e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

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Annex to D3.2 - Technology Assessment

Note on impacts of ICT on the pan-European Power System up to the 2050 Time Horizon

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Document Information

General purpose

This document contains a detailed report that fully describes a methodology designed to assess the impact of Information and Communications Technology (ICT) on the future development of pan-European power systems up to the 2050 time horizon. It is important to note that more innovative power delivery, supported by state-of-the-art ICT, will be essential for the future development of low-carbon and more extensively integrated power systems.

When considering the above goal, the impact of ICT on future power systems can be analysed with specific regard to the following seven areas of power systems technology as currently defined in Task 3.2:

1. Generation
2. Centralised storage
3. Decentralised storage
4. Passive transmission
5. Active transmission
6. Energy consuming devices
7. Demand-side management enabling technologies

Executive Summary

This report presents the findings, analysis and results under Task 3.2.8 of the e-Highway2050 project, relating to the impacts of ICT on the future development of the pan-European power system up to the 2050 time horizon. Predicting the development and utilization of ICT in future power systems up to 2050 is an ambitious and highly challenging task. ICT infrastructures are evolving at such a rapid pace that it is almost impossible to foresee the nature of the future ICT in 2050. When considering factors such as international conflicts, global financial and economic crises, political instabilities, natural disasters and increased cyber risks, creating accurate quantitative predictions can become even further complicated. However, accepting the fact that the highly accurate quantification of such cost-benefit analyses up to the year 2050 for ICT infrastructures is extremely difficult, if not impossible, it has been attempted to design a transparent and clearly justifiable methodology that can be used at most to estimate the required quantities associated with ICT infrastructure cost-benefit analyses. This methodology can then be applied to the five scenarios as previously defined within the e-Highway 2050 project.

The most physically quantitative ICT components: *data storage*, *bandwidth*, and *computational power* are introduced alongside the appropriate qualitative ICT objectives of *resilience*, *maintenance*, *privacy and cyber security*, and *interoperability*.

While the cost of physically quantitative ICT components will likely continue along an exponentially decreasing cost trend, the most likely scenario in the future is that the most significant costs for implementing the ICT infrastructure will no longer come from the costs of the hardware itself, which has historically been the most significant factor, but rather the more significant costs will be due to the qualitative ICT objectives.

Based on the physically quantitative ICT components and the qualitative ICT objectives in relation to the Smart Grid Architecture Model (SGAM) agreed at European level, relevant *ICT infrastructures* are classified and these infrastructures are mapped to the *power system domains* in order to illustrate their interactions and domain relevance. Finally, in order to consider the role

of ICT infrastructures in future scenarios, a range of potential *benefits* that ICT can bring into future power systems are quantified at the 2050 horizon, and the costs of implementing ICT infrastructures and the benefits enabled exclusively through ICT are compared for all the five *e-Highway2050 scenarios*.

The *traditional payback period* of the ICT investments relative to the present time has been estimated based on the scenarios specifications. According to the analysis, the traditional payback periods for the ‘Large fossil fuel with CCS and Nuclear’, ‘Big and market’, and ‘Small and local’ scenarios are about 20.2, 22.8, and 32.5 years respectively, which illustrates that the ICT investments can be recovered even before 2050. However, by considering the other two scenarios, ‘100% RES’, and ‘Large scale RES and no emission’, where the role of renewable energy sources is significant, the traditional payback periods are 59.8 and 106.9 years respectively.

Along with this report, seven Excel spreadsheets have been provided, used as tools to apply the proposed methodology. Utilizing the attached spreadsheets, an interested party may alter the assumptions made within this study to meet their own assumptions, and analyse the subsequent impacts on the ICT infrastructures costs and benefits.

It is important to note that, while we have attempted to estimate the costs and benefits of ICT infrastructures, there are a number of further external factors which may impact the results of this study, but which fall outside the scope of this document. For instance, all of the implemented infrastructures must be housed in some facility, and the costs for the construction, rental, or the service provision of such a facility are not directly included. Further, the future cost of energy will have a significant impact, as all of these infrastructures must be supplied with energy, and further energy will be needed to run cooling equipment. Given the near impossibility of predicting future energy prices, these effects are also not considered directly. Furthermore macro-economic impacts, such as international trade agreement, currency exchange rates, and inflation rates will all also have significant impacts on the total ICT infrastructure implementation cost, but the modelling of these effects clearly lies outside the scope of this document’s projections.

However, it is also important to note that such costs can be considered indirectly in terms of the qualitative ICT objectives.

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Glossary

2050 Relative Payback Period

The 2050 relative payback period is a financial metric which represents the number of years required to break even on an ICT investment for a specific scenario, relative to the 2050 time horizon. A negative value indicates the payback will be achieved prior to the 2050 time horizon, and a positive value indicates the payback will be achieved after the 2050 time horizon.

3Vs

3Vs is a term used to define the different attributes of big data, which includes volume, variety, and velocity.

Architecture

Fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution [1].

Architecture Framework

Conventions, principles and practices for the description of architectures established within a specific domain of application and/or community of stakeholders [2].

Big Data

Big data is high volume, high velocity, and/or high variety (3Vs) information assets that require new forms of processing to enable enhanced decision making, insight discovery and process optimization [3].

Big Data Analytics

This term refers to deploying software and statistical algorithms in order to extract patterns, properties, and significant features of big data generated and collected in a specific system.

e-Highway2050 Scenarios

From WP1, the five selected scenarios that have been taken into consideration are: Big and Market Scenario (x-10), Large Fossil Fuel with CCS & NUC (x-13), Large Scale RES & No Emissions (x-5), 100% RES (x-7), Small and Local (x-16).

Domain-ICT Interactions

A binary or discrete characterization or 'mapping', indicating what ICT infrastructure may be relevant within a given power system domain.

Domain-ICT Cost Projection Analysis

An extension of the domain-ICT interaction mapping, accounting for the impacts of the projected cost trends of the three considered quantitative ICT components and qualitative ICT objectives.

Energy Efficiency

A ratio between an output of performance, service, goods or energy and an input of energy [5].

High Velocity Data

An example of a definition for high velocity data is millions of rows of data processed and analysed per second. One of the uses cases for high-velocity data is real time analysis.

ICT Capability

ICT capability refers to the ability of an ICT infrastructure to perform a range of tasks associated with data acquisition, information management, and communications [72, 73].

ICT Components

The three quantitative ICT components that are expected to have significant impact on future ICT infrastructure: Bandwidth, Data Storage, and Computational Power.

ICT Infrastructure

A range of different future ICT infrastructure supporting applications such as: Wide Area Monitoring Systems (WAMS), energy market management and trading control systems, etc. that will have impacts with regard to the power system domains.

ICT Objectives

Resilience, Maintenance, Privacy and Cyber Security, and Interoperability are the four qualitative objectives that have been taken into consideration for analysing the impacts of future ICT infrastructure with regard to the power system domains.

ICT Scalability

ICT scalability is the characteristic of an ICT infrastructure to adapt its level of deployment according to the needs and requirements of usage patterns [70, 71].

Information and Communication Technology (ICT)

ICT consists of the hardware, software, networks, and media for the collection, exchange, storage, processing, transmission and presentation of information (data, text, voice, images), as well as related services. ICT can be split into communications technologies and Information Technologies (IT) [4].

Information Technology (IT)

Refers to the hardware and software of information collection, storage, processing, and presentation [4].

Interoperability

Interoperability refers to the standardised ability of two or more devices from the same vendor, or different vendors, to exchange information and use that information for correct co-operation [1].

Projected ICT Component Cost Trends

The projected quantitative cost trends for storage, bandwidth and computational power, based on the historical data.

Qualitative Costs

This term refers to one of the two costs that comprise the overall implementation cost of the ICT infrastructure.. They represent the costs associated with meeting the ICT Objectives; Resilience, Maintenance, Privacy and Cyber Security, and Interoperability. The qualitative costs of ICT objectives together with the quantitative costs of ICT components make up the overall implementation cost of an ICT infrastructure.

Quantitative Costs

This term refers to one of the two costs that comprise the overall implementation cost of the ICT infrastructure. They represent the costs associated with the quantifiable ICT components; Bandwidth, Data Storage, and Computational Power. These costs are incurred when implementing the ICT infrastructure. The quantitative costs of ICT components together with the qualitative costs of ICT objectives make up the overall implementation cost of an ICT infrastructure.

Reliability

Reliability describes the degree of performance of the elements of the bulk electric system that results in electricity being delivered to customers within accepted standards and in the amount desired. Electric system reliability can be addressed by considering two basic and functional aspects of the electric system: A) Adequacy: The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements. B) Security: The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements [5].

Scenario-Specific Analysis

Considering the impacts of ICT implementation within the context of each scenario.

Smart Grid Architecture Model (SGAM)

The SGAM is an architectural model defined from the electrical energy conversion chain, hierarchical levels of power system management, and also a range of interoperability layers in order to offer a support for the design of smart grids use cases. The SGAM is described in detail in [1].

Smart Grid Plane

The smart grid plane provides a reference model within the SGAM on which hierarchical zones of power system management interactions between domains take place [1].

SGAM Domain

One dimension of the Smart Grid Plane covers the complete set of electrical energy conversion and delivery steps, partitioned into 5 domains: Bulk Generation, Transmission, Distribution, DER and Customers Premises [2].

SGAM Zone

One dimension of the Smart Grid Plane represents the hierarchical levels of power system management, partitioned into 6 zones: Process, Field, Station, Operation, Enterprise and Market [2].

SGAM Interoperability Layer

In order to allow a clear presentation and simple handling of the architecture model, the interoperability categories are aggregated in SGAM into five abstract interoperability layers: Business, Function, Information, Communication and Component [1].

Smart Grid

A Smart Grid is an electricity network that can cost-efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure an economically-efficient, sustainable power system with low losses and high levels of quality, security of supply, and safety [2].

Traditional Payback Period

The traditional payback period is a financial metric which represents the number of years required to break even on an ICT investment for a specific scenario, relative to the present time.

Variety of data

The variety of data refers to the potential of highly disparate sets of data, which may need to be analysed in a power system with high levels of ICT deployment. The data will be more diverse including structured, semi structured and unstructured data in future power systems.

Velocity of data

The velocity of data describes the frequency at which data is generated and stored. Considering recent technological developments, high-velocity data can refer to the high-speed data processing, and flows in and out of an enterprise data management solution.

Volume of data

Volume of data refers to the amount of generated data, which is expected to be significantly greater in future power systems deploying ICT.

Chapter 1: Introduction

The unbundling of the power sector requires a close interaction of industry stakeholders, various authorities, and regulators. Europe has experienced the interconnection of national and regional power systems, offering a number of important benefits; for example, the sharing of reserves during both normal operation and emergency operational conditions, dividing responsibility for frequency regulation among all generators, and the possibility of generating power in the most economically attractive areas. On the one hand, large-scale deployment of renewable energy sources and internal European electricity market integration, as enabled by a future pan-European power system, brings lower Green House Gas (GHG) emissions and potentially provides greater energy security at a European wide level. On the other hand, such developments have also introduced new challenges, such as the need for secure communications and wide-area monitoring and control. In future power systems, the development of smart grid functionality will certainly depend on the underlying deployment and availability of appropriate ICT infrastructure, and thus various quality-of-service requirements for different ICT infrastructure will often be agreed through contractual service level agreements with ICT service providers. In certain cases, where for example both very reliable and high-speed data communications are required, private ICT infrastructure will be built on a cost justified basis. In a large number of cases, commercially available public ICT infrastructure is likely to be the appropriate choice [1]. This is part of the progression towards an “Internet of Energy” [1], which can be defined as an integrated dynamic network infrastructure based on standardised and interoperable ICT protocols. Furthermore, considering such huge developments, many utilities are now moving towards implementing smart meters in order to bring greater efficiency and reliability into future power systems. When fully operational, such future power systems will generate huge volumes of different types of data, including high-velocity data. In this case Information Technology (IT) architecture alongside extensive communications technologies have to be considered as essential components of a future pan-European power system.

1.1 Scope of Report

The on-going investments in ICT have made possible the restructuring of the power industry as described above [6-9]. Currently, essential ICT infrastructures exist in power systems; however, the level of functionality, scalability, and capability to maintain high quality of service should be improved for existing and especially for future power systems. Furthermore, it is essential to increase the exchange of information, either to or from the different stakeholders in the pan-European power system in order to increase the interoperability between different countries' power systems. In this case, different stakeholders can effectively cooperate in a predictable way.

