to increase the observability of the grid, particularly in terms of feeder loading, to adapt the DSOs activation of demand response to actual grid conditions.

Finally, another possible option for DSOs to activate demand response consists in adopting Time-of-Use tariffs based on ripple control. In this case, DSO's might have to invest in local ripple injectors.

3.1.5 Feed-in control of distributed generation & storage

Planning/Operational efficiency		Assets to deploy		
Investment planning	Grid operation	Hardware	Software	Communication
Line extended lifetime Deferred capacity investment Customers' investments DG hosting capacity increase	Power Quality problems reduction Voltage problems reduction Lower restoration operations	Converter with "smart" functionalities Smart Meter Storage system Extra connections lines		Radio Optic fibre PLC GSM

Possible benefits on planning/operational efficiency

Benefits on investment planning

An efficient feed-in control (including reactive power management) can lead to capacity investment deferral, by reducing the peak demand from the MV/LV substation. Reducing peak demand can also typically reduce the aging of the component.

Benefits on grid operations

As seen in [51], efficient DG converters might provide compensation in term of harmonics, voltage, reactive power and phase balancing control. This might reduce complaints from clients and the number of field interventions.

ERDF (France) is studying the implementation of local voltage regulator to perform reactive power management of DG on the MV grid. The choice of the final system has been based on a trade-off between the gain on hosting capacity and the gain on voltage losses, and its optimized value of the reactive to active power ratio and a reactive power regulation based on voltage. The system is currently in implemented two cases on their MV grid. The expectation is a reduction of 2-3% in losses, and to an overall cost reduction of 5% compared to a case with no reactive power control, thanks to avoided reinforcement. OPEX reduction is also expected, since the system self-adapts when new DG are connected.

Assets to deploy - Investments costs

In the case of a control strategy with direct communication link between DG units and the DSO (for DSOs to send set-points for the DG control system), an important cost item is related to the communication infrastructure between the DG units and the DSO.

It is worth mentioning that DG converters on the market are increasingly equipped with built-in Smart Functionalities, with limited cost premiums. Retrofitting costs need to be foreseen for older-generation converters to enable them for more advanced feed-in control schemes.

Storage system may also be coupled with DG units to provide a better feed-in control. In that case, the cost accrues to the DG owner. According to [50], storage systems could also be installed by DSOs when demand growth is uncertain, as a temporary solution to defer investment, letting time to assess which reinforcement are really needed

3.1.6 Network reconfiguration

Planning/Operational efficiency		Assets to deploy		
Investment planning	Grid operation	Hardware	Software	Communication
Deferred capacity investment Line extended lifetime	Reduced fault rate Reduced restoration time Improved voltage quality	Remote controlled switches and reclosers in substation Feeders monitoring system	Advance SCADA/DMS Control software	Radio Optic fiber PLC GSM

Possible benefits on planning/operational efficiency

Benefits on investment planning

The drivers of automatic grid reconfiguration are typically loss reduction and reduced number of interrupted customers. However, a better balance between the different feeders reduces the peaks on those lines, therefore potentially reducing the aging of the lines, and reducing replacement costs.

Benefits on grid operations

Increasing the number of remotely controlled switches reduces the number of substations to be inspected when a fault occurs. In a study ([52]) carried out by the US Department of Energy within 5 utilities, the use of remotely controlled switches reduced the number of interrupted customer by 35%. The use of automatic control for fault management leads this number to 55%. By better balancing the load in the feeders, voltage drop can also be reduced.

According to [53], a simulation of an automation algorithm to control the AES Sul grid (Brazil) showed that a 8.2% reduction of interrupted customer per year can be achieved. Moreover, the solution prevents fault occurrences by reconfiguring the grid before a critical value is reached. The benefits are particularly high in the case of rural networks.

Assets to deploy - Investments costs

The main cost item of the measure is the installation of remotely controlled switches and reclosers and (if not already available) of the associated communication infrastructure. According to [36], various U.S. utilities report that they have implemented this measure at a cost ranging between 18.750 € and 35.750 € per installed switch, including software, monitoring and communication system. For example, Adams-Colombia Cooperative mentioned a cost of 20.400 € for an overhead switch and 35.750 € for an underground one. Voltage level is one of the key drivers of the cost value.

However, it is possible to implement network reconfiguration manually, without relying on a remote communication system, and still capture interesting benefits, particularly on loss reduction. Enexis (DSO in The Netherlands) (manually) reconfigured the open points in 300 MV loops out of 44000km of their MV grid, achieving a loss reduction of 0.5%, at a reported cost of 670€/loop (according to their replies to the survey).

3.1.7 Switching off redundant transformers

Planning/Operational efficiency		Assets to deploy		
Investment planning	Grid operation	Hardware	Software	Communication
Asset extended lifetime		Remotely controlled transformers switches	Advanced SCADA/DMS Control software	Radio Optic fiber PLC GSM

Possible benefits on planning/operational efficiency

Benefits on investment planning

Switching off redundant transformers reduces their use and aging, possibly deferring needs for replacements.

Assets to deploy - Investments costs

Switching off/on redundant transformers can be performed manually. However, this critically increases the restoration time in case of the loss of the energized transformer. Implementation of remote and/or automatically controlled switches is thus to be preferred. The cost of transformer switches may vary significantly, depending on their power rating.

3.1.8 Voltage optimisation

Planning/Operational efficiency		Assets to deploy		
Investment planning	Grid operation	Hardware	Software	Communication
Line extended lifetime **Increase network capacity** **Increase DG hosting capacity**	**Power Quality problems reduction** **Voltage problems reduction** **Facilitate DG integration**	D-Facts: MV/LV STATCOM, SSSC… Capacitor banks On-Load Tap change transformers Voltage sensors Smart Meters	Advanced SCADA/DMS Control software (centralized system)	Radio Optic fibre PLC GSM

Possible benefits on planning/operational efficiency

Benefits on investment planning

Optimization of reactive power flows allows better exploitation of line capacity, reducing lines loading and possibly increasing their useful life. Voltage optimisation can also compensate the voltage rise/drop due to DG injection, allowing more units to be connected on the grid. In [56], it was shown that voltage control through on-load tap changing transformer was cost-efficient to increase the grid hosting capacity, deferring expensive line reinforcement.

CEZ (Bulgaria) plans to install capacitors and harmonics filtering equipment in two 110kV/20kV substations and in one 110kV/20kV substation. CEZ estimates an investment costs 176k€/substation of expense and CEZ expects a saving of 474k€/annum, coming from less power quality problems to be compensated to the customers, less complaints over voltage fluctuation, reduction of losses, reduction of equipment overheating and their aging.

Benefits on grid operations

Reactive power management systems can be equipped to compensate harmonics injections.
By regulating the voltage level of the grid, complains due to over/under-voltage can be mitigated and DG curtailment reduced.

Assets to deploy - Investments costs

Different options exist to carry out voltage optimization. In a substation, On-Load Tap Changing (OLTP) transformers can be installed to keep voltage within an acceptable range while optimising the operation of the grid. This solution can be more cost-effectively pursued by foreseeing an OLTP when replacing an existing transformer.

Devices injecting or absorbing reactive power can also be installed in various places of the grid. Ideally, the best reactive power reduction and power factor correction is performed by placing compensation devices the closest to the load. However, due to installation and operation cost, a trade-off is to be found between cost, loss reduction and voltage constraints [54]. The length of the network and the voltage stability of the system are therefore key parameters.

Different technologies (fixed capacitors banks, STATCOM, etc.) can be adopted. It should be noticed that, according to [55], self-commutated compensators have the highest impact on losses while having a lower cost than synchronous condenser or static compensator technologies. Manually controlled/remote controlled capacitor banks could also be considered. The cost of the system will depend on the KVAr rating of the installed devices.

To ensure more granular voltage optimisation, feeders voltage sensors or Smart Meters can also be installed to adjust the voltage regulation to the actual grid voltage profiles.

3.1.9 Conservation Voltage Reduction (CVR)

Planning/Operational efficiency		Assets to deploy		
Investment planning	Grid operation	Hardware	**Software**	**Communication**
Increased network capacity **Extended lifetime**	**Reduced fault rate** **Power Quality problems reduction**	On-load tap changing transformers Voltage regulator Capacitors banks Voltage sensors Smart meters	Advanced SCADA/DMS Control software (centralized system)	Radio Optic fiber PLC GSM

Expected benefits on operational efficiency

Benefits on the investment planning

CVR main goal is to reduce energy consumption. Results of such a measure depend on various conditions such as consumers' load, CVR technology used etc. On average, a peak reduction between 0.5% and 4% (depending on the feeder) can be expected, as seen in Denmark ([58]) and in the US ([59] [57]). With a lower peak, the utilization of the line is also reduced, possibly extending its lifetime.

Benefits on grid operations

As stated in the previous point, the peak reductions due to CVR reduces the utilisation of the line and its aging. In principle, the probability of default and the number of interventions could also be reduced.

Assets to deploy - Investments costs

Conservation Voltage Reduction (CVR) exists in various forms of implementation and is highly scalable (e.g. it can be implemented feeder by feeder). [57] describes some practical cases in the US that have shown its low cost to achieve significant benefits (total energy saving cost between 0.01 and 5 cents/kWh following Bonneville Power Administration). To provide an order of magnitude, Adams-Columbia have deployed a CVR on 10 feeders (including 10 voltage regulators, 30 monitoring sensors, 10 controlled capacitors banks and 40 solid state variable capacitors) for 157k€, including software.

3.1.10 Balancing 3-phase loads

Planning/Operational efficiency		Assets to deploy		
Investment planning	Grid operation	Hardware	**Software**	**Communication**
Line extended lifetime **Deferred capacity investment**	**Reduced neutral fault rate** **Power Quality improvement**	LV phases switches in MV/LV substation Feeders load monitoring system Three-phases connections Phase switches at connections Smart meters	Advanced SCADA/DMS Control software (centralized system)	Radio Optic fibre PLC GSM

Expected benefits on operational efficiency

Benefits on the investment planning

Unbalanced feeders lead to higher currents flowing in one of the single-phase lines, which might reach its limit faster than the others. Balancing phases might thus extend the lifetime of the lines.

Benefits on grid operations

Phase balancing reduces intervention and complaints due to Power Quality problems. Problems resulting from current in neutral lines can be reduced (up to 35% of the phase current could circulate in several lines according to [3]), since no zero current is flowing in a perfectly balanced system.

Assets to deploy - Investments costs

Various techniques can be considered to perform phase balancing.

1. Phase-switching between single-phase line can already be performed manually on a regular basis (seasonal for instance) to create a more balanced three-phase system, based on long term feeders load measurement. It is clearly the cheapest approach but the impact is limited.
2. The above technique can also be performed automatically, based on load measurements to optimise the impact.
3. Switches at connections: a more effective phase balancing can be performed by dynamically switching the phase a user is connected to, according to the user's load. This requires to have a three-phase connection for every single-phase user, and to have Smart Meters to measure the current. This technique is however much more expensive than the previous one.
4. Balancing DG injection: according to [60], replacing three-phase inverters by three single-phase inverters can control the injection phase by phase to balance the network.

4 COST-EFFECTIVENESS OF ENERGY EFFICIENCY MEASURES IN ELECTRICITY GRIDS

The goal of this chapter is to analyze in detail the cost-effectiveness of Energy Efficiency for electricity grids. The excel tool described in ANNEX V provides a step-by-step decision support to carry out the assessment.

4.1 Assessment of cost-effectiveness

Cost-effectiveness of each measure is defined as the ratio between the associated benefits and costs. This entails looking at the benefits and the implementation costs associated to each energy efficiency measure. Apart from reducing energy losses, ad discussed in previous chapters, it is considered that EE measures could also provide additional benefits in terms of reduction of OPEX (e.g. restoration time, power quality issues etc.) for the DSO and of avoidance of grid investments (CAPEX reduction).

The analysis consists in individual assessment of all potential benefits and of implementation costs of energy efficiency measures. The output is a ranking of individual energy efficiency measures according to their cost-effectiveness.

The proposed methodology is synthetized in Figure 4-1.

The assessment of the cost-effectiveness of energy efficiency measures has the following characteristics:

- **Focus on individual EE measures** – The focus is on detailed assessment of individual EE measures. The analysis does not consider the perspective of a larger investment plan which also includes a set of EE measures.
- **Assessment of grid energy efficiency benefits according to the following key dimensions**
    - Reduction of grid losses
    - Deferral/avoidance of grid investments
    - Increase of RES hosting capacity
    - Reduction of outages (security of supply)
    - Power Quality

- **Analysis of implementation costs and of factors affecting costs -** The assessment of the investment costs of each measure is done considering the capital and operational costs and the factors affecting them. Moreover, we also look into options for optimization of investments (e.g. replacing assets at the end of useful life).

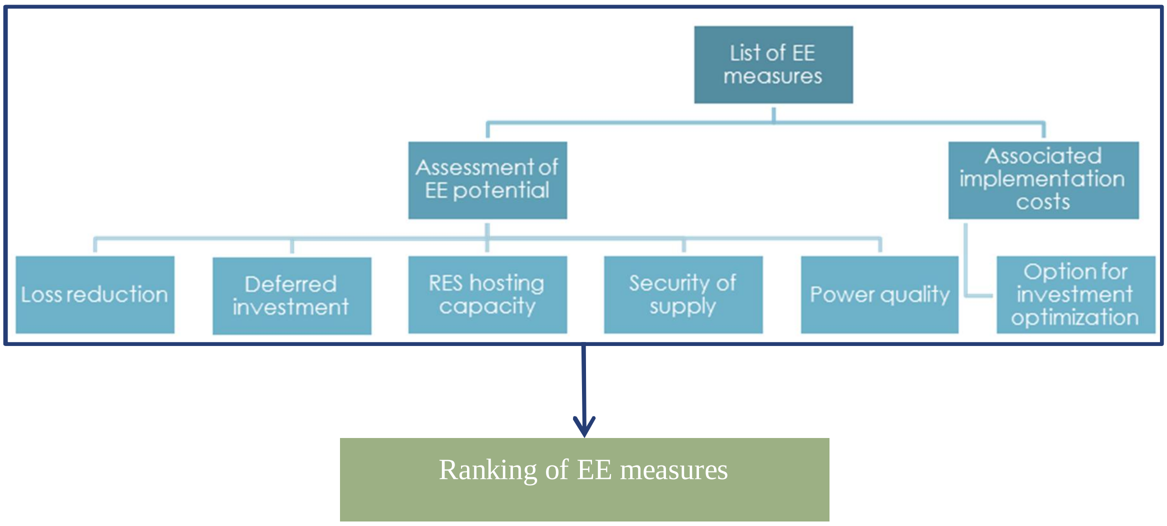


Figure 4-1 - Methodology for assessment of cost-effectiveness of individual EE measures

4.2 Synthesis of the cost effectiveness of the measures

Table 4-1, Table 4-3 –, and **Error! Reference source not found.** provide a synthetic qualitative indication of levels of benefits and costs of the different measures. The assessment assumes the stand-alone implementation of a given measure (no synergies with other measures or other investments) on a per-unit basis.

Clearly, as mentioned, the cost-effectiveness of each measure strongly depends on the specific grid conditions where it is implemented. Provided qualitative value are only intended to provide initial guidance in comparing the different measures. Table 4-4 summarizes the key factors to consider when customizing the cost effectiveness analysis of ach measures to the specific grid conditions. A detailed analysis of these factors is provided in Annex I.

Component replacement

Measure	Loss reduction	Deferred investment	RES hosting capacity	Security of supply	Power quality improvement	Cost	
						Type	Level
EE Transformers	++/+++	+/0		+	+	-Delta cost in case of planned replacement / new installation -Full cost in case of proactive replacement	Low to high
Oversizing line capacity	+++		++	+		-Delta cost in case of planned replacement / new installation -Full cost in case of proactive replacement	Low to high
Increase voltage level	+++	+++	++	+		-Limited adaptation (in case of already voltage compliant equipment) -Massive replacement of all equipment	Low to very high

Table 4-1 – Efficiency & cost of component replacement measures

Grid management

Measure	Loss reduction	Deferred investment	RES hosting capacity	Security of supply	Power quality improvement	Cost	
						Type	Level
Network reconfig.	++	+	++	++		-Mainly software in case of existing remote switches -Full installation of software and remote switches	Low to high
Transformer switching	+/+++	++		-		-Labour work only in case of manual switching -Full installation of new remote switches	Very low to medium
Voltage opt.	+++/++	+		+++	+++	- Mainly software in case of existing equipment -Full new equipment deployment (e.g capacitor/OLTP)	Medium to high
CVR	++	++		++	++	- Mainly software in case of existing equipment -Full new equipment deployment (e.g	Medium

						capacitor/OLTP)	
Bal. 3-ph. Load	++	+	+		++	-Labour work only in case of manual switching -Full installation of new remote switches	Low to high

Table 4-2 – Efficiency & cost of grid management measures

Feed-in control

Measure	Loss reduction	Deferred investment	RES hosting capacity	Security of supply	Power quality improvement	Cost	
						Type	Level
Demand response	+++	+++	++	++		Depending on the regulation	Low to medium
DG control	+/++	++	++	++	++	Depending on the regulation	Low to medium

Table 4-3 — Efficiency & cost of feed-in control measures

		High efficiency transformers	Expanding line capacity	Increase voltage level	Network reconfiguration	Switching-off redundant transformers	Demand response	Feed-in control & storage	Voltage optimisation	Conservation Voltage Regulation	Balancing 3-phase load
Factors impacting the efficiency of the measure	Load rate	X	X	X		X	X	X	X	X	X
	Age of the assets	X	X								
	Fault rate	X	X	X	X	X					
	High harmonics problems	X						X			
	Transformers power rating	X									
	Grid length			X					X		
	Voltage issues			X				X	X	X	X
	Feeders load unbalance				X						
	Number of switches				X						
	Average restoration time				X						
	Presence of a repartition grid				X						
	Number of transformers in parallel					X					
	DG curtailment level						X	X			
	Distance between DG and consumers										
	Power factor								X		
	DG penetration rate								X		
	Number of voltage level								X		
	Voltage level				X						
	Neutral conductors issues										X
Factors impacting the cost of the measure	Overhead □ underground grid		X	X	X			X	X	X	X
	Urban□ rural network			X	X				X	X	X
	Transformers accessibility	X									
	Age of the assets	X		X							
	Other replacement/expansion plans	X	X	X	X	X			X	X	X
	Technology standardization	X	X	X							
	Asset fitted for an upper voltage			X							
	Grid expansion / load growth			X							
	Voltage level				X				X		
	DG integration			X							
	Penetration of the communication system				X	X		X	X	X	
	Flexibility market						X				
	Smart Meter roll-out plan							X	X	X	X
	DG incentive to customer							X			
	Combination with CVR								X		
	LV consumers' density										X
	LV substation density										X

Table 4-4 – Factors impacting the overall efficiency and the cost of the measures

5 ASSESSMENT OF THE ENERGY EFFICIENCY POTENTIAL IN GAS GRIDS

5.1 Understanding Energy Losses in gas networks

The natural gas transmission and distribution system consists of a complex network of pipelines. As detailed in Table 5-1, in the European Union, it represents more than 2150 thousand kilometres of pipelines.

EU	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
	1717	1740	1781	1825	1874	1948	1985	2028	2041	2083	2150
AUSTRIA	30.3	31.4	32.8	33.5	35.1	36	38.3	38.6	39.9	42.8	42.9
BELGIUM	53.7	54.8	59.3	59.3	63.4	65.8	67.8	69.7	71	72.8	73.7
BULGARIA	0.85	0.91	1.3	1.6	1.8	2.2	2.7	3.1	3.4	6.5	6.7
CZECH REPUBLIC	69.4	71.1	72.8	73.3	74.4	74.4	74.6	76.2	75.9	77.1	77.4
DENMARK	18.3	18.4	18.4	18.4	18.4	18.4	18.4	18.4	20.4	20.4	17.9
ESTONIA	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3	2.3	2.9	2.9
FINLAND	2.4	2.4	2.4	2.6	2.7	2.8	2.9	3	3	3.2	3.2
FRANCE	206.5	212.1	217.8	224.1	227.4	230	217.6	229.7	229.7	230.3	231.6
GERMANY	375	375	380	390	400	420	438	443	443	475	477
GREECE	3	3.7	3.9	4.4	4.4	5.3	6.2	7.9	6.7	6.8	6.9
HUNGARY	76.7	77.7	84.3	85.1	86.1	86.6	86.9	87.2	86.9	88.4	90.8
IRELAND	9.8	10.3	10.9	11.3	11.5	12.4	12.8	12.9	12.9	13.2	13.3
ITALY	225.5	228.2	232.2	237.3	258.2	261.9	272	278.6	283.8	282.8	286.7
LATVIA	4.8	4.9	5.2	5.6	5.7	5.8	6	6	6	6.1	6.1
LITHUANIA	7.9	8	8	8.4	9	9.3	9.7	10	10	10	10.1
LUXEMBOURG	2	2.1	2.1	2.4	2.4	2.4	2.7	2.9	2.9	3	3
NETHERLANDS	132.1	135.1	135.1	146.8	146.9	147.7	148.6	150.7	150.7	138.1	135.2
POLAND	116.3	116.3	116.3	119.6	120.5	120.7	124.2	126.2	127.8	127.9	184.1
PORTUGAL	9.9	10.8	11.7	12.5	12.5	12.5	14.9	15.6	15.6	17.3	17.3
ROMANIA	11.8	11.8	11.8	11.8	11.8	46	46.9	46.9	46.9	53.7	53.7
SLOVAKIA	29	30	32.8	32.8	33	33.8	34.2	34.8	35	35.2	35.3
SLOVENIA	1	1	3.9	3.2	3.4	3.6	3.8	4	4.1	4.9	4.9
SPAIN	44.3	48.1	52.1	55.3	58.9	63.1	68.2	71.1	74.2	76.4	80.1
SWEDEN	2.4	2.5	2.5	2.5	2.8	2.8	2.8	3.1	3.1	3.2	3.2
UNITED KINGDOM	281.3	281.4	281.5	281.5	281.6	282.1	282.6	285.6	285.6	285.6	285.6

Unit: km * 1000

Table 5-1: Length of gas transmission and distribution pipelines in Europe (Source: Gas Infrastructure Europe)

In order to ensure that natural gas remains pressurized during its transmission (and more rarely during its distribution), compression, by means of compressor stations, is required periodically along the pipelines.

The following simplified diagram shows a typical natural gas transmission and distribution network.

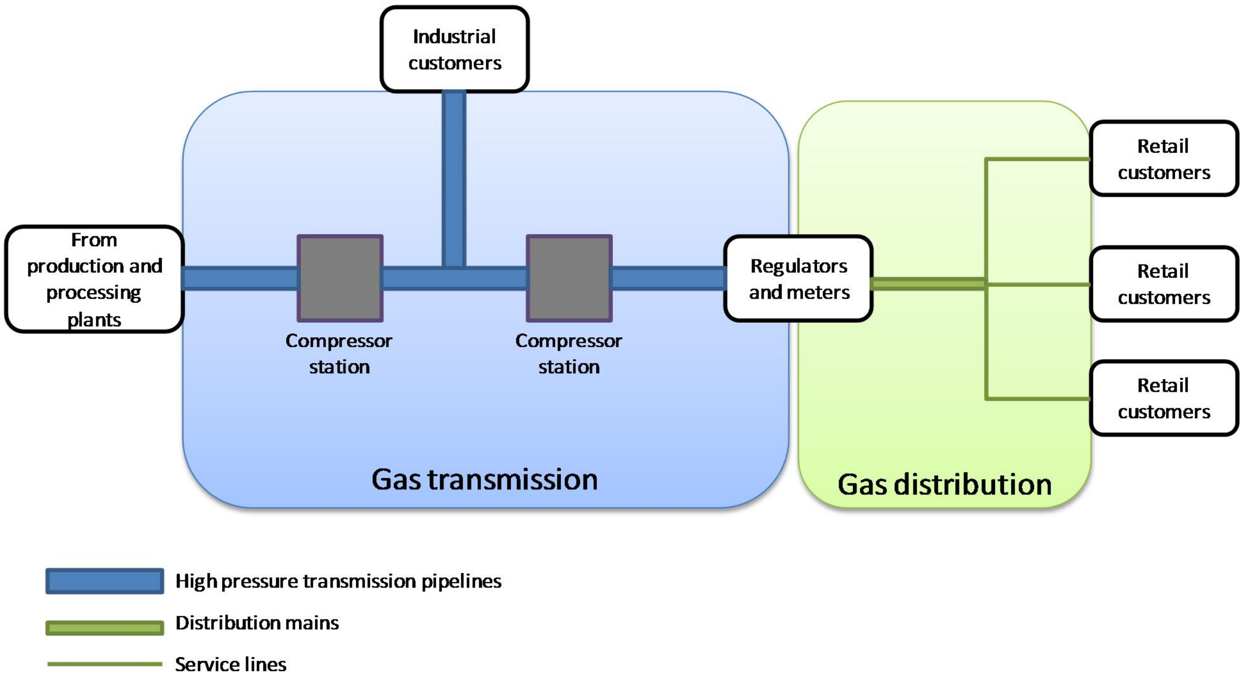


Figure 5-1: Typical natural gas transmission and distribution network

Energy losses due to gas transmission and distribution have been considered in this study to be natural gas shrinkage (gas losses and own consumption) and own electricity consumption. Figure 5-2 reports the losses level among representative Member States.

Figure 5-2 – Level of losses[19] in gas grids in selected EU Member States

Compressor stations are the largest sources of gas use on a gas distribution and transmission network. Electricity consumption can be important as well on compressor stations, when electricity is used to run compressors.