In the first chapter, the methodology for analysing the impacts of ICT on the future pan-European power system is described. In the second chapter, the key differences between present and future power systems are investigated. Based on these key differences, future pan-European power system specifications are presented, and a range of ICT requirements for such a system is analysed methodically in order to address future challenges. In order to introduce a methodology for investigating the ICT impacts on the future pan-European power system, different power system domains and zones will have to be considered, which also requires the introduction of the Smart Grid Plane [1,2,10] in the second chapter. Consequently, the Smart Grid Architecture Model (SGAM) [1,2,10] is also summarized and presented as a framework for identifying ICT impacts on the future pan-European power system. In the third chapter, the three core quantitative ICT components: storage, bandwidth, and computational power are introduced alongside the appropriate qualitative ICT objectives of resilience, maintenance, privacy and cyber security, and interoperability. Furthermore, according to the SGAM domains, relevant ICT infrastructure are classified and mapped to the power system domains in order to illustrate their interactions and domain relevance. In the fourth chapter, by applying cost projection trending analysis for the three physically quantitative ICT components and estimated cost impacts of qualitative ICT objectives on the relevant ICT infrastructure, the domain-ICT interaction mapping is quantified to reveal the impact of these costs within the various domains. The fifth chapter presents the primary results describing the impact and costs of ICT infrastructures within the e-Highway2050 five future scenarios selected in WP1 [11]. Within each of the five scenarios, both the necessity of the various ICT infrastructures for enabling the scenario, as well as the cost quantification provided by the domain-ICT cost projection analysis are simultaneously considered. Finally, in the sixth chapter the concluding remarks are specified.

1.2 Objective

According to the European Commission (EC), the research information and communication unit [12], one vision of future power systems confirms that the extensive development, demonstration and deployment of ICT infrastructure will play a significant role in the future delivery of electricity at the pan-European level. Therefore, it is essential to utilize a methodology, in order to identify the ICT portfolio, which would be needed in the future pan-European power system for each e-Highway2050 scenario [12] and to assess their potential impacts.

1.3 Methodology Description

The methodology proposed here consists of three main stages as follows:

- Stage 0- Identification
- Stage 1- Mapping and Trending
- Stage 2- Assessment

This methodology will result in a suitably descriptive and quantifiable analysis of the impacts of ICT infrastructure within future energy scenarios. Figure 1.1 presents a comprehensive workflow of the methodology.

1.3.1 Stage 0-Identification

The objective of this stage is to identify and characterize the power system *domains* from the SGAM [1,2,10]. Furthermore, a range of ICT infrastructures, which are relevant to this analysis, will be classified. These will act as input for the subsequent stages.

One dimension of the SGAM covers the complete set of electrical energy conversion steps, partitioned into 5 domains. By referring to the Figure 1.1, it can be identified that an input of Stage 0 is the SGAM framework. In this case, it is essential to introduce these domains briefly and more details will be provided in Chapter 2.

1. Generation
2. Transmission
3. Distribution

4. Distributed Energy Resources (DER)
5. Customer premises

Figure 1.2 illustrates the SGAM framework and relevant power system domains.

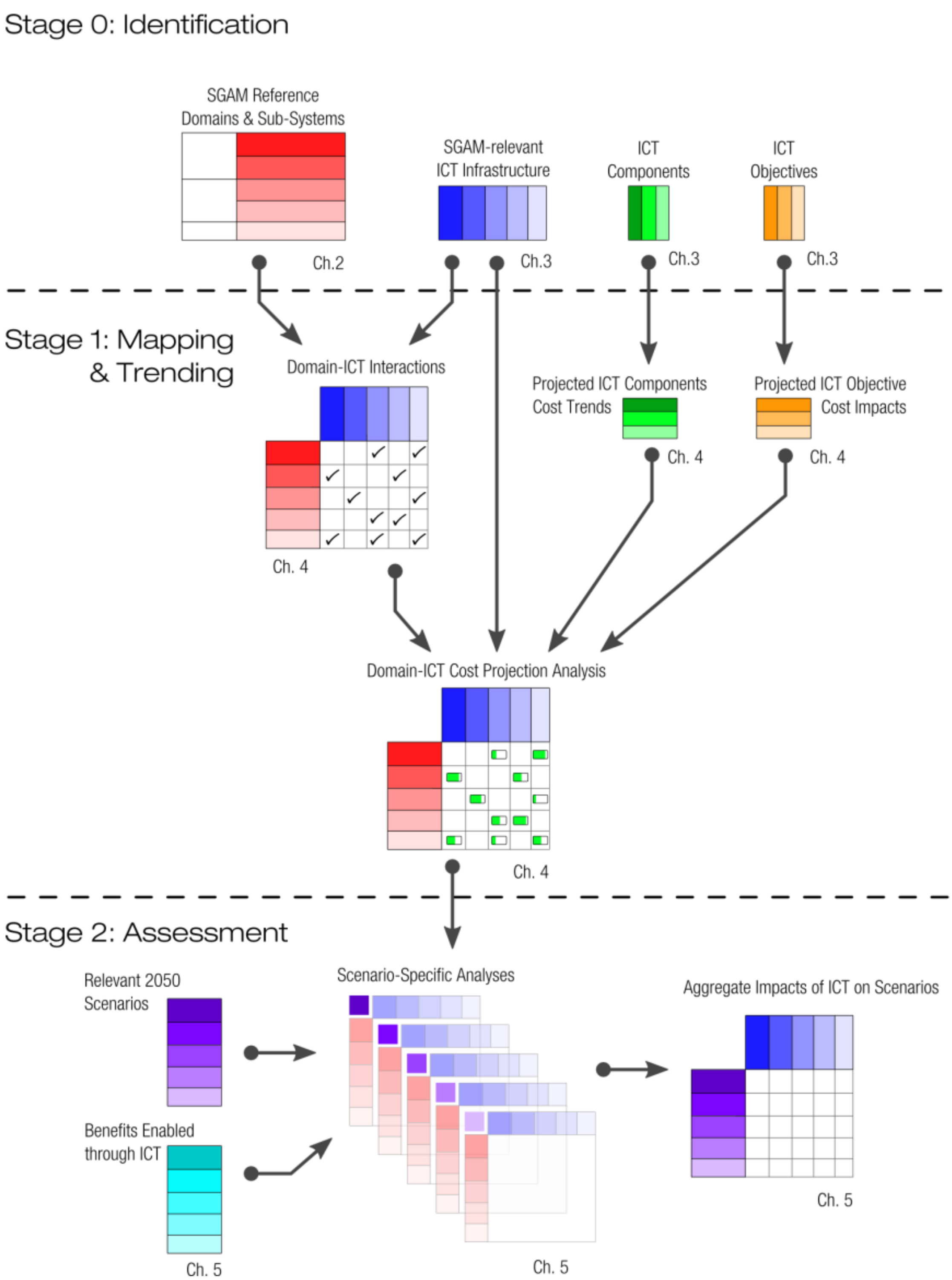


Figure 1.1: Methodology Flowchart

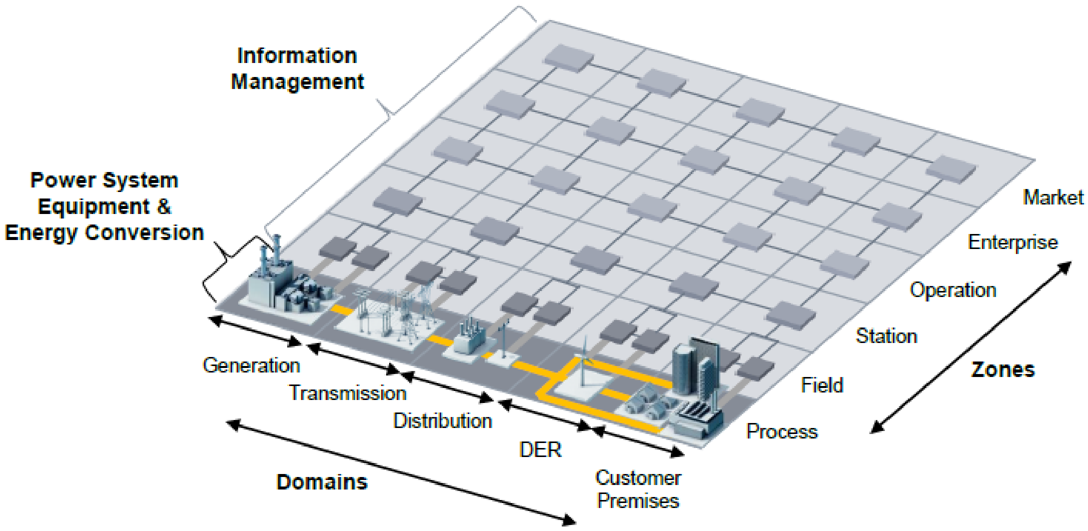


Figure 1.2: SGAM Domains

In this stage, the *SGAM–relevant ICT infrastructure* should be taken into consideration in order to investigate the role of ICT in future power systems. A range of different ICT infrastructure that have major impacts on the power system domains are presented in Chapter 4 as follows:

- Energy market management and trading control
- Weather observation and forecasting
- Asset maintenance and management/Geographical Information System (GIS)
- Advanced Supervisory Control And Data Acquisition (SCADA)/Energy management System (EMS)
- Wide Area Monitoring Systems (WAMS)
- Advanced Metering Infrastructure (AMI) and business services

In order to quantify the impacts of such ICT infrastructure on the power system domains, both quantitative and qualitative aspects have to be considered in Stage 0. The core quantitative elements considered are the *ICT components*, whereas the qualitative measures refer to *ICT objectives*.

ICT Components: In order to quantify the impacts of selected ICT infrastructure on the power system domains, it is critical to properly analyse the costs of implementation for a given ICT infrastructure. Inevitably, the ICT must be constructed from physical hardware components, and within this analysis the most physically quantifiable ICT components that should be accounted for can be listed as follows:

- Storage
- Computational power
- Bandwidth

It is important to mention that by signing contracts with an ICT service provider, the quality of service for these components can be encapsulated in the price.

ICT Objectives: In addition to the most physically quantitative ICT components that comprise an ICT infrastructure, there are additional qualitative objectives that should be taken into consideration when analysing the impacts of ICT infrastructure on the power system domains. Broadly speaking, these objectives are more qualitative aspects of an ICT infrastructure, which lead to an increase in the implementation cost of an ICT infrastructure.

The major objectives are listed as follows:

- Resilience
- Maintenance and Support
- Privacy and Cyber Security
- Interoperability

These objectives are explicitly addressing the issues related to the ICT infrastructure. In this case, these qualitative ICT objectives attempt to address potential ICT infrastructure pricing impacts due to requirements, which may be placed on the ICT infrastructure itself.

In this analysis, the correlation between the ICT components, ICT objectives and each of the selected ICT infrastructures will be taken into consideration in order to achieve the complete cost of integrating an ICT infrastructure within the power system domains.

1.3.2 Stage 1-Mapping and Trending

The inputs of this stage of the methodology are the relevant SGAM domains and ICT infrastructure, as well as physically quantitative ICT components and qualitative ICT objectives identified in Stage 0. The interaction between the domains and ICT infrastructure will be analysed in order to determine if a given ICT infrastructure is expected to have an impact within a domain in future scenarios. The output of this stage will be a *domain-ICT infrastructure interaction table* to summarize the relation between power system domains and the ICT infrastructures.

The domain-ICT infrastructure interaction table is a binary or discrete characterization or 'mapping', indicating what ICT infrastructure may be relevant within a given SGAM domain. For the identified domain-ICT interactions, relevant qualitative cost data are estimated and presented.

In order to facilitate a quantitative analysis of the impacts of ICT infrastructures on the future pan-European power system in this methodology, a cost trend analysis will be performed for the three most quantitative ICT components, in order to yield the *projected ICT components cost trends*. This trending analysis will be based on the historical cost data for:

- *Cost per Tera-Byte (TB) for Storage*
- *Cost per Tera-flops (TFlops) for Computational Power*
- *Cost per Giga or Mega-bit per second (Gbps/Mbps) for Bandwidth*

Considering the likelihood of a massive increase of ICT deployment in a future smart grid infrastructure, the reliance on the three core ICT components (storage, computational power, and bandwidth) is expected to increase proportionally. Therefore, the analysis will take these three ICT components into account when assessing their impact on the considered ICT infrastructure, and subsequently, their impacts on the power system domains in the future scenarios.

Furthermore, it is essential to have a clear and complete presentation of ICT infrastructure impacts on future power systems. In this case, a range of more qualitative ICT objectives, which can drive both the ICT infrastructure costs and their level of deployment in the power system domains, should be taken into consideration. An example of a qualitative ICT objective is interoperability. This objective should be taken into consideration in order to recognize the existing and future standards in the pan-European power system. ICT standards are key to optimising the management of the future power systems and the ICT's own energy footprint. ICT can apply smart and integrated approaches to energy management of systems and processes, including benefits arising from both automation and behavioural change and develop alternatives to high carbon activities across all economic sectors. Furthermore, the maintenance and support aspect of ICT infrastructure should be taken into consideration.

While the future power systems will become more productive and efficient, the energy sector will face an unprecedented challenge in protecting systems against cyber incidents and threats. Therefore, cyber security and privacy is another qualitative aspect that needs to be accounted.

Figure 1.3 presents the *ICT infrastructure cost flow,* considering the impacts of both physical quantitative ICT components and qualitative ICT objectives on the ICT infrastructure complete implementation costs.