Gas losses can arise from multiple causes. They have been grouped in three categories:

- **Vented emissions:** Direct gas releases to the atmosphere of natural gas resulting from equipment design, regular process operations, maintenance activities, or emergency releases (e.g. process designed flow to the atmosphere through seals or vent pipes, equipment blowdown for maintenance or an emergency, and direct venting of gas used to power equipment (such as pneumatic devices)).

[19] Both technical and non-technical losses, based on the Ecofys analysis from EuroStat database

- **Fugitive emissions:** Unintentional leaks of gas from piping and associated equipment components (e.g. leaks from valve seals, packing or leaks resulting from corrosion, faulty connections). Such emissions can occur on many different parts of the network and are very difficult to estimate.
- **Emissions due to incidents:** Inadvertent damages to pipelines may also cause gas emissions.

A mapping of energy losses due to gas distribution and transmission is presented in the three following sections.

5.1.1 Mapping of losses in gas transmission network

Gas transmission is achieved by means of high pressure underground pipelines. These pipelines are usually made of steel that is coated and cathodically protected[20].

Figure 6 reports the mapping of mechanisms leading to losses in gas transmission network. These losses can be either natural gas emissions from pipelines (vented, fugitive or caused by incidents), electricity used for pipeline cathodic protection or gas to fuel heaters at regulation stations.

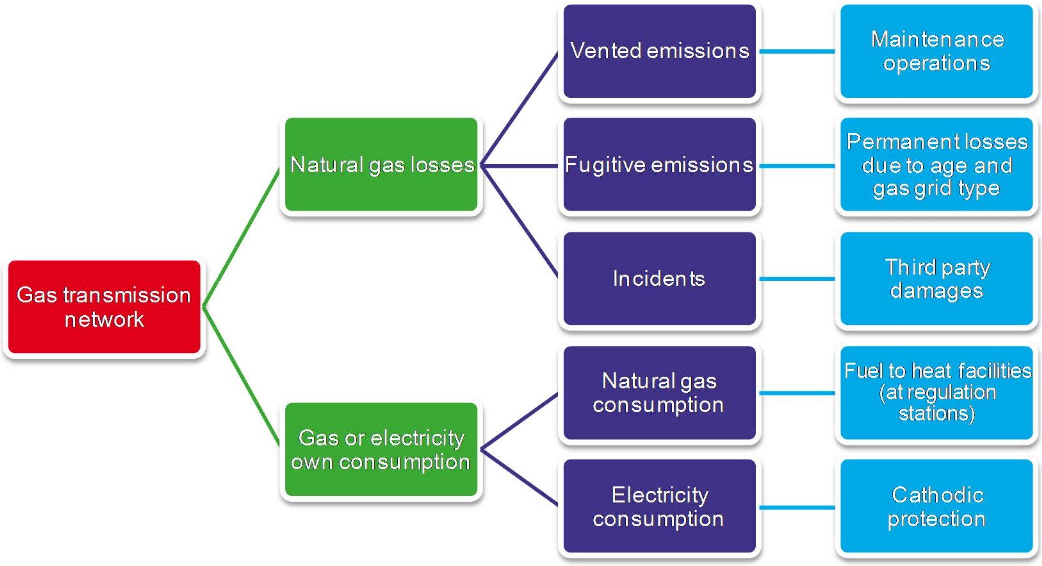


Figure 5-3: Mapping of losses in gas transmission network

[20] Cathodic protection is a technique of running an electric current through the pipe to prevent corrosion and rusting.

5.1.2 Mapping of losses in compression stations

Along the transmission (and sometimes the distribution) networks, compressor stations are placed at regular interval. When gas enters the compressor station, it is compressed by either natural gas fuelled engines or turbines, or electric motors.

Figure 8 reports the mapping of mechanisms leading to losses in gas compressor stations. Fuel used to compress gas is the most important source of gas and electricity consumption. Gas losses can be due to vented emissions from compressors, valves and pneumatic-driven devices or fugitive emissions.

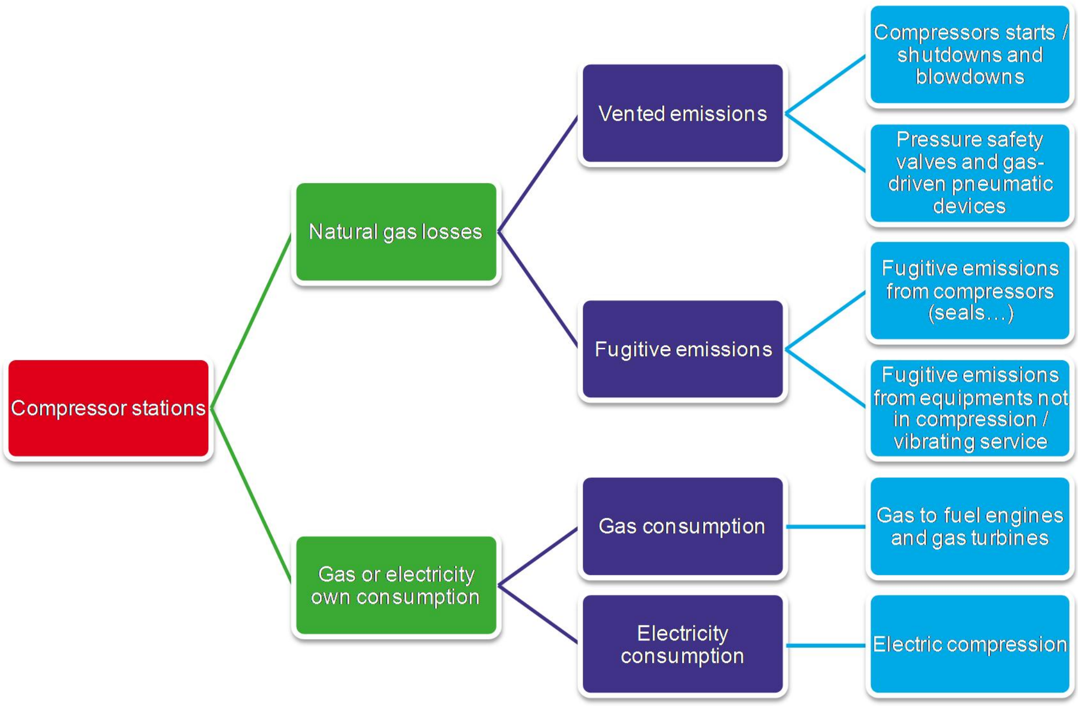


Figure 5-4: Mapping of losses in gas compressor stations

5.1.3 Mapping of losses in gas distribution network

Natural gas is distributed to residential and small industrial customers through medium to low pressure underground pipelines (distribution mains and service lines). Pipeline materials can be very different depending on the localization, the pressure and the age of the network. For example, oldest distribution mains were constructed from cast iron pipes and yarn/lead joints or unprotected steel. New materials are mainly cathodically protected steel and plastic (e.g. polyethylene).

Figure 7 reports the mapping of mechanisms leading to losses in gas transmission grids. Losses can be due to natural gas emissions and gas or electricity consumption. Gas emissions can vary widely depending on the pipeline material as fugitive emissions from older networks are much higher than more recent ones. Gas or electricity consumption can differ from one network to another, depending on situations (e.g. existence of cathodically protected steel, heaters at regulation stations).

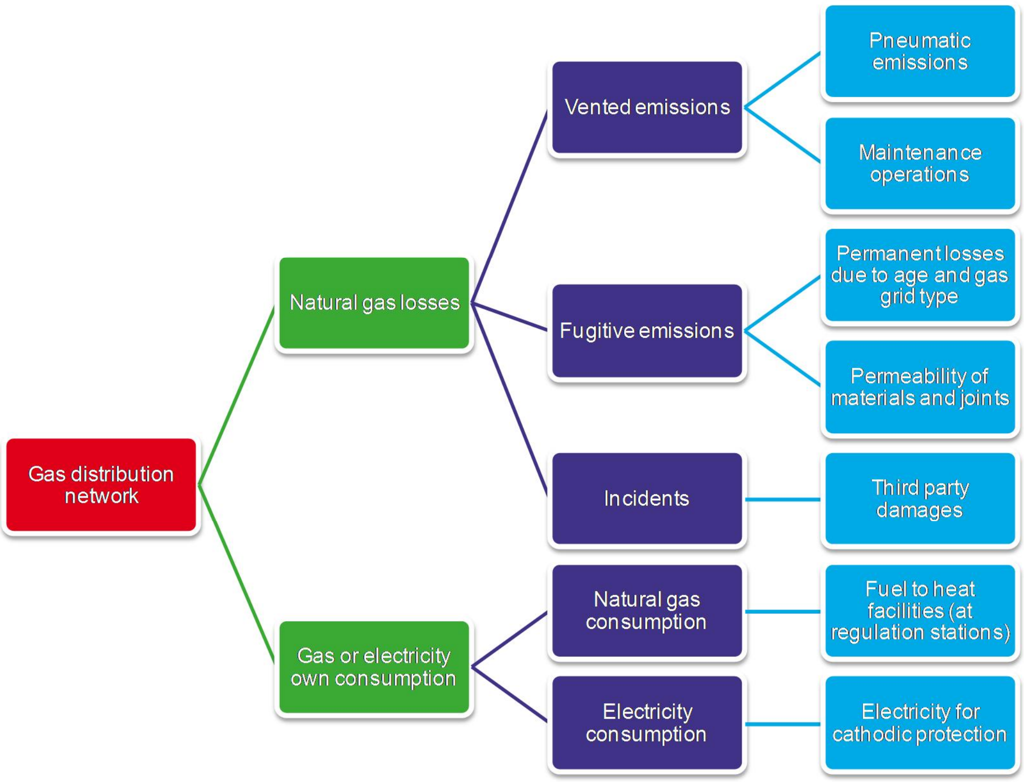


Figure 5-5: Mapping of losses in gas distribution grids

5.2 Energy efficiency measures in gas networks: categorisation and potential

Energy efficiency measures in gas networks are considered in this study to be minimisation of gas losses and own gas and electricity consumption. The three following sections present various energy efficiency measures associated to transmission network, compressor stations and distribution network.

5.2.1 Gas transmission network: energy efficiency measures and reduction potential

The table below reports the list of measures addressing the sources of loss in gas transmission network identified in the previous section. It also describes the reduction potential of each measure and identifies the key factors affecting this potential.

Opportunities to improve energy efficiency measures in gas distribution networks are mainly related to natural gas losses. Measures to reduce vented gas during maintenance operation (e.g. allow customers to use natural gas in order to lower the pressure in the affected section of pipe or gas recompression) can potentially lead to substantial minimisation of losses. For example, a 80% reduction of gas losses can be achieved when gas is recompressed instead of vented before maintenance ([61]).

Category of losses	Type of losses	Associated measures	Qualitative potential	Key factors
Natural gas losses	Maintenance operations	Reduction of vented gas	++	Pressure level, volume of vented pipe
		Recompression	++	Pressure level, volume of vented pipe
	Permanent losses due to age and gas grid type	Inspection and maintenance programs	+	Length and age of the network
	Third party damages	Mapping, relation with contractors, emergency call centers…	+	Length of the network, pressure level, sensitivity of the pipe area (urban or rural, works area…)
		Automatic shut-off valves	+	Length of the network, pressure level, sensitivity of the pipe area (urban or rural, works area…)
Gas or electricity own consumption	Fuel to heat facilities (at regulation stations)	Improved burner design and avoid heating when possible	+	Number and efficiency of heaters, necessity of burners
	Electricity for cathodic protection	(-)	(-)	(-)

Table 5-2: Mapping of energy efficiency measures –Transmission

5.2.2 Compressor stations: energy efficiency measures and reduction potential

Table 5-3 reports the list of measures addressing the sources of loss in compressor stations identified in the previous section. It also describes the reduction potential of each measure and identifies the key factors affecting this potential.

Category of losses	Type of losses	Associated measures	Qualitative potential	Specific key factors
Natural gas losses	Compressors starts / shutdowns and blowdowns	Optimal strategies for cycling on- and off-line	+++	Base or peak load compressor
		Reduction of vented gas (no depressurizing after shutdown…)	+++	Base or peak load compressor
	Pressure safety valves and gas-driven pneumatic devices	Replacement of high bleed devices	+	Number of high bleed devices
		Installation of compressed air/electric systems	++	Number of gas-driven pneumatic devices
	Fugitive emissions from compressors (seals…)	Inspection and maintenance and replacement of seals	++	Inspection frequency, type of seals to be replaced
	Fugitive emissions from equipment's not in compression service	Inspection and maintenance	+	Inspection frequency
Gas own consumption	Engines (reciprocating internal combustion)	Optimization of equipment dispatch	++	Number and capacity of compressors (Pressure and flow regulation)
		Increased efficiency (retrofit control)	++	Compressor efficiency (before and after engine retrofit)
		Replacement with a more efficient unit	+++	Compressor efficiency (before and after engine replacement)
	Gas turbines	Optimization of equipment dispatch	+	Number and capacity of compressors (Pressure and flow regulation)
		Replacement with a more efficient unit	+	Compressor efficiency (before and after gas turbine replacement)

Table 5-3: Mapping of the energy efficiency potential of each measure –Compression

Measures to improve energy efficiency in compressor stations can be either technical solutions (e.g. replacement of seals) or optimized work practices (e.g. optimal strategies for cycling compressors on- and off-line).