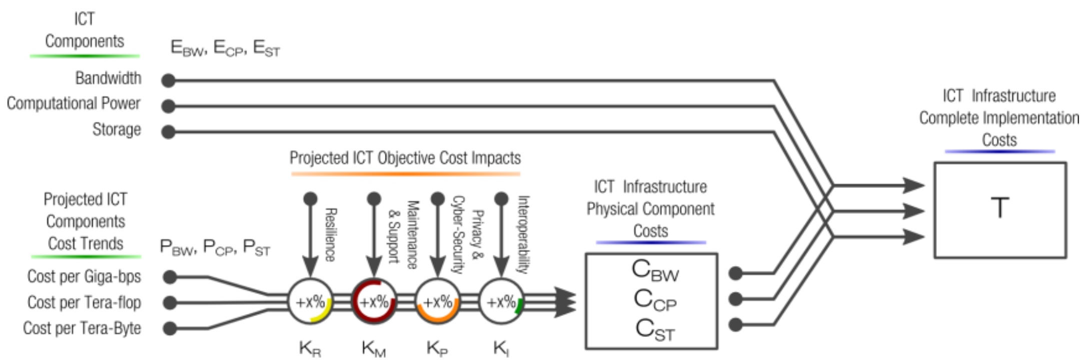


Figure 1.3: ICT Infrastructure Cost Flow Diagram

According to the above figure, the ICT infrastructure complete implementation cost includes the ICT infrastructure physical component costs plus the projected qualitative ICT objective cost impacts. The P_{BW}, P_{CP} and P_{ST} are the projected physically quantitative costs of bandwidth, computational power and storage respectively. In order to consider the impacts of each of these physically quantitative ICT components on different ICT infrastructure, the purchased values of these quantitative ICT components have been introduced: E_{BW}, E_{CP} and E_{ST}. It is important to note that these purchased values will depend on the necessity of the component for system implementation that will be required in implementing an ICT infrastructure. This leads us to the physically quantifiable estimate of the ICT infrastructure component cost.

By considering the qualitative ICT objectives, the impacts of other factors such as interoperability, maintenance, privacy and cyber security, and interoperability will be assessed, by weighting these objectives for each ICT infrastructure in order to determine the *projected ICT objectives cost impacts*. These factors are far more difficult to quantify in terms of costs due to their more indirect relationship with the physical hardware components, but are nonetheless important objectives in the proper operation of an ICT infrastructure, and achieving these objectives will inevitably lead to increased costs in most cases. In order to reflect the impacts of these objectives on the complete cost of implementing an ICT infrastructure, K_R, K_M, K_P and K_I can be introduced as coefficients for resilience, maintenance and support, privacy and security, and interoperability respectively. These coefficients can increase the cost of physically quantitative ICT components in each ICT infrastructure:

The impact of all the projected ICT component and objective cost trends on the domain-ICT interactions will be analysed in order to quantify the potential impacts of ICT infrastructure on the power system domains, resulting in the creation of a *domain-ICT cost projection analysis* table.

In this case, the interaction between ICT infrastructure and the domains will be quantified according to a projected cost measure. The domain-ICT cost projection analysis table is an extension of the domain-ICT interaction mapping, accounting for the impacts of the projected cost trends of the three considered quantitative ICT components and four qualitative ICT objectives. This extended mapping will attempt to provide a quantitative measure of the costs of implementing an ICT infrastructure within a domain. It should be noted that these costs are dominated by factors not depending on the future energy scenarios and it was assumed that the costs are scenario independent. More detailed explanations will be provided in Chapters 3 and 4.

1.3.3 Stage 2-Assessment

The relationship between the ICT infrastructures, quantitative ICT components and qualitative ICT objectives was investigated in the Stage 1. It was demonstrated that these could have an impact on the cost of implementing ICT infrastructure in power system domains. In Stage 2, the five e-Highway 2050 scenarios (Figure 1.4), potential benefits from ICT deployment, and the domain-ICT cost projection analysis will serve as inputs.

These five scenarios are [11]:

- Big and Market Scenario (x-10)
- Large Fossil Fuel with CCS & NUC (x-13)
- Large Scale RES & No Emissions (x-5)
- 100% RES (x-7)

Small and Local (x-16) Since all of these five scenarios cover a wide range

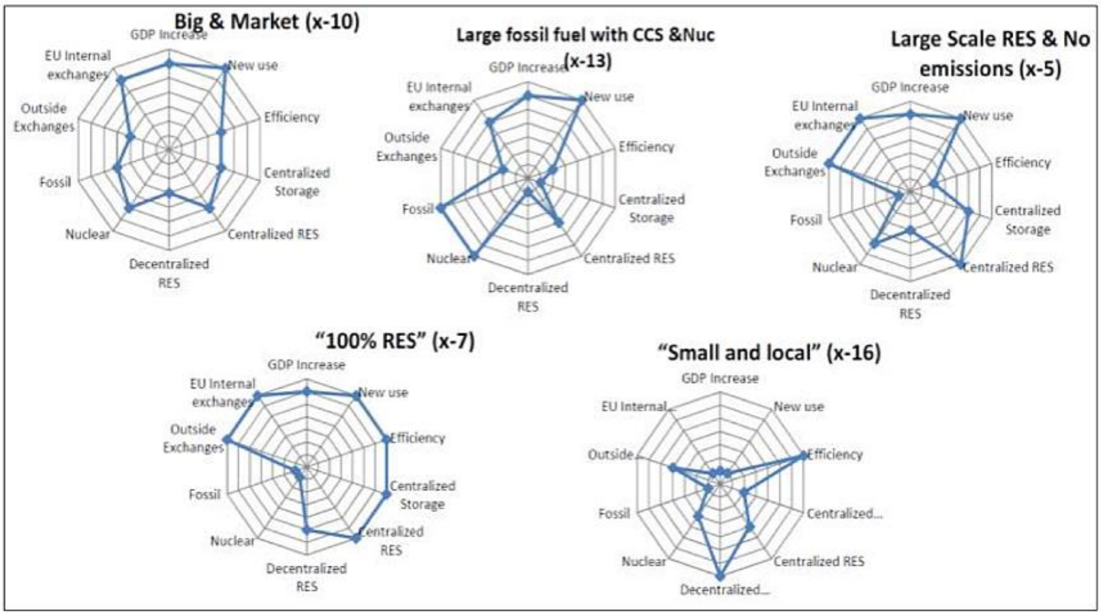


Figure 1.4: e-Highway2050 Five Scenarios

of possibilities for the future pan-European power system, the role of ICT infrastructure will be varied for each scenario. For instance, the considered ICT infrastructure will have varied relevance and impact on the 'Big and Market' scenario (x-10) as compared to the 'Small and Local' scenario (x-16).

Taking PMU deployment as an ICT infrastructure example, the requirements for bandwidth and storage will emerge from high data-sampling rates and consequently large volumes of stored data. This must be weighed against the potential improvements to system operation, through improved situational awareness and greater knowledge of network stability. This in turn should lead to a more secure and resilient system, which in itself could yield financial savings. As part of this analysis, it is important to recognize that if PMU deployment is extensive, network observability may become a useful benefit that becomes critical for power system control, but increased reliance on this system will then likely lead to an increase in ICT infrastructure costs. The cost increase would be due to the needs for increased resilience if observability were to become critical for system stability.

Finally, based on the specifications of each scenario, the interaction between each ICT infrastructure and the scenarios will be assessed, where the potential benefits of ICT implementation will be considered, in order to analyse the ICT infrastructure deployment within the context of each scenario. In this case, the ICT infrastructure themselves may have impacts on the scenarios as well. For example, a particular ICT infrastructure may lead to greater deployment of that system, thus leading to a reduction in costs due to economy of scale. However, it is important to note that the use of ICT worldwide throughout all industries is likely to be so extensive that power system usage of ICT will have nearly no impact on overall market prices for the components, which constitute an ICT infrastructure. In this case, it will be possible that relatively minor economies of scale for labour deployment in the implementation and maintenance of ICT infrastructure might be achieved for a power system scenario. A benefit inventory was made based on several international studies published recently. Where the analysis was country-specific, the quantification was converted and scaled to the European level. In conclusion the *aggregated impacts of ICT on all scenarios* will be presented. More detailed analysis will be provided in Chapter 5.

Chapter 2: Technological Background

Energy security and climate change are two very important topics when considering the development and planning of energy infrastructure, and have thus become some of the EU's top energy policy priorities. One objective of European policy makers is to increase the proportion of Renewable Energy Sources (RES) to 20% by 2020, and to facilitate even further increases in RES looking ahead to 2050 [13]. In order to reach the target of remaining under a 2°C temperature increase, 80-95% reductions of greenhouse gas (GHG) emissions by 2050 are required in developed countries, as compared with the level of GHG in 1990 [13]. In this case, the European Commission (EC) has acknowledged that ICT-based innovations can assist Member States in a cost-effective way in order to reach to these targets.

Firstly, this chapter provide a summary of relevant background information and review a range of ICT requirements for future power systems looking into different time horizons from 2020 up to 2050. Additionally, as specified in the analysis methodology in Chapter 1, the SGAM domains of the power system infrastructure are specified in Stage 0, and serve as inputs to Stage 1 of the proposed methodology. In order to identify and define these domains, which represent a complete set of electrical energy conversion steps, the Smart Grid Architecture Model (SGAM) is introduced in this chapter.

2.1 Comparison between Present and Future Power Systems

In order to identify ICT impacts on future power systems, it is essential to investigate the potential differences between present and future power system infrastructures. The future European power system faces new challenges and opportunities, which must be responded to in a vision of the future. The future pan-European power system, compared with the existing one, will have different characteristics based on a range of principles as follows [14]:

1. <u>Various generation technologies</u>: In the present pan-European power system, renewable energy sources and coal or gas-fired power plants provide a significant share of the national/European energy mix. However,

both large-scale concentrated renewable energy sources and small-scale distributed energy sources are expected to play significantly greater roles in the future pan-European power system.

2. New electricity market structure: An integrated pan-European electricity market, where all participants play an equivalent role in all market arrangements and decisions, will replace non-transparent and illiquid wholesale electricity markets. In the future pan-European power system, flexible and predictable tariffs, along with high flexible demands, will require the introduction of greater controllability and interoperability [14].
3. Optimised asset management plan: The existing limited-functionality operational data and asset management schemes will be replaced by big data acquisition infrastructures [14].
4. Active customers: End-users will be more informed and are likely to take a more active role in future power systems. Demand-response and distributed energy resources are expected to have significantly greater impact in the future pan-European power system.
5. Self-healing features: Existing power systems respond to an outage or failure in order to prevent further disconnections or supply losses in the system. However, future power systems will automatically detect and respond to a greater range of possible outages or faults. They will also act faster, more intelligently, and with a greater level of coordination in order to prevent possible outages or failures [14].
6. Restoration capabilities: Future power systems will be more robust and flexible in restoration.
7. Cyber security: Future power systems will become more exposed to the cyber-attacks.

By considering the above principles, an extensive range of ICT requirements for future power systems can be identified.

2.2 ICT Requirements for Future Power Systems

The integration of Renewable Energy Sources (RES), such as wind and photo-voltaic (PV) systems, will create intermittent and unpredictable fluctuations in the generation pattern of the future pan-European power system [15]. Since a large portion of RES is likely to be smaller, distributed generation sources, it is possible that the flow of electricity in medium-voltage distribution grids will be bidirectional. In addition to the changes expected in generation sources, consumption characteristics will also change through the deployment of smart appliances, electric vehicles (EVs), and heating pumps. The future pan-European power system may have a drastically different structure, driven not only by the integration of various transmission systems within a single market, but also due to distribution grid alterations and a variety of applied smart technologies in the power system.

2.2.1 Pan-European Power System Features

According to the European Commission (EC), the future pan-European power system must have a range of features as follows [12, 74]:

1. **Accessibility:** allowing fair connection access to all network users, particularly for renewable energy sources and high efficiency *local and small* generation with zero or low carbon emissions. This feature may play a significant role in the future pan-European power system, especially in the scenario x-16: “Small and Local” as one the five proposed scenarios in e-Highway2050 project [11].
2. **Flexibility:** satisfying stakeholders in terms of market and operational needs whilst responding to the future challenges.
3. **Efficiency:** providing best-value services to all stakeholders through innovative schemes, providing new technologies, supporting efficient energy management systems and enabling the adoption of new regulations or policies.
4. **Reliability:** ensuring or improving security and quality of supply in the future pan-European power system can be consistent with future ICT infrastructures.

2.2.2 Integration of ICT in Future Power Systems

Considering the above requirements, a significant component enabling the development of the future pan-European power system will be the integration of both extensive IT infrastructures and communications platforms in order to ensure *reliability*, *efficiency, accessibility* and *flexibility*. In this case, a range of advanced ICT applications in future power systems have to be analysed as follows [16]:

1. Deployment of *real time* and interactive ICT for operational and market communications, metering, distribution automation, energy consumptions and also monitoring the state of different assets in various conditions. In this case, the overall state of a future power system will be continuously tracked and reported. Therefore, real-time monitoring and historical trending will play significantly greater roles in the future pan-European power system.
2. Developing different standards for communications between different stakeholders and power system components in order to bring greater levels of interoperability into the future pan-European power system.
3. Integration of distributed energy resources (DER) can bring controllability issues and future power systems should be controlled and monitored more intelligently in order to acquire, store and analyse the huge volumes of data generated by different components.
4. By moving towards smart grids, considerably more data is now available with regard to power systems and big data analytics will play a significantly greater role in the future pan-European power system. The capability of identifying, capturing, storing and analysing such large data volumes will be essential for the future pan-European power system.
5. Integration of advanced electricity storage and plug-in Electric Vehicles (EVs), which act as peak shaving technologies.
6. Integration of smart components and devices at different domains of power systems.
7. Maintaining cyber security, privacy and reliability in both data communications and power system operations.
8. Incorporation of demand response (DR), demand side management (DSM) and energy efficiency resources.

2.3 ICT Applications to Future Power Systems

ICT refers to a range of *software* and *hardware* that provide access to information through communications infrastructure. It is important to note that, considering ICT in a general context, information and communications technologies are two distinct concepts. Considering both technologies separately, information technology (IT) can be defined as covering all matters relating to process, manipulation and management of information. It concerns big data acquisition, observation and analytics. In contrast, communications technologies refer to anything related to the use of assistive devices for processing and transferring data between different power system components or stakeholders. Consequently, a smart grid can be defined as a transition process from the existing power system to the future ICT-based power system, where both information and communications technologies are clearly linked together [17].

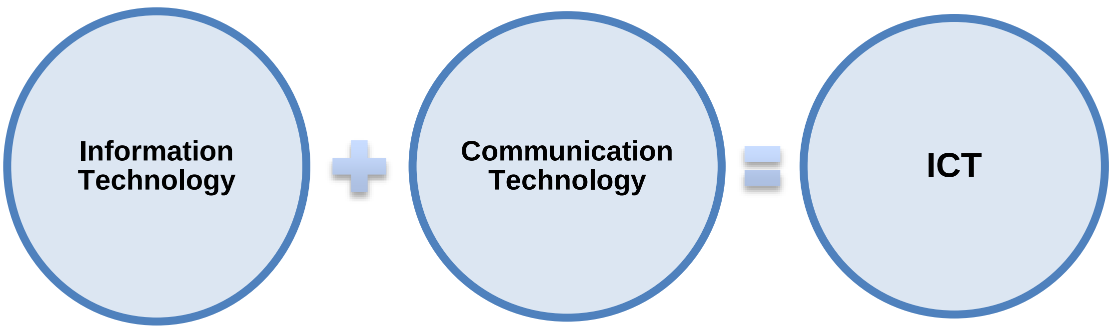


Figure 2.1: Information and Communications Technology

In this case, the smart grid concept combines a range of technologies; end-users service provisions and also a range of regulatory and policy drivers. The European Technology Platform [12] defines the smart grid as:

"A Smart Grid is an electricity network that can cost-efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure an economically-efficient,

sustainable power system with low losses and high levels of quality, security of supply, and safety."

In order to satisfy a range of fundamental requirements of the smart grid, ICT must be developed and implemented to [16]:

- Provide two-way communication technologies. In this case, different power system components and stakeholders can communicate and share data in the most efficient way.
- Offer all power system stakeholders access to more information. In this case, the integration of essential software and hardware will be required in order to enable stakeholders to trade electricity in the future pan-European electricity market, and end-users to provide demand response.
- Provide scalability by ensuring and maintaining interoperability standards and protocols.

2.4 Smart Grid Plane

On March 1st 2011, the EC published a Mandate called M/490 [1] to European Standardisation Organizations (ESOs) in order to develop a set of standards within a common European framework of communications and electrical architectures, in order to present the design of smart grid use cases and ICT infrastructure. The deliverable of this framework, published by the Reference Architecture Working Group (SG-CG/RA) [1,2] working under the Smart Grid Coordination Group (SG-CG), was "*a technical reference architecture, which will represent the functional information data flows between the main domains and integrate several systems and sub-systems architectures*" [1]. This chapter describes the steps used in building such an architectural model, and the various components of the SGAM are introduced.

The general purpose of utilizing the SGAM is to demonstrate the design of smart grid use-cases from an architectural point of view. In this case, the roles of different ICT infrastructures in both the current and future state of power systems can be investigated. Generally, there is a difference between electrical process and information management viewpoints [10]. In order to consider these two viewpoints simultaneously, the concept of the Smart Grid Plane can be introduced. The Smart Grid Plane consists of the domains of the electrical energy conversion chain, and on a separate axis describes the hierarchical management zones of the electrical process [10]. Figure 1.2 in Chapter 1 presents the Smart Grid Plane.

2.4.1 SGAM Zones

From the perspective of information management, the SGAM identifies six different hierarchical zones, where the idea behind zone definition is that it presents a hypothetical boundary between which certain power system management aspects may be aggregated, whereas certain aspects must still be considered separately. Within the aggregation concept, different aspects can be investigated [10], such as:

- Data aggregation: In order to deal with a huge amount of data in future power systems efficiently, different data from different zones can be aggregated. For instance, data from the *field* zone can be integrated in the *station* zone in order to reduce the volume of data to be communicated, stored, and analysed.
- Spatial aggregation: Different equipment measurements can be aggregated from several distinct locations to represent a wider area; for instance, multiple DERs can form a power plant station, or DER meters in the customer premises can be aggregated by concentrators.

On the other hand, different zones within power systems have different functionalities and this leads to the separation concept. For example in some power systems' zones, such as *field* and *station*, the real time ICT infrastructure play a significant role for a range of purposes including metering, protection, phasor measurement, etc. However, in other zones like *operation*, ICT applications have impacts on the other issues like wide area monitoring, load management, meter data management, etc.

Therefore, six different zones in this model can be classified as follows:

1. Process: This zone includes the physical and spatial conversions of electrical energy. In this zone different types of physical equipment, which are involved in such a process, have been considered, such as: transformers, circuit breakers, overhead lines and cables.
2. Field: This zone includes different equipment related to monitoring, controlling and protection of a power system, such as: protection relays and electronic devices for data acquisition, and processing including application of wide range of sensors.
3. Station: This zone uses the aggregation concept described above, and includes aggregation of *field* zone data, e.g. SCADA, substation automation, data analytics, etc.
4. Operation: This domain includes operation and management of power systems including: distribution management systems (DMS), energy management systems (EMS) in generation and transmission domains, virtual power plant (VPP) management systems, and electric vehicle (EV) fleet charging management systems. Therefore, ICT infrastructures will play an important role in the integration of this zone into with the power system domains.
5. Enterprise: This domain includes commercial processes and different services for utilities, energy traders, and market participants. These services can include asset management, billing processes, staff training, customer relation management, etc.
6. Market: This zone includes possible market operations and trading in the wholesale and retail markets between different participants. The role of this zone will be highlighted when considering the pan-European electricity market, when electricity can be traded across national borders.

The impact of these power system management zones can be seen to be tightly correlated to the impacts of ICT infrastructures within different power system domains. Chapter 3 will expand the analysis of these impacts of ICT infrastructures within the domains.

2.4.2 SGAM Domains

In order to consider the role of ICT infrastructure within future power systems, various *domains* of power systems should be investigated. This encompasses the technical management aspects of power systems, and is divided into five domains within the SGAM [6] as follows:

1. **Generation**: This domain represents large-scale generation of electricity from a range of sources, such as: fossil fuels, hydropower, nuclear, offshore and onshore wind energy, PV, etc. This domain typically has been directly connected to the transmission network. ICT can have major impacts on communications between different stakeholders participating in the pan-European electricity market.

2. **Transmission:** This domain represents different systems, FACTS, and infrastructures for transporting electricity over long distances. The role of ICT in this domain is very significant, especially in the e-Highway 2050 project, since in order to address the European energy pillars: *affordability, security of supply, and climate change* [12], large quantities of electricity will need to be transported over long distances across national borders. For example wind energy will be transported from the North Sea to mainland Europe at ever increasing levels, or solar energy can be transported from Northern Africa to Europe. In this case various monitoring, communications, data collection, and measurement technologies will increase in deployment and enhance system functionality in the future pan-European power system.

3. **Distribution:** This domain represents the systems, infrastructures, and stakeholders that distribute electricity from generation resources to the end-users, and in addition to the traditional distribution infrastructure, on-going development of the power system will also likely include ICT-enabled solutions such as demand side management system, substation automations and etc.

4. **Distributed Energy Resources (DER):** In this domain, small-scale power generation technologies are given their own treatment. For DERs in this domain, the considered resources are expected to be directly connected to

the distribution network. The role of ICT in this domain will also be significant, especially for the *Local and Small* scenario, which is one of the five proposed scenarios in the e-Highway2050 project [11].

5. **Customer premises:** This domain consists of industrial, commercial, and home systems. The roles of EVs, small-scale PV generation, and small-scale battery-based energy storage in future power systems have been included in this domain. ICT is expected to have a significant impact on future power systems within this domain, through the acquisition, monitoring, storing, and analysis of customer energy usage data.

It will be discussed further in Chapter 3 the expected influence of ICT infrastructures' impacts within the SGAM-defined power system domains.

2.5 SGAM Interoperability Layers

Observing the Smart Grid Plane architecture, a model for the role of ICT infrastructure in future power system domains can be identified. However, in order to have a clear and complete presentation of ICT impacts on future power systems, different interoperability layers can be taken into consideration in order to recognize the existing and future standards, which may be desirable or necessary for scalable operation of the pan-European power system.

Interoperability will be the key assumption, since it allows the future power system to autonomously integrate all components required in integrating Electricity Highway Systems (EHS), particularly monitoring, measurement, management, and communication equipment. Through the application of an interoperability initiative, the need for human intervention will be minimized and scalability will play a major role. Therefore, future power systems may face a range of challenges, including the need of developing and adopting comprehensive standards. As seen in Figure 2.2 [18], several standards can

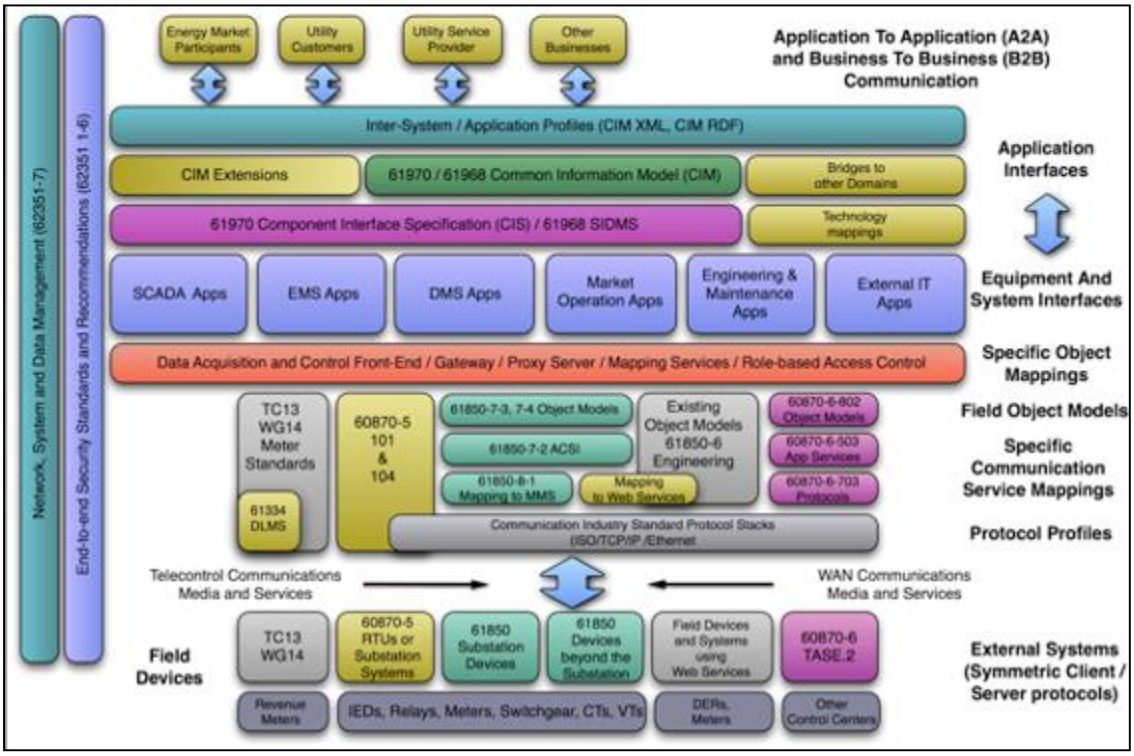


Figure 2.2: Different Standards in Transmission and Distribution Layers [18]

be introduced for different power system domains identified in the previous section.

Figure 2.2 displays the three major standardised interfaces as:

1. Market communications
2. Transmission network
3. Smart metering – at distribution level

In order to gain a better understanding of the different interoperability layers introduced in the SGAM, a brief summary of each layer is provided [10]:

1. Business Layer: In this layer, the market structure and policies, alongside the business models and products of market participants are taken into consideration.
2. Function Layer: This layer explains the different services and functions within the SGAM, and includes alignment between operational business processes and procedures.
3. Information Layer: The interoperable data exchange between different functions, power systems components and stakeholders can be described in this layer.
4. Communication Layer: Different protocols, mechanisms, and standards can be introduced in this layer, in order to exchange information between power system components or stakeholders at different layers, such as business or component layers. In accordance with Figure 2.2, different standards can be introduced at different layers in order to exchange information between power system layers in an interoperable manner.
5. Component Layer: This layer represents the physical distribution of all components in future power systems. This layer includes the mechanism to establish physical and logical connection between systems.