Various solutions can be implemented to reduce gas losses. For example, a Marcogaz report ([61]) describes the replacement of pneumatic actuators with devices operated by compressed air in a compressor station in Italy that enabled gas emissions to be reduced by 45%. Another example is the reduction of gas emissions when taking compressor off-line. This can be achieved by keeping compressors pressurized (estimated emission savings: around 30% for a base load compressor ([62])).

Gas and electricity consumption can be reduced when replacing old engines or gas turbines with more efficient units. Another option is to optimize equipment dispatch (e.g. optimisation of pipeline system operations in order to operate compressors at their nominal capacity and avoid as much as possible compressor starts and shutdowns).

5.2.3 Distribution grids: energy efficiency measures and reduction potential

Table 5-4 reports the list of measures addressing the sources of loss in gas distribution network identified in the previous section. It also describes the reduction potential of each measure and identifies the key factors affecting this potential.

The most efficient way to reduce gas losses is to replace or repair/reline old grey cast iron pipes with yarn/lead joints, as they are responsible for the highest emissions. For example, a program of replacement of old pipes in the UK is expected to achieve 10 times lower emissions than previously ([61]).

Third party damages to gas distribution pipes can be another important cause of gas losses. Safety is the primary driver to reduce these gas losses. Emissions can be reduced when implementing measures to prevent damages (e.g. enhancement of the grid mapping accuracy or training and technical guidance provided to contractors in charge of digging works). For example, reduction of the number of third party damages (with gas emissions) of around 30% during the period 2010-2014 has been achieved in a French gas network (GrDF, 2015).

Category of losses	Type of losses	Associated measures	Qualitative potential	Key factors
Natural gas losses	Pneumatic emissions	Reduction of vented gas	+	Number of gas-driven pneumatic devices
	Maintenance operations	Reduction of vented gas	+	Pressure level, volume of vented pipe
		Recompression	+	Pressure level, volume of vented pipe
	Permanent losses due to age and gas grid type	Inspection and maintenance programs	++	Length and age of the network
		Pressure management	*NA*	Length and age of the network
	Permeability of materials and joints	Replacement or repair/relining of old pipes	+++	Length and age of the grid, pipes and joints materials
	Third party damages	Mapping, relation with contractors, emergency call centers, protection of pipes in sensitive areas, shut-off valves	++	Length of the grid, pressure level, sensitivity of the pipe area (urban or rural, works area…)
Gas or electricity own consumption	Fuel to heat facilities (at regulation stations)	Improved burner design and avoid heating when possible	+	Number and efficiency of heaters, necessity of burners
	Electricity for cathodic protection	(-)	(-)	(-)

Table 5-4: Mapping of the energy efficiency potential of each measure –Distribution network

6 ASSESSMENT OF COST-EFFECTIVENESS OF SELECTED ENERGY EFFICIENCY MEASURES - GAS

In the following we analyze more in detail the cost-effectiveness of energy efficiency measures with most relevant potential at transmission, distribution and compressor station level.

The excel tool described in ANNEX V provides a step-by-step decision support to carry out the assessment.

6.1 Gas Transmission Network

Table 6-1 describes the type of implementation costs and an estimation of cost levels associated to measures with a significant reduction potential in gas transmission network.

Avoiding emissions during maintenance has significant energy efficiency potential. However, some measures can be quite expensive and may be not economically relevant in all cases (e.g. recompression of gas before maintenance with a mobile compressor unit). Less costly measures, with minor facility modifications, can also be implemented (e.g. use inert gases and pigs to perform pipeline purges instead of venting).

Additional benefits are less greenhouse gas emissions.

Category of losses	Type of losses	Associated measures	Qualitative reduction potential	Type of costs	Cost level
Natural gas losses	Maintenance operations	Reduction of vented gas	++	Capital costs (minor facility modifications), operating costs (maintenance), labour costs	+
		Recompression	++	Capital costs (pump-down compressor), labour costs	+++

Table 6-1: Type of implementing costs and estimated cost levels – Transmission network

Examples of implementation costs are given in Table 6-2. These figures give an order of magnitude and should be considered with caution since situations may differ from one network to another.

Measure	Capital costs estimation	Operating costs estimation
Reduction of vented gas (Use inert gases and pigs to perform pipeline purges)	-	$500 (for 2 miles of 10-inch diameter pipeline) ([62],2011)
Reduction of vented gas (Inject blowdown gas into low pressure mains or fuel gas system)	$1,000 (minor facility modifications: additional piping) ([62],2011)	-
Recompression (mobile compressor unit)	200,000 € (for one case with 630,000 Nm^3 natural gas saved from venting) ([61])	

Table 6-2: Implementation costs of measures – Examples – Transmission network

6.2 Gas Compressor Stations

Table 6-3 describes the type of implementation costs and an estimation of cost levels associated to measures with a significant reduction potential in compressor stations.

Possible measures that can be applied within compressor stations can vary widely. Some of them can be implemented with no (or nearly no) costs (e.g. avoid compressor depressurization after shutdown). Conversely, an engine replacement with a more efficient unit represents a very expensive investment.

Overall, these measures can contribute to improve operational efficiency, less greenhouse gas emissions and cost savings due to reduction of gas losses and own gas consumption.

Category of losses	Type of losses	Associated measures	Qualitative reduction potential	Type of costs	Cost level
Natural gas losses	Compressors starts / shutdowns and blowdowns	Optimal strategies for cycling on- and off-line	+++	Labour costs	+
		Reduction of vented gas (no depressurizing after shutdown…)	+++	No costs (with the option: no depressurizing after shutdown) or minor capital and labour costs with other options	+
	Pressure safety valves and gas-driven pneumatic devices	Installation of compressed air/electric systems	++	Capital costs (compressed air/electric systems)	++
	Fugitive emissions from compressors (seals…)	Inspection and maintenance and replacement of seals	++	Capital costs (seals), operating costs (maintenance), labour costs	++
Gas own consumption	Engines (reciprocating	Optimization of equipment dispatch	++	Labour costs	+

	internal combustion)	Increased efficiency (retrofit control)	++	Capital costs (minor engine modification), operating costs (maintenance), labour costs	++
		Replacement with a more efficient unit	+++	Capital costs (new compressor), operating costs (gas or electricity + maintenance), labour costs	+++

Table 6-3: Type of implementing costs and estimated cost levels – Compressor stations

Examples of implementation costs are given in Table 6-4. These figures give an order of magnitude and should be considered with caution since situations may differ from one compressor station to another.

Measure	Capital costs estimation	Operating costs estimation
Optimal strategies for cycling on- and off-line	-	Labour (very variable costs depending on available equipment and optimization possibilities)
Reduction of vented gas (no depressurizing after shutdown)	-	-
Reduction of vented gas (Keep compressor pressurized and route gas to fuel system or install static seal)	< $5,000 for one compressor ([62], 2006)	
Installation of compressed air/electric systems	$45,000 to $75,000 (per facility)	-
Inspection and maintenance (identification of leaks and cost-effective repairs)	-	$26,248 (average value, for one compressor station) ([62], 2003)
Replacement of seals (compressor rod packing system replacement)	$5,346 ($2008) (per compressor) (US EPA, 2014)	-
Replacement with a more efficient unit (case of an electric compressor)	$6,050,000 (per 5 reciprocating compressors replaced) (EPA Gas STAR Program, 2011)	$6,200,000 (per 5 reciprocating compressors replaced) (EPA Gas STAR Program, 2011)

Table 6-4: Implementation costs of measures – Examples – Compressor stations

6.3 Gas Distribution Network

Table 6-5 describes the type of implementation costs and an estimation of cost levels associated to measures with a significant reduction potential in gas distribution network.

As stated previously, replacement of grey cast iron pipes with polyethylene pipes can reduce significantly gas emissions. This measure can be very expensive, especially in urban areas. This should, however, be put in balance with associated benefits (higher safety level, less greenhouse gas emissions, cost savings due to reduced gas losses and lower repair costs over the next decades).

Less costly measures can be implemented as well (e.g. prevention of third party damages, improvement in inspection and maintenance programs) and will contribute to a greater safety of the network, less greenhouse gas emissions and cost savings due to reduction of gas losses.

Category of losses	Type of losses	Associated measures	Qualitative reduction potential	Type of costs	Cost level
Natural gas losses	Permanent losses due to age and gas grid type	Inspection and maintenance programs	++	Operating costs (maintenance), labour costs	+
	Permeability of materials and joints	Replacement or repair/relining of old pipes	+++	Capital costs (new pipes or liners), operating costs (maintenance), labour costs	+++
	Third party damages	Mapping, relation with contractors, emergency call centers, protection of pipes in sensitive areas, shut-off valves	++	Mainly labour costs Capital costs (for protection of pipes and shut-off valves)	Variable

Table 6-5: Type of implementing costs and estimated cost levels – Distribution network

Examples of implementation costs are given in Table 6-6. These figures give order of magnitude estimation and should be considered with caution since situations may differ from one network to another.

Measure	Capital costs estimation	Operating costs estimation
Improvement in inspection and maintenance programs (increased walking survey)	-	$11,000 for a pipeline system of 2,900 miles (labour costs: $10,000 and additional equipment: $1,000) ([62], 2011)
Replacement of grey cast iron pipes with PE pipes	200,000 € (per km) ([63])	
	> $1,000,000 (for 1 mile of cast iron main replacement) ([64])	
Insert gas main flexible liners (for cast iron and unprotected steel)	$10,000 (for 1 mile of cast iron main and 1 mile of unprotected steel service lines) ([62], 2011)	
Mapping, relation with contractors, emergency call centers	-	Mainly labour (Very variable costs depending on implemented measures)
Shut-off valves (for service lines)	$6,300 (for 350 valves installed) ([62], 2011)	-

Table 6-6: Implementation costs of measures – Examples – Distribution network

ANNEX I - PARAMETERS INFLUENCING THE IMPLEMENTATION AND THE COST-EFFECTIVENESS OF THE MEASURES – DETAILED ANALYSIS

1. HIGH EFFICIENCY TRANSFORMERS

Factors affecting benefits

Grid Parameters	Efficiency impact
Transformer load rate	The optimal efficiency of a transformer is reached at a loading of 30-40 of rated capacity. The potential for energy savings can therefore higher by first replacing overloaded/underloaded transformers and oversize/downsize the new ones to reach the optimal operating point (clearly, oversizing costs must be taken into account in the evaluation).
Age of the transformers	Old transformers are the main contributors to losses, since they had to meet less stringent efficiency standards. The study on transformer replacement carried the in the APEC ([46]) regions show that for instance, an old efficiency standard 25kVA transformer in Russia has a 98% efficiency, compared to 98.9% for 1500 kVA. New standards allow them to reach respectively an efficiency of 99.5% and 99.7%).
Transformers fault rate	Regularly defective transformers can be targeted to improve the quality of supply and reduce the O&M cost.
High harmonics problems	If a transformer encounters non-linear loading and therefore harmonics problems, losses due to Eddy currents might appear and reduce the efficiency of the transformers (Simulations carried out in [65] on 200 kVA transformer showed an efficiency reduction from 98.1% to 96.5% due to harmonics). New transformers equipped with harmonics filters, better core structure, etc. might improve the operating efficiency.

Factors affecting costs

Work constraints	Cost impact
Transformers accessibility	The conditions of installation works (outside, overhead, underground, in a private building, etc.) can have a significant impact on implementation costs.
Transformer power rating	According to the study made on the APEC countries [46], extra-cost related to switching to higher standards is more cost-effective with small transformers. However, in case of proactive replacement, transformers of medium power rating replacement are more cost-effective than replacing small or very large ones.

Investment optimisation	Cost impact
Age of the transformer	The residual value of an old transformer can be close to zero. Its replacement has thus a limited accounting impact.
Other replacement plans / new transformers	As already explained, transformers can be replaced for various reasons, and it is cost-effective to seize those occasions to implement low-loss transformers. Moreover, the implementation of a new transformer can be coordinated with a voltage increase plan or plan to perform voltage control (by installing on-load tap changing transformers). In general, changing the minimal requirements for all new transformers improve the long term efficiency of the asset population
Technology standardization opportunities	Limiting the number of technologies present on the grid leads to O&M cost reduction (less variability in the types of operation; lower cost in maintenance and procurement)

2. EXPANDING LINE CAPACITY

Factors affecting benefits

Grid Parameters	Efficiency impact
Age of the network	The use of new cables with up-to-date technological standards can reduce the risks of defaults/malfunctioning and improve continuity of supply.
Load rate	Heavily loaded feeders generate higher losses. Heavily loaded feeders are also the key target of replacement plans, to increase grid capacity. From an energy efficiency perspective, the cost-effectiveness of this measure is clearly maximized when carried out within a replacement plan which aims at reducing congestions and takes also into account the minimization of losses.
Fault rate	When replacing lines presenting a high fault rate, due to previous faults, isolation damages, etc., oversizing of the lines can be considered.

Factors affecting costs

Work constraints	Cost impact
Overhead / underground grid	Excavation works cost are much higher (depending on the area) than laying lines overhead. All benefits being equal, targeting the replacement of overhead lines is more cost-effective.
Urban / rural areas	Cables or overhead lines installation can be made more quickly and more easily in

	rural area, resulting in lower cost.

Investment optimisation	Cost impact
Age of the network	Targeting the replacement of old cables is more cost-effective thanks to their lower residual value.
Replacement plan already scheduled	As stated in the previous points, various drivers could lead to a line replacement plan. Opportunities to introduce new line size standard have to be taken into account. Synergies can here be found with an increase of the voltage level, where lines replacement may be needed to fit the new voltage level.
Technology standardization opportunities	Limiting the number of technologies present on the grid leads to O&M cost reduction (less various types of operation; optimization of purchasing operations)

3. INCREASING VOLTAGE LEVEL

Factors affecting benefits

Grid Parameters	Efficiency impact
Feeders length	An increase of voltage level could be particularly useful in rural areas, which typically present longer feeders.
Feeders load rate	Current in the conductors is directly proportional to the voltage level. Heavily loaded feeders generate the highest marginal losses and would benefit the most from a voltage increase.
Fault rate	Lines with higher fault rate could be firstly addressed when considering this measure.
Current voltage problems	If there are known local voltage problems (due to DG for instance), increasing voltage on those feeders could reduce clients complains and O&M cost. If DG injection must be curtailed due to too high voltage rise, increasing line voltage would have a mitigation effect.

Factors affecting the costs

Work constraints	Cost impact
Number of already fitted assets	A key point in the cost-effectiveness of the measure is the number of assets (feeders, transformers, etc.) to be replaced. If the insulation level of the asset is sufficient to stand higher voltages, the measure can be less costly to deploy. Otherwise the measure can be highly CAPEX intensive. In LV, going from a 230V

	to 400V network represent more significant cost (need of a four-lines network, three-phases user installation adaptation, etc.)
Underground /overhead grid	If the implementation of the measure requires asset replacement (and particularly cable replacements), an underground grid will much more expensive to replace
Rural /urban area	Asset replacement is easier and less costly in rural area, where the accessibility of the installation is easier and where less work constraints are generally to be encountered.

Investment optimisation	Cost impact
Grid expansion / load growth	If a grid expansion is envisaged to the future load growth, the voltage level supplying those zones has to be considered, especially if the expansion will require high feeder length. Feeders of higher voltage are cheaper (a 34.5kV feeder can be 45% cheaper than a 12.5kV lines [66]), but on the other substations equipment is more expensive. Substation density per feeder is a key point when assessing the measure.
Age of the network	Targeting assets at the end of their lifetime is more cost-effective thanks to their lower residual value.
Technology standardization opportunities	Limiting the number of technologies present on the grid leads to O&M cost reduction (less various types of operation; optimization of purchasing operations). A limitation of the number of voltages level also limits the number of transformers to be installed in the upper voltage level.
Combination with transformers, substations or lines replacement plans	All planned asset replacement actions represent an opportunity to increase the number of asset fitted for higher voltages
DG integration plan	If it is planned to invest in the grid to improve the hosting capacity of distributed generation, the opportunity to increase voltage level should be assessed.

4. DEMAND RESPONSE

Factors affecting the benefits

Grid Parameters	Efficiency impact
Feeder load rate	Critically loaded feeders can be firstly address by such a measure.
DG curtailment	Feeders where the DG's are often curtailed will benefit from an interruptible load, especially if curtailment compensation is to be paid by the grid operator.

Factors affecting costs

Work constraints	Cost impact
Flexibility market	How the flexibility can be purchased is a key component, its price will impact the day-to-day flexibility activation

Investment optimisation	Cost impact
Smart Meter roll-out plan	When and to which extent the smart meters will be placed on the network is to take into account to define which feeders will be targeted first.
Penetration of the communication system	As the above, the extent to which the load can be easily controlled thanks to an existing communication tool impact the cost of measure deployment.

5. FEED-IN CONTROL OF DISTRIBUTED ENERGY GENERATION & STORAGE

Factors affecting the benefits

Grid Parameters	Efficiency impact
Level of harmonics	Harmonics injected in the network by consumer appliances can lead to Power Quality problems and to an increase of losses in the transformers Incentives to place efficient inverters can be made where high levels of harmonics are met.
Feeder load rate	Loss reduction is always most important to be performed on highly loaded feeder. However, depending on the situation, DG can sometimes increase the load rate. Storage solution could also be envisaged.
Distance between DG and consumers	The placement on a DG unit on a feeder can have a significant impact on the increase/decrease of losses. In [66], it has been demonstrated that, depending on the load pattern, an optimal placement on a radial feeder can lead to a loss reduction between 71% and 86%.
Poor power factor	Advanced inverter can enhance the Power Factor by controlling the injection/absorption of reactive power. Incentives to promote those inverters where a local poor power factor is known can be made.
Voltage quality problems	Following the above, good inverters can control the reactive power and therefore the voltage. Local voltage problems, especially those leading to a bad DG integration, can be solved by good inverters.

Factors affecting costs

Work constraints	Cost impact
Overhead / underground	If extra connections works are carried out, excavation works will increase the costs.

grid	
Participation to the user asset cost	Depending on the local regulation, DSO can participate to the cost of the inverter to promote efficient equipment.

Investment optimisation	Cost impact
Smart Meter roll-out plan	With a complete access to the local consumption data, an inverter or its centralised control can make the best forecast and control. A Smart Meter roll-out is a good opportunity to improve the grid efficiency.
Penetration of the communication system	The choice of the control solution (stand-alone, centralised or decentralised) can be made depending on the existing communication system on the targeted grid.

6. NETWORK RECONFIGURATION

Factors affecting benefits

Grid Parameters	Efficiency impact
Number of switches / substation on a feeder	The impact in terms of reduction of losses and of restoration times highly depends on the number of remote switches which are included in the grid reconfiguration. The optimal balance between number of switches and level of benefits should be assessed depending on the specific grid conditions. According to the Synergird study [67], moving the open-point in the middle of the loop can lead to 66% of reduction compared to an end of loop open-point on a feeder with 4 substations, but this reduction can go up to 73% in the case of 16 substations loop.
Current unbalance between feeders	A load repartition of 70%/30% between two feeders can lead to 1.4 times the losses in a case of a 50%/50% repartition ([68]). This makes it clear that the first feeders to be addressed by such a measure should be feeders with strong unbalances.
Current average restoration time	Feeders with an high restoration time, due to the distance between switches, the accessibility of the installations, the number of switches to be controlled, etc. highly benefits from the implementation of remote switches. EnergyUnited (North Carolina – see in [36]) reduced its Customer Minutes Interrupted (CMI) of 90% on specific feeders thanks to automatically remote controlled switches.
Current fault rate	Feeders with a high fault rate would particularly benefit from this solution, reducing the total yearly interruption time.
Presence of sub-transmission / reparation grid	Repartition grids carry more load and impact more consumers than the final grid on a same voltage level.

Factors affecting the costs

Work constraints	Cost impact
Overhead / underground grid	Installation of switches on overhead lines does not represent major work Installation cost for underground grid would be significantly higher.
Urban / rural areas	Field deployment of remotely controlled switches is generally easier and less costly in a more rural area, where installations can be more easily accessible.
Voltage level	Higher voltage levels require switches of higher insulation, which are more expensive.

Investment optimisation	Cost impact
Existing assets	Feeders already equipped with remotely controlled switches would mainly need software adaptation to integrate new functionalities (e.g. for balancing load; for reducing restoration time). Investment will be much lower than in the cases where the implementation and integration of new switches is to be foreseen.
Substation renovation plans	Old substations which must be restored can be easily targeted by such a plan.
Penetration of the communication system	The implementation cost of this solution could greatly be diminished if a robust communication system already exits.

7. SWITCHING OFF REDUNDANT TRANSFORMERS

Factors affecting the benefits

Grid Parameters	Efficiency impact
Number of transformers in parallel	Substations including more than two transformers working in parallel are expected to have higher energy efficiency potential.
Load rate	At a certain load rate level (according to [67]), it might become more efficient in term on losses to connect both transformers to feed the load at the same time. Load pattern of one substation must be measured to assess the best transformers operation mode.
Low transformers fault rate / Low SAIDI	Switching off redundant transformers has the negative side effect to increase the restoration time, since the transformer needs to be magnetised before reaching its full operation mode. The measure will be more efficient in case of feeders with a low transformer fault rate and a non-critical SAIDI. In the case of manual switching, the restoration time and cost increase significantly.

Factors affecting the costs

Investment optimisation	Cost impact
Substation renovation plans	Transformers switches replacement will be optimised if other works are to be carried out in the targeted substation.

8. VOLTAGE OPTIMISATION

Factors affecting the benefits

Grid Parameters	Efficiency impact
Low power factor	The lower the power factor, the higher the potential benefits of reactive power compensation. Specific analysis shall be carried out to select most suitable feeders to be targeted.
Voltage stability problems	Feeders where known voltage problems exist could be firstly targeted.
DG penetration rate	Feeders with high levels of DG injection can be affected by voltage problems and thus could represent good candidate for the implementation of the measure.
Low (advanced) DG penetration rate.	If DG units on the feeders already performed voltage control, CVR would be redundant.
Feeders load rate	Power factor correction is expected to be particularly effective on heavily loaded feeders, leading to higher benefits in terms of reduction of losses and of congestions.
Number of voltage level	If power factor correction is performed in an upper level of the grid, the effect will impact all the downstream levels. Implementing reactive power compensation on a few places on a sub-transmission grid can be more cost effective than implementing it in various locations at lower voltage level.
Length of the network	Following the above, the longer the path between the reactive consumption and the compensation device, the higher the losses.
Line specific characteristic	According to [23], a low R/X ratio leads to a less efficient reactive power control by DG converters.

Factors affecting the costs

Grid Parameters	Efficiency impact
Underground/Overhead grid	The installation cost is significantly higher in the case of an underground grid. Installation of capacitors banks or voltage regulator on overhead lines does not involve major works.

Urban / rural grid	Accessibility of the installation is easier in rural condition. Moreover, long feeders in rural areas are the most subject to voltage drops.
Voltage level	Voltage level has a significant impact on the cost of one capacitor. According to [69], purchase cost for 4.16kV capacitors is 20$/kvar and 25$/kvar at 13.8kV.

Investment optimisation	Efficiency impact
Combination with CVR	Assets for voltage optimisation at the LV level can also be leveraged to perform Conservation Voltage Reduction (CVR), as presented in the following section.
Smart meter-roll out plan	Implementation of Smart Meters would greatly increase the observability of the grid (measures regarding voltage profile and reactive/active power flows) supporting the implementation of voltage optimization measures.
Substation renovation plan	Works to be carried out in substations can be opportunities to install capacitors banks.
Penetration of the communication system	Depending on where Volt/VAR control assets will be installed and on their number, the availability of a robust communication system is important, and must be taken into account.

9. CONSERVATION VOLTAGE REDUCTION

Factors affecting benefits

Grid Parameters	Efficiency impact
Feeders load rate	CVR is highly scalable. Targeting only specific highly loaded feeders can already lead to a major losses reduction (the U.S. Department of Energy determined in [59] that if only 40% of all feeders would have been equipped with CVR, 80% of the target can be reached, and 37% of the objective when deployed only on 10% of the feeder). The main impact of CVR can be achieved with a limited cost. Test can be made before deploying the solution.
Voltage Stability problems	Feeders encountering regularly voltage problems may be the first target of a CVR deployment plan.
Number of final LV customers	CVR objective is to reduce the end-user consumption by reducing voltage level (while remaining in the required nominal voltage range). Therefore, the more customers are connected on the LV, the more effective the impact will be in term of losses reduction and on peak reduction, leading to customer's peak reduction and to investments deferral.

Factors affecting costs

Work constraints	Cost impact
Overhead / underground grid	The installation cost will be significantly higher in the case of an underground grid. Installation of capacitors banks or voltage regulator on overhead does not represent major works.
Urban / rural areas	Field deployment of CVR will be facilitated in a more rural area, where installations can be easily accessible. Moreover, rural grids are usually not meshed, allowing an easier voltage control.