2.6 Smart Grid Architecture Model (SGAM)

Considering the power system domains, zones and interoperability layers, the outcome of combining all these elements into a single model is the Smart Grid Architecture Model (SGAM) [1]. This model presents the design of future smart grids using an architectural approach, yielding the SGAM as a three-dimensional model, consisting of (Figure 2.3):

- Two dimensions of the *Smart Grid Plane* including:
    - *Zones*, representing different management levels of power systems
    - *Domains*, representing complete electrical energy conversion steps
- Five interoperability layers as the third dimension

By introducing such a model, it will be possible to map the role of ICT infrastructures in future power systems, considering the variety of potential applications for both communication infrastructure and information technologies within the domains. This mapping will be performed in *Stage 1: Mapping and Trending* of the proposed methodology. A more detailed investigation will be provided in Chapter 3.

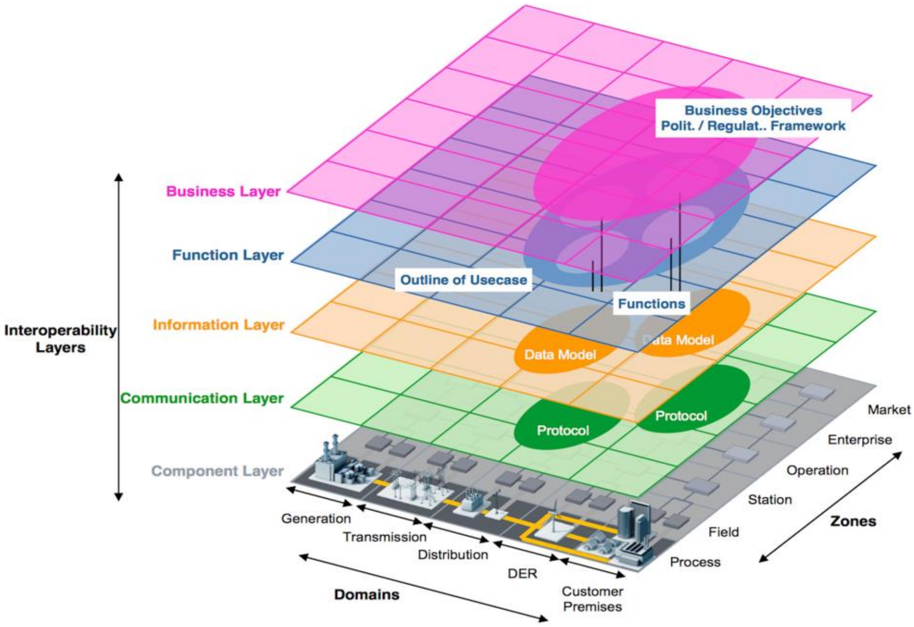


Figure 2.3: SGAM Framework

Chapter 3: ICT Components, Objectives and Infrastructures

In the previous chapter the power system domains were identified according to the SGAM framework. With reference to Stage 0 of the methodology in Chapter 1, it is essential to identify the most quantitative and qualitative elements that influence ICT deployment in power systems. In this respect, the quantitative elements were identified as the core technological components (bandwidth, storage and processing power), and the qualitative elements were grouped into ICT objectives in order to identify the impacts of ICT infrastructures on the power system domains. The first section of this chapter describes the most quantitative ICT components and describes a series of qualitative objectives. Furthermore, a range of relevant ICT infrastructures are introduced as inputs for Stage 1 of the methodology.

3.1 Quantitative ICT Components and Qualitative ICT Objectives

According to the methodology explained in Chapter 1, in order to analyse the impact of ICT infrastructures in future power systems, it is essential to calculate the complete cost of implementation. This cost consists of physically quantitative ICT components cost plus the qualitative cost of ICT objectives. By considering the qualitative ICT objectives, the impacts of other factors such as interoperability, maintenance, privacy and cyber security, and interoperability can be assessed, by weighting these objectives for each ICT infrastructure in order to determine the *projected ICT objectives cost impacts*.

These added costs are more difficult to quantify in terms of costs due to their indirect relationship with physically quantitative hardware components, but are nonetheless important objectives in the proper operation of an ICT infrastructure, and achieving these objectives will inevitably lead to increased costs in most cases.

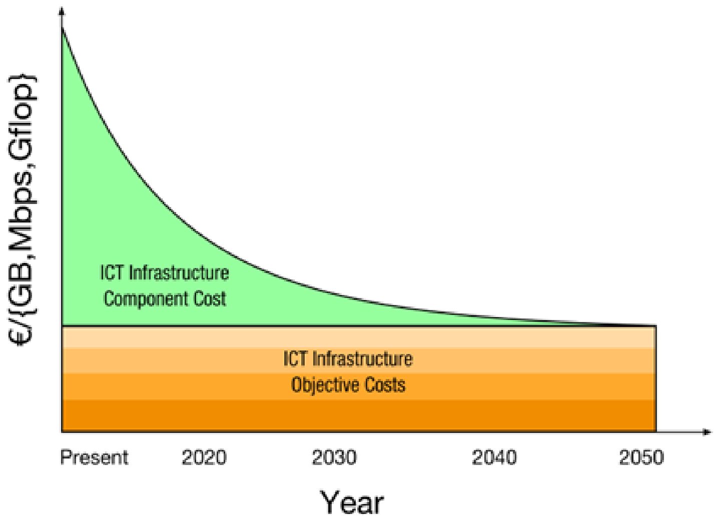


Figure 3.1: Added ICT Objective Costs

3.1.1 Quantitative ICT Components

The three physically quantifiable ICT components, expected to have significant impact on ICT infrastructures, are as follows:

- Bandwidth
- Storage
- Computational power

3.1.1.1 Bandwidth

By considering the deployment of new technologies such as fibre optic cables in future power systems and considering the fact that the future power systems' stakeholders will require on-demand bandwidth capability [19], the bandwidth will play significant role in the future ICT infrastructures. The real time measurement and monitoring of the future power system features can drive the need for more bandwidth in the communication network. These requirements can increase further as new remote real-time protection and control applications become more widespread. In this case, high bandwidth could provide better quality of service and efficient operation, especially for the following applications [20-22]:

- Utilities information management, such as Geographic Information System (GIS), data warehouse, etc.
- Substation automation systems, such as supervisory control and data acquisition (SCADA) and energy management systems (EMS).
- Maintenance, in order to diagnose and monitor the system remotely.
- Electricity market, in order to trade energy across national borders.

Download speeds have increased exponentially since 1985 [22]. By extrapolating such a historic trend over the next following years, it is estimated that the downstream bit rate in 2020 will be around 1Gbps.

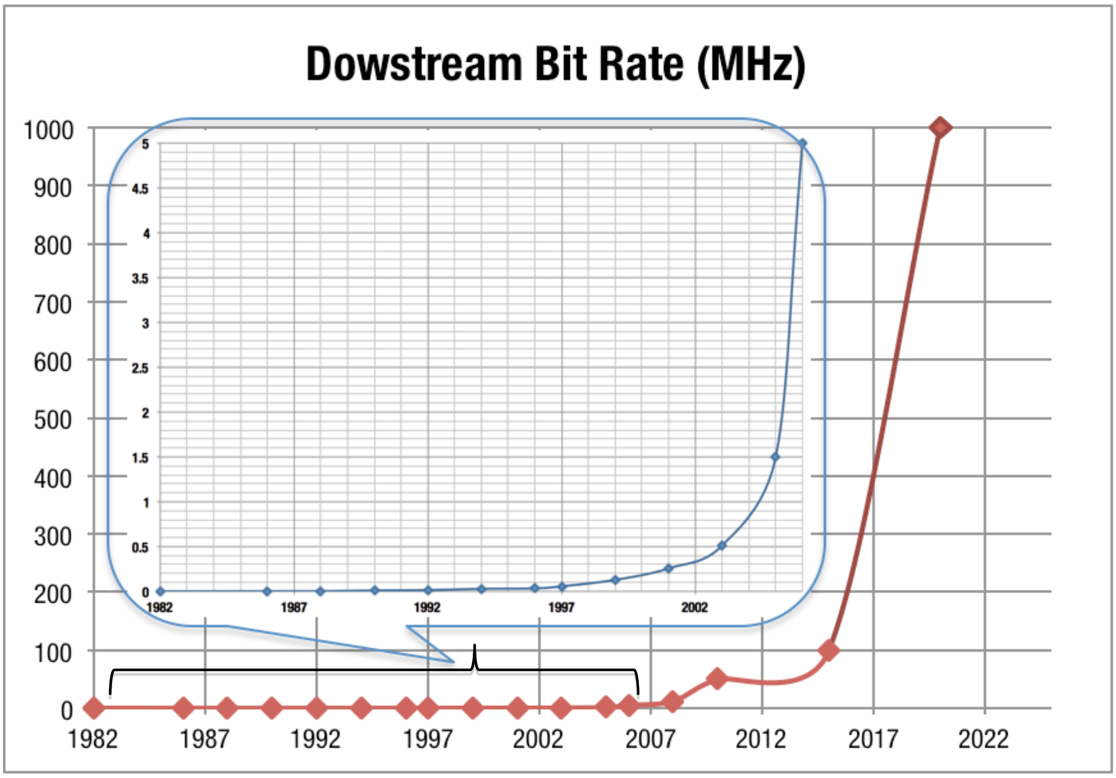


Figure 3.2: Bandwidth Downstream Bit Rate

According to [23], bandwidth is increasing at rates between 20% up to 60% depending on where it is measured; however, the capital expenditures only rose by 2.6% over the past five years. Based on [21,22], the growth of average bandwidth faces technical limitations because of a range of main reasons as follows:

- The conservative nature of telecoms companies: The installation of new equipment and especially cables require high investment, due to the underground setting of cables which sometime involve affecting streets and pavements. Therefore, telecom companies have to plan wisely before investing huge amount of money.
- Users reluctant to spend money for bandwidth: Compared to the speed of processing and storage, if users were to buy a modem with twice the speed of their current one, they wouldn't be able to transfer data twice as fast, since the speed of internet is not only a function of individual users connectivity, but also of the overall infrastructure.

3.1.1.2 Data Storage

The future pan-European power system should be capable of gathering and analysing both structured information and unstructured data. There are 3Vs that define big data in future power systems [24]:

1. Variety: The data will be more diverse including structured, semi structured and unstructured data.
2. Velocity: The rate of generating data will be much faster.
3. Volume: The amount of generated data will be much greater.

Figure 3.3: 3Vs

Two major IT aspects that should be taken into consideration for future power systems are as follows:

- Storage

- Big data analytics

Taking into account the first aspect, the next generation of storage should include a range of features as follows:

- Data reduction
- Automated data tiering between solid-state drives or cloud storage

According to [25], a classic measure for extendibility of storage class memory devices such as Hard Disk Drive (HDD) and Solid State Flash Drives (SSD) is *areal density* roadmap. This metric represents the number of bits stored per unit area. IBM has announced that for the last 16 years these storage devices have been influenced by annual areal density increases of 40% [25]. Figure 3.4 shows HDD areal density projection trend based on the historical data. According to the International Technology Roadmap for Semiconductors (ITRS) and IBM [25], a conservative projection for HDD is maintaining a 20% annual areal density increase from 2010.