Investment optimisation	Cost impact
Existing assets	Feeders already equipped with capacitors banks, feeder voltage sensors or on-load tap changing transformers only needs automation to perform CVR.
Smart meter roll-out plan	End-users voltage monitoring facilitates and optimizes the implementation of the measure, and limits the number of voltage sensors to deploy.
Transformers replacement plan	To be more effective, the first substation targeted by the measure might be ones where transformers have to be replaced. On-load tap changing transformers can therefore be installed.
Penetration of the communication system	In the case of centralized CVR, the implementation will be facilitated if a robust communication system already exits.

10. BALANCING 3-PHASE LOADS

Factors affecting benefits

Grid Parameters	Efficiency impact
Feeders load rate	The higher the power demand on one feeder, the more the imbalance will have an effect on the losses and on the cable capacity.
Neutral conductors load rate	Current flowing in neutral conductors also results in losses in a 4-lines system, and can cause protections to work in case of overloading. Feeders with frequently overloaded neutral conductors can be firstly addressed.
Neutral conductors fault rate	As the above, fault related to the neutral conductors can be reduced, as no current would normally flow in it.

Factors affecting the cost

Work constraints	Cost impact
Overhead / underground	Installing switches and replacing connections can be made cheaper in an overhead

grid	grid.
Urban / rural grid	Switches installations can be cheaper if an easy access is available.
LV consumers' density	The more LV consumers, the more adaptation work will be need to perform an optimal balancing. Grid with less but more important connection will require less works, but might be less accurate.
LV substation density	As the above, the number of LV substations is important to assess to which extend and with accuracy the measure can be implemented.

Investment optimisation	Cost impact
LV substation renovation plan	If LV substations are to be renovated, it presents an opportunity to installed phase switches.
Connections replacements plan	Every connection replacement is an opportunity to increase the number of three-phases connection.
Smart Meters roll-out plan	Phase connection balancing requires measuring the instantaneous load. If Smart Meter are to be installed, such measures will be provided.

ANNEX II ENERGY EFFICIENCY MEASURES IN EUROPEAN MEMBER STATES: SURVEY

In order to collect experiences and best practices from the field and to integrate the views of main stakeholders in this study, a survey was carried out among stakeholders with respect to the implementation of energy efficiency measures in gas and electricity grids. Mainly DSOs have been targeted, as most of losses occur at distribution level. European DSO associations (EURELECTRIC, GEODE, EDSO, CEDEC) have been involved to facilitate the distribution of the questionnaire

In particular, the survey aimed at collecting information about:

- Their experience with the implementation of grid energy efficiency measures
- The Regulatory mechanisms in place in their country to incentivise the implementation of energy efficiency measures.
- Their view on the list of energy efficiency measures proposed in this study

The detailed description of the questions in the survey and the detailed list of respondents is reported in ANNEX I.

Despite numerous attempts it was not possible to have CEER's view on the regulatory mechanisms to incentivise energy efficiency measures and their view on the level of mobilization in the implementation of article 15.2 in their members' countries.

A total of 16 replies have been collected, providing a good geographical coverage of EU Member States. Since the great majority of respondents were electricity DSOs, in this chapter we will mainly focus on the experiences of DSOs in **electricity grids.** Figure 0-1 reports the list of respondents.

Collected responses have provided very useful insights in the implementation of grid energy efficiency measures by DSOs in different Member States, facing different grid conditions.

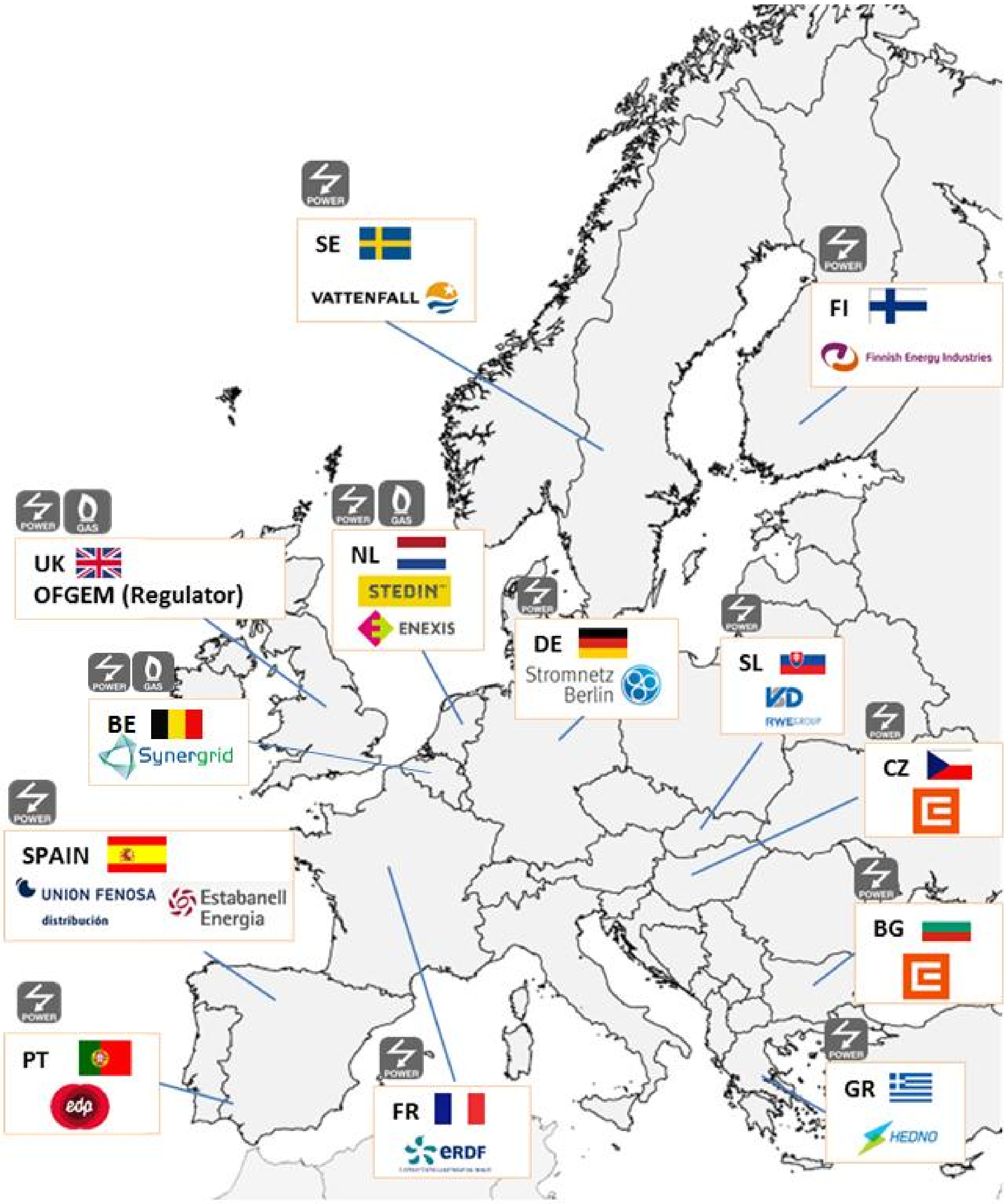


Figure 0-1 - Overview of respondents to the survey

Level of mobilization in Member States regarding the implementation of article 15.2

According to collected information, the level of mobilization in EU Member States in the implementation of the provisions of article 15.2 (definition of investment plans to improve grid energy efficiency) appears to be generally limited. European associations report that most of their members have not yet been actively involved by Member States in addressing the provisions of article 15.2. However, as was confirmed, a number of Member States are working on the topic and would likely publish their assessments in the period after the completion of this study.

Examples of available information from some Member States include:

UK:

- OFGEM (UK regulator) is carrying out a study to comply with the requirements of the regulation [2]. A separate assessment of energy networks in Northern Ireland is being prepared by the Northern Ireland Authority for Utility Regulation.
- In this context, OFGEM has launched a survey among UK system operators to collect best practices and information to
  - Assess the energy efficiency potentials of the gas and electricity infrastructure of Great Britain
  - Identify a list of concrete measures and investments for the introduction of cost-effective energy efficiency improvements in the network infrastructure, with a timetable for their introduction.
- Findings have to be delivered before or on 30th June 2015 to the Secretary of State.

FINLAND:

- The proposal for the transposed legislation was discussed and handled in the Finnish Parliament during autumn 2014 and the legislation has come in force beginning of 2015.
- In May 2015, the Finnish Ministry of Employment and Economy together with the Energy Authority have launched a survey on fulfilling the requirements of Article 15(2). Authorities have also invited other stakeholders (like Finnish Energy Industries and Finnish Gas Association) to join the survey. The survey is carried out by Lappeenranta University of Technology (LUT) and will end in June 2015.
- The main topics of the survey are:
  - the technical losses and the overall efficiency of the system
  - the technical losses of the Finnish electric system are around 1%- so the focus will be more on the overall energy efficiency of the system, including distributed generation, demand response and energy storage. New technology like smart meters, smart grids and LVDC (Low Voltage Direct Current) distribution system will have a big role.

- the concrete measures and investment will also be identified

BELGIUM

- In the context of the implementation of the article 15.2 by 30th June 2015, Synergrid (federation of electricity and gas network operators in Belgium) carried out an assessment of the energy efficiency potentials of gas and electricity infrastructure, together with the energy regulators (FORBEG, Forum for Regulatory Bodies).
- The scope of the study considers energy efficiency in a larger sense than just the reduction of losses. In particular, the study looks at:
    - 1. Potential for reduced grid losses and reduced energy consumption by the network operators.
    - 2. Potential to improve the efficient operation of available energy infrastructure, which in turn could allow reducing the need for investing in new infrastructure
- Categories of measures that will be considered:
    - Investing measures by the network operators
    - Operational measures by the network operators
    - Changing the behaviour of the consumers, considering incentivizing Mechanisms (e.g. tariffs by Time-of-Use, or flexibility vs. capacity tariffs)
- A public (shorter) version of the report has been made available. The document will serve as support for regulator to review the investment plans from the grid operators.

SWEDEN:

- The Swedish Energy Agency has carried out a study to assess the energy efficiency potential of gas and electricity grid in Sweden.
- The energy saving potential in grid infrastructure is considered to be relative low, although not to be neglected
    - The main share of the loss reduction potential in electricity grids by 2030 could be obtained by changing the location of electricity generation units. This is however outside the responsibility of grid operators.
    - The potential that is achievable through measures conducted by the grid companies themselves is around 175GWh/year by 2020 and 400GWh/year by 2030. In relation to total losses, these potentials are quite small: 4% by 2020 and 7% by 2030.
    - Standards for new transformers through the EcoDesign Directive are expected to incentivise energy efficiency improvements.

    - Losses in gas grids are considered very limited and therefore investments in energy efficiency measures would not be justified.
- A key remark made by the study is that reduction of losses should not be the main driver of grid investments, as that can lead to sub-optimal solutions. It is important to adopt a systems approach for energy efficiency.
- In this respect, the introduction of regulatory incentives to improve more efficient network operations are expected to support investment plans which take also loss reduction into account.

Summary of key insights of the survey

The following insights have been derived from the analysis of the survey respondents. Further literature analysis has been carried out to further validate received replies:

State of play in Member States

- **Significant differences across Member States** concerning the level of losses.
- Starting conditions of grids (e.g. voltage level; number of transformers) and potentials for energy efficiency improvement are different. Transposition of best practices should be done with care.

Drivers

- **Energy efficiency within larger grid investment decision plans -** Energy efficiency is typically taken into account in grid investment decisions, however often it is not the main driver. Energy efficiency is considered as one of the variables of a larger investment optimization plan. The importance of energy efficiency as a criterion in grid investment decisions clearly depends on the existence of regulatory incentives to reduce losses.
- **Compliance with energy efficiency obligations**: In specific cases, energy efficiency investments (particularly concerning loss reduction) are undertaken to comply with regulatory requirements and quality standards (e.g. compliance with the EcoDesign directive leading to installation of higher efficiency transformers)

Mapping of losses

- Electricity losses mainly occur at distribution level
- The implementation of adequate metering systems at substations and at customers' premises is an important first step to identify where losses are actually occurring in the distribution grid.
- The following factors have a key impact on the level of losses in the system
    - Loading (including peak demand)

- Number of energized transformers
- Lengths of the feeders and grid voltage levels
- Level of power quality
- Presence of distributed energy resources

Catalogue of energy efficiency measures

- A variety of energy efficiency measures exist, and their potential is very much related to the specific local grid conditions.
- In general, system operators opt for traditional investments (replacement of assets; reinforcements etc.) to improve grid energy efficiency.

Factors impacting grid energy efficiency potential outside control and responsibility of system operators

- Smart Grid-related EE measures (e.g. feed-in control) are less common: in many cases the right regulatory framework is not in place to make them a viable option.
- External factors outside the control of system operators can also greatly impact the potential of EE measures: e.g. the development and location of DERs.

Cost-effectiveness

In general, a number of factors can greatly impact the cost-effectiveness of energy efficiency measures, including:

- Monetary value of losses, i.e. the average price of wholesale electricity (the higher, the more cost-effective are EE measures)
- Loss reduction is a side-benefit of investments driven by other needs. Therefore the cost-effectiveness of an energy efficiency measure depends on additional benefits in terms of CAPEX/OPEX reduction.
- When implementing EE measures, additional benefits in terms of reduction of CAPEX and OPEX should be considered. However, for some measures, a trade-off needs to be found between improvement of energy losses and other benefits (e.g. trade-off with hosting capacity for DER voltage measure).
- Parallel developments (e.g. roll-out of smart meters; built-in smart functionalities in DG converters etc.) make the enabling infrastructure for certain EE measure already available, reducing their implementation costs.
- Most adopted EE measures concern implementation of higher efficiency assets (e.g. higher capacity cable; higher efficiency transformers) within a planned asset replacement strategy. An overall investment optimization strategy is therefore key to ensure that most cost-effective energy efficiency measures are implemented.

Energy efficiency measures implemented by survey respondents

Figure 0-2 provides a brief synthesis of grid energy efficiency measures implemented by respondents. The survey results show that classical measures such as transformers replacement and line capacity increase are the most commonly adopted measures, as their implementation fits with traditional replacement programs, where old or inefficient assets are targeted. Reactive power Management is also well adopted, since voltage quality and distributed generation can also be addressed.

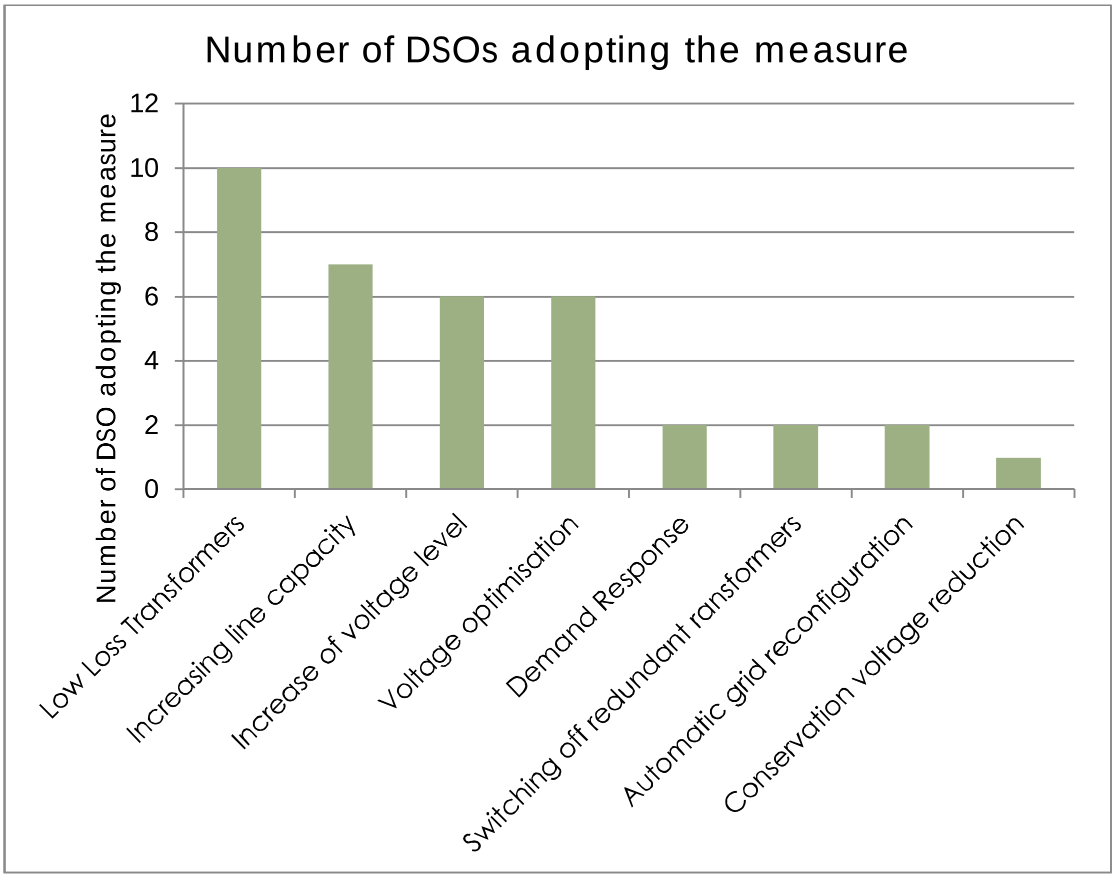


Figure 0-2 - Grid energy efficiency measures in electricity grids adopted by survey respondents

Table 0-1 shows examples of achieved energy efficiency results thanks to implemented measures:

Measures	Implementation example	Highlights of loss reduction	Costs	Additional benefits
High efficiency transformers	**VSD** is replacing 100 transformers/year since 2011 – 10% have been replaced so far. **CEZ Bulgaria** replaced their four 110kV/20kV transformers with the highest losses. **Enexis** is replacing their oldest MV/LV transformers by more recent re-use transformers.	**VSD** expects 8.5% of losses reduction. **CEZ Bulgaria** saved 6.7 k€/year on losses per replaced transformer. **In the UK,** low loss transformers appear as one the most efficient solution.	For **CEZ Czech Republic**, costs increase of at least 20%. Enexis is replacing old MV/KV transformers for 5.3k€/transfo	Higher quality of supply, lower overheating
Increasing line capacity	**VSD** increase their maximum cross section of their LV lines from 70mm² to 150mm². **Belgian DSO's** are developing a tool to incorporate losses in the selection of the minimal cable section.	**VSD** expects on average a 5% (locally up to 20%) reduction of losses,		Higher voltage quality, lower probability of fault, increase capacity
Voltage optimisation / Reactive power management	**CEZ Bulgaria** equipped three of their 110kV/10-20kV substation with capacitors and harmonics filtering units. **CEZ Czech Republic** is conducting a pilot project where 20 synchronous generators in 110kV receive set point in voltage and reactive power.	**ErDF** implemented Volt/Var control of distributed generation. 2-3% of loss reduction is reported. **CEZ Czech Republic** performed a loss reduction of 7% per line, leading to 2.5% overall reduction.	**CEZ Bulgaria** equipped 3 110kV/MV substation at a cost of 528k€	Distributed Generation integration Optimisation of the voltage profile
Increase voltage level	**Vattenfal** is currently studying area per area at optimising the voltage level in their regional grid. **HEDNO** and **EDP**	**Vattenfal** expects a 5% to 15% loss reduction from the increase in voltage levels, with locally 25-30%		

	increased the number of higher voltage transformers, thus increasing the share of higher voltage portion of the grid.	**HEDNO** and **EDP** increased the number of higher voltage transformers, thus increasing the share of higher voltage portion of the grid.		
Conservation Voltage Reduction	**Stromnetz Berlin** has already conducted voltage reduction	According to an OFGEM study, the increase share of voltage-insensitive loads is undermining the potential of this measure.		

Table 0-1 - Highlights of energy efficiency measures in electricity grids implemented by survey respondents

ANNEX III - SURVEY - QUESTIONNAIRE FORMAT

A Project CONTEXT and goal of the QUESTIONNAIRE

- According to Article 15(2) of the Directive, Member States shall ensure, by 30 June 2015, that:
  - (a) an **assessment** is undertaken of the **energy efficiency potentials of their gas and electricity infrastructure**, in particular regarding transmission, distribution, load management and interoperability, and connection to energy generating installations, including access possibilities for micro energy generators;
  - (b) **concrete measures and investments are identified** for the introduction of cost-effective energy efficiency improvements in the network infrastructure, with a **timetable for their introduction**.
- The European Commission has recently launched a study to provide support to Member States in fulfilling the requirements of article 15.2 of the Energy Efficiency Directive
  - The study is titled "Measures for grid energy efficiency in gas and electricity grids"
  - The European Commission considers that **cooperation of relevant stake**holders (system operators, regulatory authorities) is a key element to maximize the pertinence and impact of the study.
- The goal of this questionnaire is to collect data and best practices from system operators:
  - Description of **energy efficiency measures** for **electricity grids** (measures for reducing **technical losses**)
  - Description of **energy efficiency measures** for **gas grids** (measures for reducing **gas losses** and for optimizing **use of energy** in grid operations)

B Survey Part 1 - Energy efficiency in electricity grids

1. Please provide a description of your specific grid conditions :

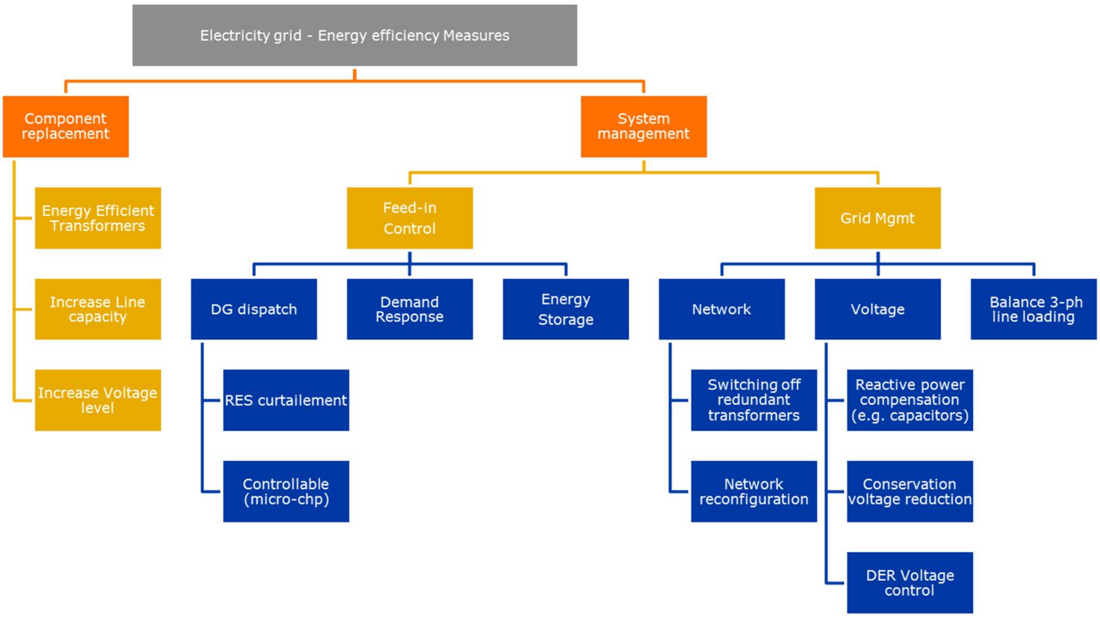
Average number of customers per KM^2	
Average length of feeders	
Number of customers	
Number of voltage levels in the grid?	

Length of the network per voltage level?	
Number of transformers?	
Average age of transformers?	
Level of losses on the grid in the last five years?	

2 Please provide a short description of the on-going and planned energy efficiency measures (measures for reducing technical losses):

Are there any regulatory incentives to reduce grid energy losses?	
Which energy efficiency measures have been taken so far?	
Which energy efficiency measures are you planning?	

3 Please find below a proposed list of energy efficiency measures. Could you please provide your comments?



4 Please provide a description, as detailed as possible, of energy efficiency measures you have implemented or are planning to implement.

DESCRIPTION OF ENERGY EFFICIENCY MEASURES –ELECTRICITY GRIDS	
Which measure? Please describe.	
Level of penetration of the measure? (e.g. number of impacted feeders, transformers…)	
Which losses reduction has been observed (%)?	
Which factors have a high sensitivity on the cost-effectiveness of the measure? (e.g. age of asset, peak load,…)	
Additional Benefits? (reduction of CAPEX/OPEX,…)	
Estimation of the cost of the measure?	
Which lessons learned to optimize the implementation of this measure?	

C Survey Part 2 - Energy efficiency in gas grids

1 Please provide a description of your specific grid conditions by filling in this table:

Average number of customers per Km^2	
Number of customers	
Number of pressure levels in the grid?	
Length of the network per pressure level?	

Number of pressure reduction stations?	
Average age of gas heaters in pressure reduction stations?	
Level of losses on the grid in the last five years?	

2 Please provide a short description of the on-going and planned energy efficiency measures (measures for reducing gas shrinkage and for optimizing use of energy in grid operations)

Are there any regulatory incentives to improve grid energy efficiency (i.e. reduction of gas losses and of use of energy)?	
Which energy efficiency measures have been taken so far?	
Which energy efficiency measures are you planning?	