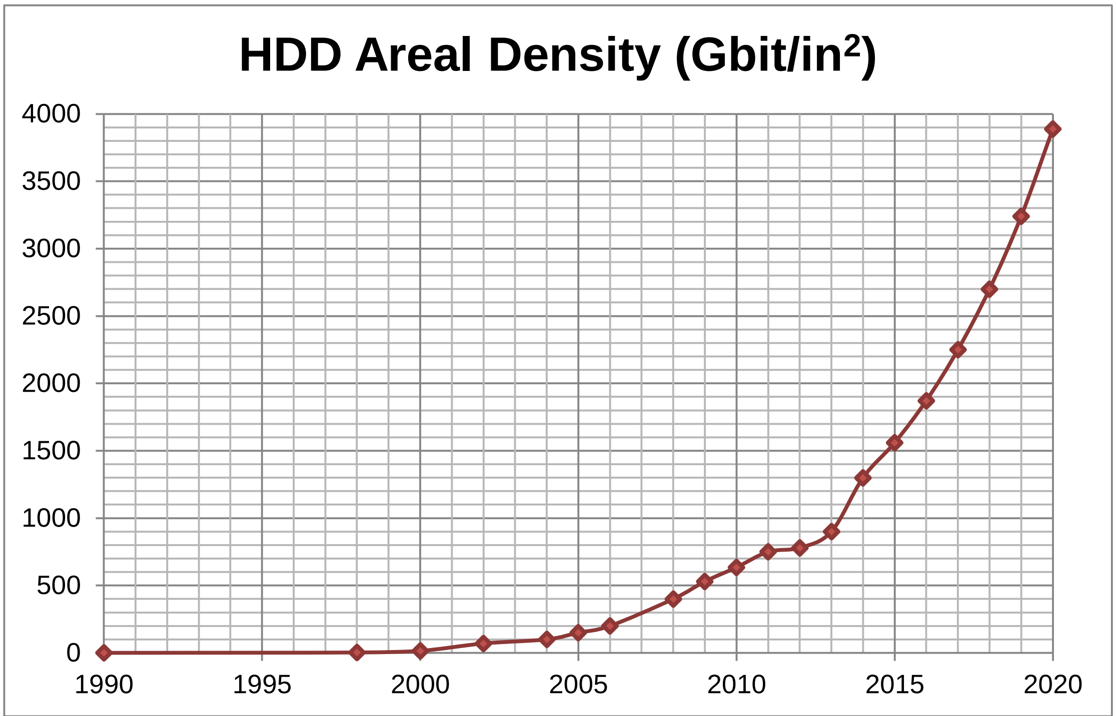


Figure 3.4: Areal Density Trend

Lithography plays a significant role in assessing the future areal density for future memory devices [25]. Furthermore, investment cost for new technology development in media strategies such as patterning can result in HDD areal density increases. In recent years, the areal density for HDD is showing a slow progression of 20% rather than 40% [25]. This is happening because of two reasons as follows [25]:

- The bit cell size for future areal densities is approaching thermal fluctuation limits associated with the media grains in the bit cell.
- The width of the bit cell cannot be reduced due to limitations in sensor resolution.

Additionally, cloud storage can enhance the business agility, while it reduces the costs and increases the efficiency. Although cloud storage continues to become mature, there are different companies around the world that are trying to expand their services. According to the 3V concept introduced above, it will be essential for power system utilities to store large volumes of data, produced by future smart grid. Google, Amazon, Intel and IBM are some of the successful cloud vendors [26, 27].

The cloud services can be offered in a public, private or hybrid networks [27]:

Public Cloud: A pool of computing resources and services at vendor locations that is multi-tenant. In this case, logical boundaries will be established in order to maintain the management security. Generally, public cloud service providers both own and operate the infrastructure and users can have an access via Internet. These service providers can be listed as: Amazon AWS, Microsoft and Google.

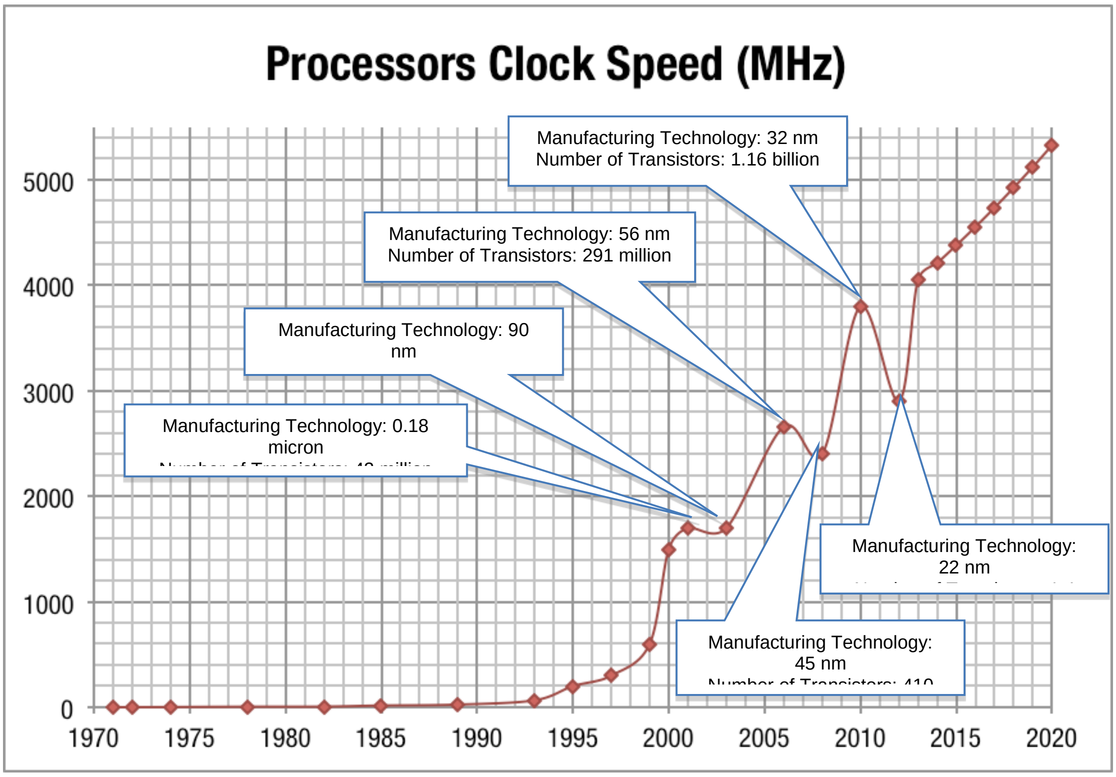
Private Cloud: A pool of computing resources and services that are dedicated to one consumer. This can be at the consumer's premises or in any other locations.

Hybrid Cloud: A pool of computing resources and services that can span on premise and off premise boundaries. The hybrid cloud consists of two or more private and public clouds. Hybrid clouds will be more applicable in future, since by using such a cloud, organizations and utilities can store sensitive client data on a private cloud application and interconnect with other public clouds in order to obtain less sensitive information [27].

3.1.1.3 Computational Power

The future pan-European power system will require extensive computational power. In future, simulating, optimizing, controlling and analysing the power systems will become more complex and computationally intensive [28]. Therefore, in order to ensure the reliability and security of supply, it is essential to find efficient computational methods. In this case, high performance computing (HPC) will play significant role in future power systems.

According to the Intel chips historical timeline [29], the clock frequency has increased over the time. In 1971 the clock frequency was 108 KHz with 2,300 transistors and manufacturing process size of 10 micron. In 2012 the clock frequency was 2.9GHz, with 1.4 billion transistors and manufacturing technology of 22 nm. Based on ITRS projections [30], the clock frequency can be changed through the roadmap range at compound annual growth rate (CAGR) of average 4% based on 3.6 GHz. This CAGR doesn’t consider any technological breakthrough with regard to number of transistors and manufacturing technology size. Figure 3.5 presents the clock frequency trend up to 2020.



According to the above figure, the processor clock frequency is dependent on the number of transistors and the manufacturing technology. Therefore, during the past times, the clock frequency has not increased at certain points because of reduction in the size of processors and growth in the number of transistors. The reasons behind the fact that the rate of clock frequency has stayed relatively similar over that past years is that the transistors are no longer the only and biggest factor in how fast a processor can run anymore. The wires that connecting these transistors have now become the dominant delay factor [30]. Another issue that needs to be considered is the cooling issue as transistors can leak a little electricity and this can create heat.

Efforts have been made in order to improve the computational tools by applying other means, resulting in the development of multicore computing and Graphics Processing Units (GPUs). In recent years, the multicore technology has entered into the commodity market and due to the economy of scale the prices have been reduced. Intel and AMD are releasing processors that contain two to 12 multi cores and many more multi-core processors will be commercialized in near future [28]. While multicore processors have become popular in recent years, the most significant breakthrough in this area is the appearance of GPUs for general purpose processing. GPU computing has been applied in only a handful of power system applications; however, this technology will play major role in the future power systems' analysis such as:

- Contingency analysis
- Economic dispatch
- Load flow
- Optimal power flow
- Reliability assessment
- Simulation

- State estimation
- Transient stability control
- Unit commitment

It can be concluded that the three criteria identified for the quantitative ICT components play significant roles in the future deployment of ICT infrastructures, as they are likely to lead the cost of quantitative ICT components to become inexpensive relative to the qualitative costs of the ICT objectives for the future time horizons. The role of downstream bit-rate will be significant in real time measurement and monitoring of the future power system as it is expected to reach to 1Gbps by 2020. Big data storage will be influenced by yearly areal density increase by 20%. In this case, the current strategy of ‘save important information’ will be replaced by ‘save all information’ strategy. Furthermore, high performance computing will play major role in big data analytics as the clock frequency is changing at CAGR of average 4%.

3.1.2 Qualitative ICT Objectives

With reference to Chapter 1, there are other qualitative objectives that explicitly address the issues related to the ICT infrastructure. These objectives should be taken into consideration for analysing the impacts of ICT infrastructure on the power system domains. It is important to mention that due to the nature of these objectives, their impacts on the ICT infrastructure will be inevitably qualitative. The core qualitative ICT objectives can be listed as follows:

- Resilience
- Maintenance and Support
- Privacy and Cyber Security
- Interoperability

3.1.2.1 Resilience

A resilient system continues to operate at normal condition while a number of sub-systems or components are suffering from a range of failures. This can be achieved by installing additional equipment in the system and well-planned maintenance [31].

The resilience concept has become very popular in the area of ICT. Reliable communication networks are becoming significantly essential for present and future power systems.

According to the European Network and Information Security Agency (ENISA) [31], the ICT network service relies on three different types of activities:

- <u>End-users:</u> Customers access to the network for various purposes such as connectivity, VPN, VoIP, etc.
- <u>Control and signalling:</u> A range of activities that include efficient functioning of the network, such as communication between different users and stakeholders in the network.
- <u>Management:</u> A range of management and supervisory activities for networks' elements and applications.

In this case, the ICT infrastructure should be prepared against any faults and challenges by implementing resilience provisions in order to provide and maintain an acceptable level of service. In the field of ICT these acceptable service levels are defined in a Service Level Agreement (SLA) [31] between ICT service provider and customers.

3.1.2.2 Maintenance and Support

Another qualitative ICT objective is maintenance and support. ICT maintenance is considered as a range of activities in order to retain an item, or restore to a state in which it can perform the required function [32]. In future power systems, ICT will play significant role in different power systems' domains. For instance, advanced metering systems will give near real-time information on billions of data, and energy trading platforms will require secure communications between different stakeholders in different countries. Therefore, maintenance and support will play major role in storing and analysing those huge volume of data, efficiently. According to [32], the ICT maintenance can be classified as:

- Preventive: Maintaining the ICT infrastructure capabilities before occurrence of any failure.
- Corrective: Restoring the defective ICT infrastructure to the required state.
- Adaptive: Adjusting software products in order to interface with a changing environment.
- Perfective: Adding new capabilities and modifying exiting features of an ICT infrastructure.

By considering the above types of maintenance, it can be identified that the need for skilled labour and support will be essential in future. On the other hand, due to the economy of scale, ICT may have impacts on the demand for skilled labour in future as well [32].

3.1.2.3 Cyber Security and Privacy

With the rise of potential risks from different attacks on the ICT infrastructure, the investment in cyber security and privacy is a critical objective for many organizations. Cyber security involves measures to ensure and improve the level of integrity, confidentiality, and availability of the information technology and telecommunications infrastructure [33]. In this case, it will be essential to find a standard approach to quantify the ICT investments for preventing such attacks.

Table 3.1 represents and compares the traditional and future threats facing the ICT infrastructures [33].

Table 3.1: Threats Facing the ICT Infrastructure [33]

	Traditional Threats	**Future Threats**
Impacts	Direct damage to physical infrastructure	Indirect damage to physical assets through damage to software systems
Location of origination of threat	Local	Local or remote
Target	Individuals	Individuals and organizations

Point of attack	Single site	Multiple point simultaneously
Duration of damage	Immediate damage causing obvious damage	Attack may be undetected and then be triggered later
Occurrence	Single episode	Continued damage associated with attack
Restoration	Restoration after attack	Attackers may have continued impact preventing restoration

Advanced Metering Infrastructure (AMI) is a combination of communication infrastructure and supporting information systems [33]. Such an infrastructure can be an appropriate example for representing the fact that cyber security and privacy of ICT infrastructure will play essential role in the future pan-European power system.

3.1.2.4 Interoperability

ICT standards are the keys to optimising the management of the future power systems and the ICT's own energy footprint. ICT can apply smart and integrated approaches to energy management of systems and processes, including benefits arising from both automation and behavioural change, and develop alternatives to high carbon activities across all economic sectors. Furthermore, the deployment of ICT in homes, such as: home networks, sensors, smart meters, displays, etc. can reduce energy-user bills [34, 35].

In the future pan-European power system standardization can support interoperability and interoperability can result in scalability. Therefore, it is important to acknowledge that ICT for future power systems must be carefully designed and standardised in order to:

- Maximize smart grid benefits
- Guarantee a stable energy system
- Avoid ICT to become an unacceptable energy burden itself

Since 2009, ENTSO-E has supported the integration of Member TSO business requirements and user cases into the Common Information Model (CIM), along with contributions to its further development. The International Electrotechnical Commission Technical Committee is currently developing the

IEC CIM 62325 series of standards for the exchange of data required by deregulated energy markets [36]. The Working Group 16 is developing these standards, which act as a framework for energy market communications encompassing two styles of markets: the European-Style and North American-Style markets [36].

Furthermore, a range of standards can be applied to the distribution network. All new appliances in smart grids rely on vast networks of Intelligent Electronic Devices (IEDs) that monitor power system conditions. The communication between IEDs and protection can be standardized through dedicated channels [14]. This will then ensure interoperability at the device level. For instance, ZigBee is based on IEEE 802 and is a low-cost, low-power standard [35]. The low cost feature allows the technology to be deployed widely in wireless control and monitoring applications. Additionally, the low power-usage feature allows longer life using smaller batteries. This standard intends to interface with smart metering and smart appliances [35]; therefore, it can immediately increase the interoperability.

Another example is DLMS/COSEM standard [34]. In order to deliver electric energy more reliably and efficiently to the end-users, the smart grid has to monitor and control demand appropriately. This can be achieved through the use of smart meters. However, for a long time there has been no unique, generally accepted protocol for delivering and interpreting meter data, which has generated many problems for both AMI developers and utility distributors. DLMS/COSEM is a widely accepted, standard-based language for meter communication, whose main goal is interoperability between metering equipment [34]. It should be noted that the scalability caused by standardization will also become a very important aspect in future power systems.

These four qualitative ICT objectives should be taken into consideration when attempting to predict the costs of future ICT infrastructure deployments, but it is important to note that due to the qualitative nature of these objectives, a precise prediction of the impacts of these qualitative objectives on total cost of implementing ICT infrastructure is a very challenging task. In this case, a set of coefficients will be introduced in sub-section 4.2, where the qualitative impact of these ICT objectives on the cost of implementing ICT infrastructure can be considered. It is important to note that the qualitative cost of these ICT objectives will dominate the total cost of implementing ICT infrastructure as the quantitative cost of ICT components become inexpensive at different time horizons. More details will be explained in sub-section 4.2.

3.2 ICT Infrastructures

In order to analyse the impact of ICT on the pan-European power system, a range of ICT infrastructure that could play major roles in the power system domains have to be introduced. Six ICT infrastructures are considered in this study and they have resulted from aggregating different ICT applications in power systems, considered to be representative in each ICT infrastructure. For example, virtual power plants (VPPs) represent an ICT application that has been included in the Energy Market Management and Trading Control infrastructure. The six ICT infrastructures are detailed in the following.

3.2.1 Energy Market Management and Trading Control

Regional marketplaces provide a platform to allow all market participants to act freely in order to make more profits. In the future pan-European power system, the role of industrial, commercial, and domestic customers will be much more significant. They can participate actively in the energy trading in order to integrate the load flexibilities into the market. In this case Demand Response (DR) will also have major impacts in the energy market trading.

It is essential to note that the role of distributed energy sources (DERs) and VPPs have been encapsulated and categorised in this ICT infrastructure, since, in future power systems the level of DERs will be increased. Therefore, they will actively participate in the energy market through new pricing regimes [15]. These flexible loads and DERs can either be traded directly on the energy marketplace, or they can be aggregated to form VPPs or other collective organizations. In the VPP, distributed power management and communication play significant role in order to deliver active power and system services.

Energy market management and trading control can be a platform for automated trading between all market participants. Additionally, it provides all market participants with a communication platform to interconnect with each other at the business and enterprise level. In the future pan-European power system, a large number of market participants will be involved with high number of transactions across national borders; therefore a scalable marketplace is required. The pan-European electricity market can include a technical coordination process for market coupling. This can replace the existing process based on the available transfer capacity. In this case, 2 days ahead, day ahead and intraday congestion forecasting will play significant role in the future market coupling.

3.2.2 Weather Observation and Forecasting

Weather condition observation and forecasting indicates a range of systems required for performing weather forecast for VPPs, DERs, etc. This includes: wind forecasting, solar forecasting, temperature forecasting, situational alerting, general atmosphere forecasting, future lightning, storm approaching, etc.

In general, weather observation and forecasting infrastructure includes a secured IT system [2], possibly connected to the international weather observation centre or a range of weather sensors.

3.2.3 Asset Maintenance and Management/GIS

Asset Maintenance and management involves a range of optimization and prioritized investments in the assets in order to increase their performance. The objective of this ICT infrastructure is to optimize the way in which all the assets are deployed and planned over their lifecycle [15]. In this case the potential assets must be differentiated according to their role in power system.

Asset management and maintenance can include a range of activities as follows:

- Archiving Maintenance information
- Monitoring Assets conditions
- Optimizing field crew operation
- Supporting periodic maintenance

Future power systems will focus on deploying a range of sensors such as IEDs, smart meters and also PMUs in order to manage different assets in the power industry, but which will become assets themselves. According to [37], the future smart asset management will seamlessly provide needed data from across the enterprise through tighter integration. For instance, by using AMI meters associated with a specific asset in the distribution system, it will be possible to identify its utilization at different conditions [37]. Furthermore, Geographical Information System (GIS) plays significant role in the asset management and maintenance. GIS acts as an integrated platform, which associates the automated digital maps of utility infrastructure to databases [16]. According to [2], the GIS application server can host an application, which is capable of storing, analysing, managing, and manipulating all types of geographical data. Therefore, it can be concluded that GIS can combine all the statistical analysis and data base technology in order to assist asset managers and system operators regarding any kind of decision making; thus, it has been encapsulated in the asset maintenance and management ICT infrastructure.

In future power systems, all the operating data related to a specific asset will be collected over the time and evaluated and scheduled in a form of *resource health-check* [15]. In this case, the previous and new conditions of the assets will be considered in order to make sure that they will operate at their optimum conditions.

3.2.4 Advanced SCADA/Energy Management System (EMS)

SCADA/EMS includes all the elements required to support the relevant operational activities used in the transmission automation at control centres

[2]. A major disadvantage of current SCADA is their static, inflexible and often centralized architecture. This can have negative impacts on their interoperability with other systems. The advanced SCADA refers to a future real-time information system. Therefore, it provides a range of functions as follows:

- Data acquisition: Remote Terminal Units (RTUs) can collect the information describing the state of the system. This information can be transferred to the control centre close to real-time [16].
- Real time monitoring, outage management system and alarms: One of the functions of SCADA/EMS is to compare the collected data with the nominal values and limits in order to detect changes in the state of the system and provide feeder automation and outage management. All the events can be process by the event processing function [16]. In this case all the events can be classified and delivered to the system operator through the Human-Machine Interface (HMI).
- Control: This function of SCADA can be initiated automatically by an event or at specific times.
- Data storage, analysis and reporting: SCADA/EMS can store the real time data. Currently, data is not polled nor stored in real time in SCADA/ EMS, but we envisage that future power systems will rely on advanced SCADA systems enabled by the advancement of ICT and the reduction of physically quantitative ICT components costs. In this case, the time-tagged data will be stored in the historical database at periodic intervals [16].

According to the above features for advanced SCADA/EMS, it can be concluded that other services such as managing power quality, outage management system, and feeder automation system can bundled together within this ICT infrastructure.

3.2.5 Wide Area Monitoring Systems (WAMS)

WAMS can inform system operators, grid planning engineers and transmission system operators from voltage instabilities, frequency deviations and collapses by monitoring and analysing medium-term changes in the power system [15].

WAMS can be realized as a supplement to SCADA for a region or country future power system [2]. Although future SCADA will provide real time monitoring and outage management system; however, these data are central measurements at a data rates in the order to seconds, while WAMS can make local measurements at very high data rates of thousands per seconds. Compared to the conventional protection devices, which provide monitoring for individual asset, WAMS can provide comprehensive protection. In this case, PMUs located in the substations can play significant role in recording the measurements. The recorded measurements are time-stamped using signals from Global Positioning System (GPS) and sampled at a rate of up to 50 measurements per second. All the recorded measurements can be sent to the Phasor Data Concentrator (PDC) through IP communication network. Therefore in this study, all the roles of PMUs, PDCs, and other Measuring Instrument Devices (MIDs) have been encapsulated in the WAMS.

In near future, recording the grid condition in the distribution grid will be available using PMUs and RTUs [15]. Furthermore, according to [15], it is anticipated that the WAMS will be deployed in the individual LV pilot projects. In this case the system will able to handle massive data movements.

3.2.6 Advanced Metering Infrastructure (AMI) and Business Services

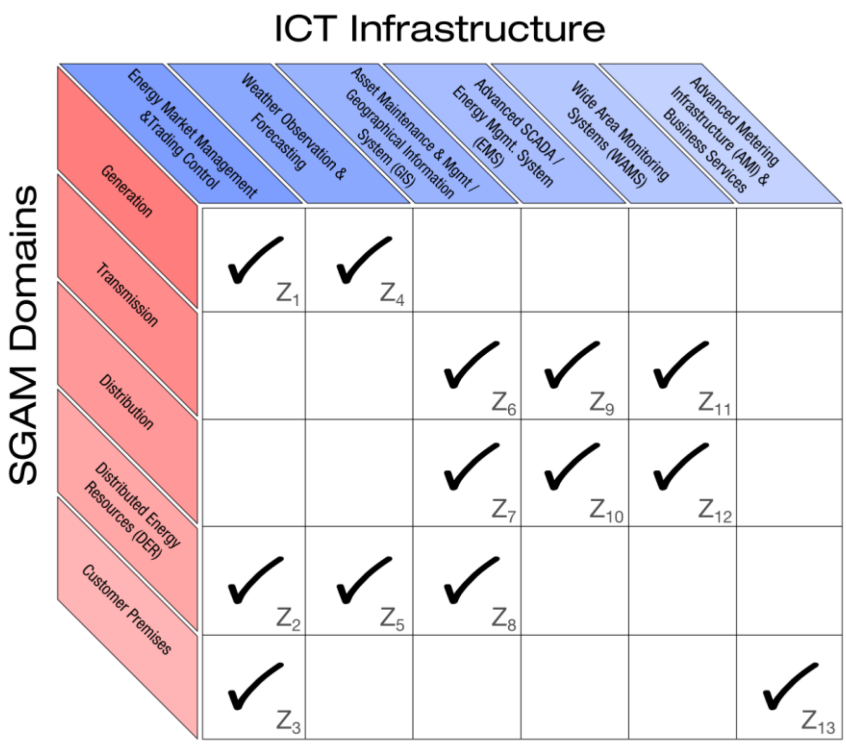
The AMI is an infrastructure to implement smart metering processes for huge volume of data from smart meters installed at the customers' premises. The AMI includes the context of an automated meter reading (AMR) [15]. Through the AMR infrastructure all the energy consumption data can be recorded via a one-way remote reading process [15]. AMI can increase the features of an AMR by providing the option of bidirectional communications between metering service providers and the field level.

Generally, the AMI consists of smart meter itself, a display device, meter data concentrator, and in-home gateway [2]. At present, there is no large installation of AMI [15]; however, in future power systems all kind of required standards that must be supported by the meters will be available. Furthermore, Advanced Meter Management (AMM) will be commercially available in future power systems. The AMM includes additional business services within households, such as Customer Relationship Management (CRM) and Meter Data Management (MDM) [2,15]. It is important to note that all these business services have been encapsulated in this ICT infrastructure. The CRM refers to a range of interactions between utilities and end-users for service-related aspects such as: billing, issuing statements of payments on the account and energy consumption [15]. Furthermore, MDM maintains all the end-users' information to calculate the energy bill based on the obtained data from AMI [2].

3.3 Domain-ICT Interactions

Previous sections identified a range of ICT infrastructure that can have impact on the power system domains. Furthermore, in Chapter 2, five different power system domains were identified based on the SGAM framework.

At this stage of methodology, it is essential to identify the distinct characterization of these ICT infrastructures in order to map their impacts to the power system domains. Based on the specifications of ICT infrastructure, the results of this mapping will be a binary table, which indicates what ICT infrastructure may be relevant within the power system domain. In the next chapter, these impacts will be quantified. Figure 3.6 illustrates the domain-ICT interactions.



In this case, the interaction pair Z specifies the ICT infrastructure required to enable a certain function within a given domain. According to Figure 3.6, $M = 13$ critical interactions have been identified, denoted as:

$$Z(j), j \in [1, M]. \qquad E3.1$$

For any variable in this study, which has domain-ICT interaction dependence, the index j is used to specify the relevant interaction *(ICT Infrastructure x Domain).*

Z_1-Energy Market Management and Trading Control x Generation: This ICT infrastructure can provide a platform for automated trading between all generation companies. Therefore, it can be mapped to the generation domain.

Z_2-Energy Market Management and Trading Control x DER: The DERs can actively participate in the energy market through different pricing regimes. They can either be traded directly on the energy marketplace, or they can be aggregated to form VPPs. In this case, communications play significant role in order to deliver active power and system services. Therefore, this ICT infrastructure has been mapped to the DER domain.

Z_3-Energy Market Management and Trading Control x Customer Premises: The role of industrial, commercial and domestic customers will be much more significant in the future pan-European power system. They can participate actively in the energy trading in order to integrate the load flexibilities into the market. Therefore, this domain-ICT interaction has been taken into consideration.

Z_4-Weather Observation and Forecasting x Generation: The weather observation infrastructure can provide useful information for the generation companies in terms of temperature and situational alerting.