3 Please find below a proposed list of energy efficiency measures. Could you please provide your comments?

Measures for reducing energy use for grid operation (e.g. optimization of compression; pressure profiles)	
Gas heating	Increase the use of multistage regulator lines, lines insulation, heat exchanger...
	Use of high-efficiency gas heaters in pressure reduction stations
	Use of CHP
Cathodic protection	Autonomous generation through solar panels
Quantity of gas delivered to LP users	Optimization of the delivered pressure
Reduce transmission needs by using decentralized generation	Biogas plants
	Storage
	Power-to-gas
Measures for reducing gas losses	
Scheduled for operation	Lower pressure through a closed by LP-grid
	Optimization of the valves placed on the grid to reduce the volume to evacuate
	Increase the use of mobile flow interrupter
Unscheduled (leakages)	Replacement of old pipes to PE pipes
	% of steel pipes cathodically protected
	Number of valves on the network
	Use of automatic flow-stopper on grid and connections
	Limitations of the operating pressure
Assessment of losses	Smart Meters
	Frequency of leakage detections

4 Please provide a description, as detailed as possible, of energy efficiency measures you have implemented or are planning to implement. Please include additional slides to describe additional measures.

DESCRIPTION OF ENERGY EFFICIENCY MEASURES –ELECTRICITY GRIDS	
Which measure? Please describe.	
Level of penetration of the measure? (e.g. number of impacted pipelines/pressure stations)	
Which losses reduction has been observed (%)?	
Which factors have a high sensitivity on the cost-effectiveness of the measure? (e.g. pressure level, age of asset,…)	
Additional Benefits? (reduction of CAPEX/OPEX,…)	
Estimation of the cost of the measure?	
Which lessons learned to optimize the implementation of this measure?	

ANNEX IV - TOOL FOR RANKING MEASURES ACCORDING TO THEIR COST-EFFECTIVENESS

An excel tool has been set-up to guide project promoters in the assessment of the cost-effectiveness of different energy efficiency measures according to their local grid conditions. The tool highlights the main factors affecting the benefits and cost of each measure and provides examples for benchmark.

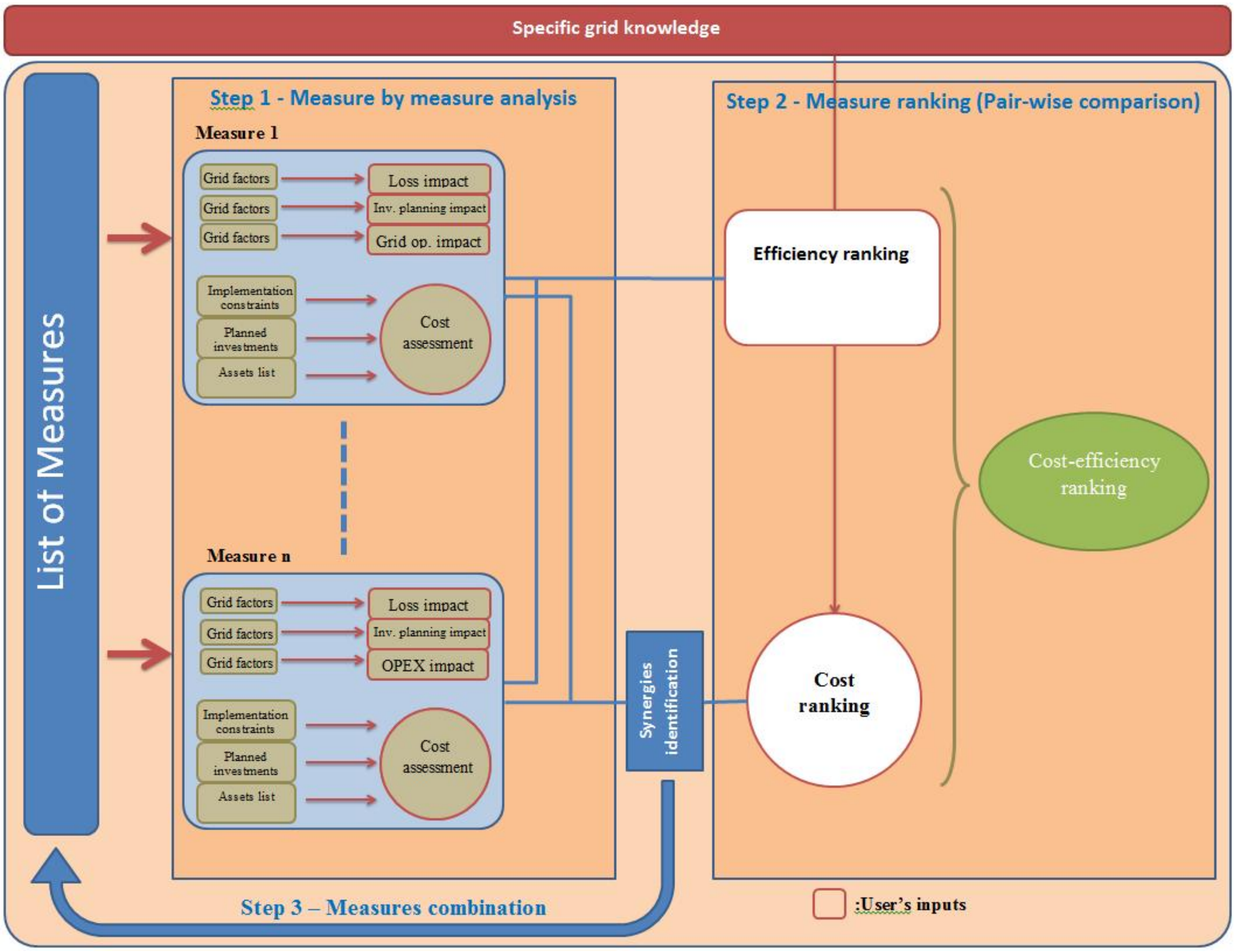
The goal of the tool is to help project promoters in selecting good candidate measures and come up with an overall Energy Efficiency strategy.

This document is the support to an Excel tool, whose goal is to help the user to make up a qualitative cost-efficiency ranking. Those forewords aim to present the general methodology behind this tool.

The analysis provided through the tool is divided in two mains steps:

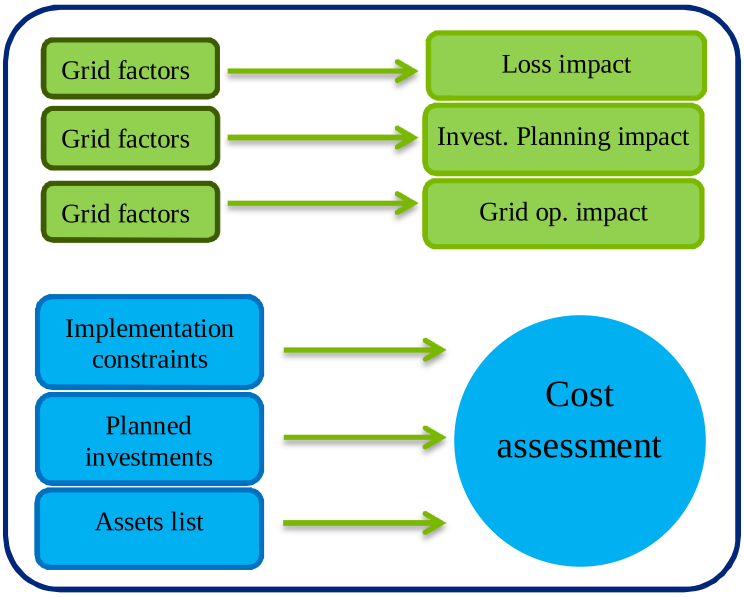
1. Measure by measure impact and cost assessment
2. Ranking of those measure in term of efficiency and cost

The figure here below shows the schematic organisation of the tool:



Step 1 – Measure by measure analysis

The goal of this step is to assess, on one hand, the impact of one measure on the user's specific grid losses, investment planning and grid operations, and, on the other hand, to assess the cost of its implementation. It is important to note here that all the final assessment is on the user's hands, with strong guidelines provided by the Task 1 and 2, presented in this report. The analysis to be done for one measure is presented in figure 2.



The elements providing by the present report and being the guidelines of the tool are classified as follow:

- **Grid factors**: losses, CAPEX and OPEX reduction highly depends of the specific conditions of each grid, such as the current technology in use, the fault rate, the average of assets,…
- **Implementation constraints:** present the elements of the grid how influence the cost of work, such as the situation of the lines (underground/overhead), facility of access, age of the assets
- **Planned investments:** list other investments which may provide opportunities for synergies and reduce implementation costs.
- **Asset list:** list of the assets which should be implemented for the measure.

Step 1.1 – Impact assessment

The users will be guided in the tool following open question, based on open questions, in order to allow the user to build a complete analysis in function of his own grid factors. Each measure should be assessed independently from the others, as well as each factor, following an exhibit as presented down here:

MEASURE N	Loss reduction	Investment planning impact	Grid operation impact
Open question to guide experts reflexions	Current load rate?	Future capacity needs?	Fault rate?
	Possible penetration?		

Expected impact	…	…	…

It is important to repeat at this point that the expected impact here is a totally free judgement from the user. It will serve as basis for the ranking of the measure in the next step.

Step 1.2 – Cost assessment

Secondly, the cost assessment of the measure has to be performed. As for the impact assessment, open questions guide the user to assess his costs in his own case, based on the local work constraints, the asset list for a measure and the current investments already planned for the concerned assets. It is especially for this last point that the final exhibit (presented here below) of this cost assessment make a parallelism between all the measure and the planned investment, asset by asset, in order the identify replacement already in the pipe and synergies between measures. If such synergies appear, the measure list should be adapted, and a new assessment should be done, taking this time the merged measures into account.

	Investment currently planned	Measure 1	Measure 2
Asset 1			
Asset 2			
Asset …			

Step 2 – Ranking of the measures (pair-wise comparison)

Based on the step 1 analysis, the user should rank the measures between them, for each KPI and for the cost. This is performed in the tool through a Multi-Criteria Analysis. The principle is the following:

1. For one KPI, each measure is weighted in front of the others, between 0.1 (very low efficiency compared to the other measure) and 9 (highly efficient).
2. A relative priority is then given for each measure (the higher the score, higher was the efficiency of the measure in front of all the others). An exemple of those two first step is given below

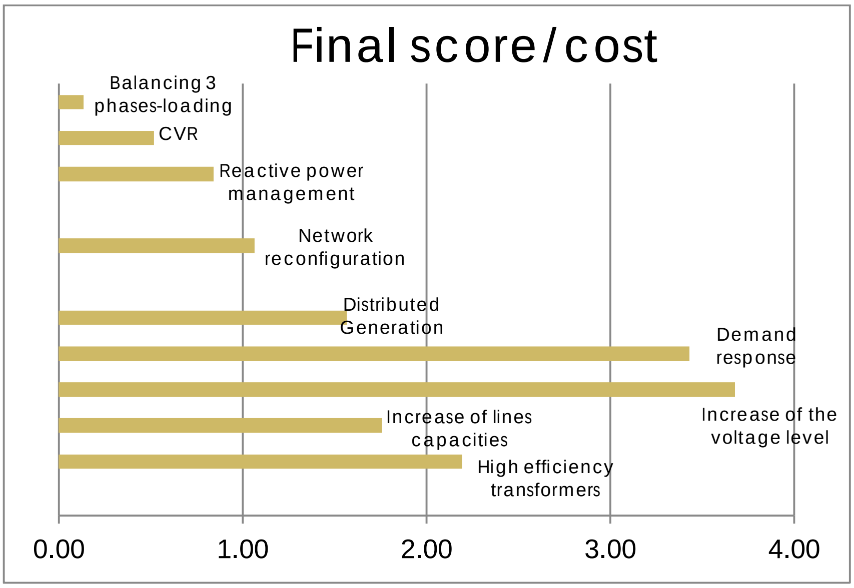
	Measure 1	**Measure 2**	**Measure 3**	**Measure…**	**Relative priorities**
Measure 1	1	1/3	1/2	…	0,3
Measure 2	3	1	2	…	0,17
Measure 3	2	0.5	1	…	0,04
Measure …	…	…	…	1	…

3. A priority should also be given to the KPIs. A MCA comparison is also perform between each KPI. The ranking is made by taking into account the current level of losses, the targeted level, the regulatory framework, the presence of incentive aiming to reduce losses, CAPEX, OPEX… The relative priority calculated for each KPI is used to weight the different priorities given to one measure between them.
4. The sum of the weighted priorities gives the overall ranking of the efficiency of the measures, such as showed in exhibit xxx.

	KPI 1	**KPI 2**	**KPI 3**	**Weighted priorities**
KPIs weights	**0,5**	**0,2**	**0,3**	
Measure 1	0,3	0,02	0,4	0,29
Measure 2				
Measure 3				
Measure …	…	…	…	…

5. Following the same rules, a ranking of the costs is performed, and is used as qualitative assessment of the costs.

6. The final cost-efficiency ranking is given by the ratio $\frac{Efficiency\ weight}{Cost\ weight}$. It is important to note the results provided here are qualitative, and should only be used to identify which measure should be further investigate in more quantitative way. The graph provided here below give an exemple of the results, where "quick wins" and 'must do" can be easily identified.



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