Z_5-Weather Observation and Forecasting x DER: DERs such as wind turbines and PVs can make benefit from this ICT infrastructure in order to fine-tune their outputs. Therefore, this ICT infrastructure play significant role in this power system domain.

Z_6-Asset Maintenance and Management/GIS x Transmission: The operation of assets in the transmission domain can be monitored using this ICT infrastructure. Furthermore, periodic maintenance and field crew optimization can be provided. Therefore, this domain-ICT interaction has been considered.

Z_7-Asset Maintenance and Management/GIS x Distribution: The operation of assets in the distribution domain can be monitored using this ICT infrastructure. Furthermore, periodic maintenance and field crew optimization can be provided. Therefore, this domain-ICT interaction has been considered.

Z_8-Asset Maintenance and Management/GIS x DER: The operation of assets in the DER domain can be monitored using this ICT infrastructure. GIS application server can also store, analyse, and manipulate all types of geographical data. Therefore, this domain-ICT interaction has been considered.

Z_9-Advanced SCADA/EMS x Transmission: SCADA/EMS includes all the elements required to support the relevant operational activities used in the transmission automation, such as: feeder automation system, managing power quality, real-time outage management system. Therefore, this ICT infrastructure has been mapped to the transmission domain.

Z_{10}-Advanced SCADA/EMS x Distribution: SCADA/EMS includes all the elements required to support the relevant operational activities used in the distribution automation, such as: feeder automation system, managing power quality, real-time outage management system. Therefore, this ICT infrastructure has been mapped to the distribution domain.

Z_{11}-WAMS x Transmission: WAMS can provide beneficial information regarding voltage instabilities, frequency deviations and collapses by providing monitoring and analysing changes in the power system. Based on

the specifications of this ICT infrastructure, WAMS has been mapped to the transmission domain.

Z_{12}-WAMS x Distribution: WAMS can provide beneficial information regarding voltage instabilities, frequency deviations and collapses by providing monitoring and analysing changes in the power systems. Therefore, this ICT infrastructure can play significant role in the LV network and has been mapped to the distribution domain.

Z_{13}-AMI and Business Services x Customer Premises: Huge volume of data from smart meters installed at the customer premises can be produced from the AMI. Therefore, this ICT infrastructure has been mapped to the customer premises domain.

Chapter 4: Domain-ICT Cost Projection Analysis

In the previous chapter, six ICT infrastructures mapped to the five power system domains. At this stage of methodology, it is essential to apply cost projection trending analysis for the three physically quantitative ICT components. Furthermore, the cost impacts of qualitative ICT objectives on the relevant ICT infrastructure are taken into consideration. The mapping is finally quantified to reveal the impacts of these costs within the various domains.

In order to calculate the cost of implementing an ICT infrastructure for each power system domain, it is essential to consider both the physical ICT components quantitative costs and qualitative cost of ICT objectives.

4.1 Physically Quantitative ICT Components Cost Projection Trends

In order to identify the role of ICT infrastructure in future power systems, it is essential to consider the quantitative costs of ICT components. In this case, a cost trend analysis needed to be performed for the three physically quantifiable ICT components in order to achieve the projected ICT components cost trends. This trending analysis is based on the historical cost data for storage, bandwidth and also computational power. It is expected that because of a massive deployment of ICT in future power systems, the reliance on these core quantitative ICT components increase in portions.

In order to identify the cost of physically quantifiable ICT components, at different time horizons, it is essential to define different time intervals from present time (2014) up to 2050 time horizon. The number of time intervals in this study is $N = 5$. It is important to note that the durations of these time intervals are not the same, and their length is denoted as:

$$L(i), i \in [1, N]. \qquad E4.1$$

The time interval lengths are: $\mathrm{L}(1) = 3, \mathrm{L}(2) = 8, \mathrm{L}(3) = 10, \mathrm{L}(4) = 10, \mathrm{L}(5) = 5$ years (Figure 4.1). For any other variable which has time-dependence, the index i is used to specify the relevant time interval.

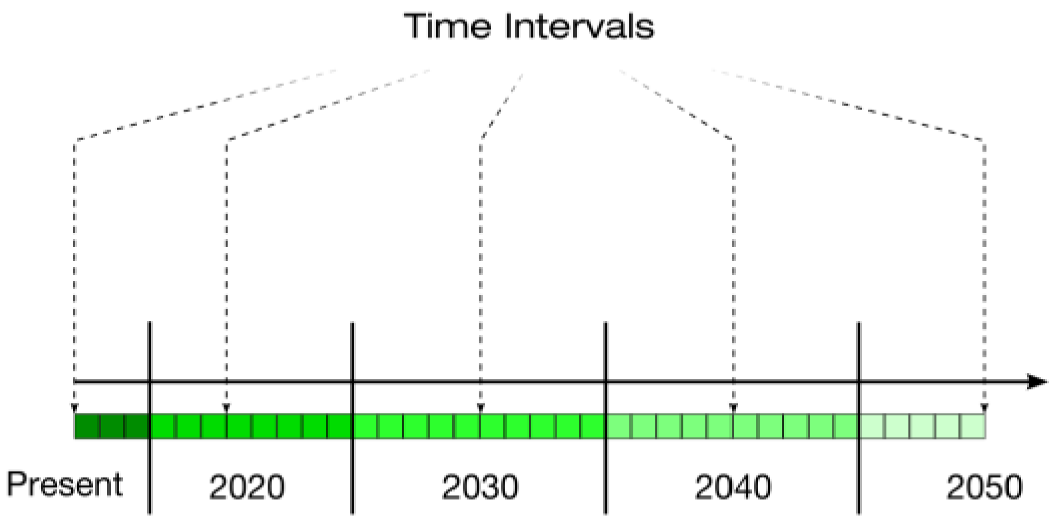


Figure 4.1: Time Intervals

At this stage of the methodology the marginal costs per unit of bandwidth, data storage, and computational power will be respectively defined as: P_{BW}, P_{ST}, P_{CP}. As it will be demonstrated in the following sections, the costs of these hardware components are expected to decrease over the time; therefore, the time dependence of these quantitative components should be taken into consideration:

$$P_{BW}(i), i \in [1, N],$$

$$P_{ST}(i), i \in [1, N],$$

$$P_{CP}(i), i \in [1, N]. \qquad E4.2$$

4.1.1 Data Storage Physical Cost Trend

Over the past 30 years, the competitive market has predictively driven the cost per gigabyte of storage down [38]. The cost of storage has decreased from over $1 million in 1981 to less than a dollar in recent years [39]. According to [26], the feature sizes and corresponding areal density increase are still following exponential curves as explained in Chapter 3; however, it is expected that these high growth rates will be declined in near future due to the technological restrictions, when the feature sizes of current technology approach the 10 nm range. However, there might be some technological breakthroughs in future that affect these limitations. For instance, Intel has recently announced that its roadmap extends to the 5nm scheduled by 2019 [44].

According to [39], there is a strong exponential correlation ratio between the storage and the price. In order to bring a numerical observability to the data storage projected cost trend line, Table 4.1 presents the quantitative cost of data storage (€/GB) at certain time horizons based on historical data. In addition to the extrapolation up to 2050, which would not insure reliability of the extrapolated values, the qualitative ICT objectives costs will be taken into account (Section 4.2). As presented in Table 4.1, the cost of storing data, $P_{ST}(i)$, will drastically decline at different time horizons. It is important to note that these are the quantitative costs of the bandwidth as one of the three predefined quantitative ICT components. By considering the impacts of qualitative costs associated with the ICT objectives, the ICT infrastructure overall implementation cost can be calculated as explained in Section 4.2.

Table 4.1: Data Storage Quantitative Cost at Different Time Horizons

Data Storage Cost Trends

	Present	2020	2030	2040	2050
€/GB	0.043	1.2×10^{-4}	3.8×10^{-7}	1.2×10^{-9}	4.3×10^{-12}

ICT infrastructures are evolving at such a rapid pace that it is almost impossible to imagine the nature of the future ICT landscape. It is important to note that in the cost projection analysis, a range of factors that may have impacts on the price of physically quantitative ICT components, such as international conflict, global financial and economic crises, political instabilities, natural disasters, and increased cyber risks have not been taken into consideration. For instance, according to [26, 38], during the past 2 years, there have been some considerable changes in the Hard Disk Drive (HDD) market due to the abrupt flooding that caused the Thailand drive crisis created a worldwide shortage of hard disk drives in 2011. This caused the prices for hard drives to rise dramatically and led to a price increase, which persists even to this day (Figure 4.2).

At present, only three major companies are sharing the 30 billion Euros HDD market [26]. Due to the Thailand crisis the average growth rate was -4.5% and the forecast for upcoming years is 7-8% positive growth. The major demand will come from cloud storage, which is at 50% level at present [26].

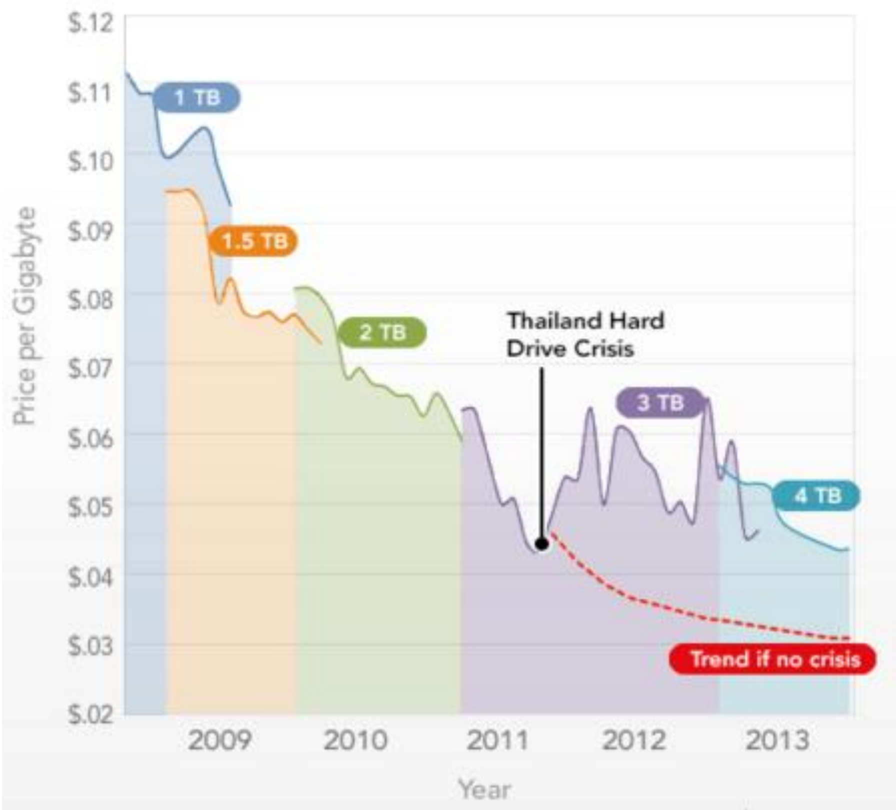


Figure 4.2: Thailand Crisis Impact on the Hard Drives Prices [38]

4.1.2 Bandwidth Physical Cost Trend

As Ethernet technology scales in production, all the manufactures try to invest more money in relevant technologies in order to decrease the costs. Based on [40], the prices for the wholesale bandwidth continued to decline globally over the last few years. The Gigabit Ethernet (GigE) prices declined at annual rate of 34% in London, 28% in New York, 26% in Hong Kong and 20% in Sao Paulo between the second quarter of 2009 and 2012 [40].

It can be identified that the bandwidth price has declined by 61% from 1998 up to 2010 [41]. Furthermore, in order to provide more information in addition to the bandwidth cost trend line, Table 4.2 illustrates the quantitative cost of bandwidth (€/Mbps), $P_{BW}(i)$,at different time horizons.

Table 4.2: Bandwidth Quantitative Costs at Different Time Horizons

Bandwidth Cost Trends

	Present	2020	2030	2040	2050
€/Mbps	0.68	0.043	4.6×10^{-4}	4.8×10^{-6}	5×10^{-8}

4.1.3 Computational Power Physical Cost Trend

In computing, floating-point operations per second (FLOPS), is a measure that represents the computational performance [42]. In recent years, the performances of computers have been drastically increased and their prices have decreased. The cost per Gigaflops is the cost of a hardware that would operate at one billion floating-point operations per second.

According to [43], every 1.14 year the performance of computers doubles. Considering the current speed of progress, it is anticipated that by 2018, high performance computers will reach to 1 exaFLOPS [44]. Furthermore, with reference to [45], it is predicted that in order to accomplish full weather modelling, a zettaFLOPS computer will be required by 2030.

Like the previous two physically quantifiable ICT components, Table 4.3 presents the quantitative cost of computational power (€/GFLOP), $P_{CP}(i)$, at different time horizons.

Table 4.3: Computational Quantitative Power Costs at Different Time Horizons

Computational Cost Trends

	Present	2020	2030	2040	2050
€/GFLOP	0.086	0.008	2.9×10^{-5}	8.3×10^{-7}	3.6×10^{-10}

4.2 ICT Infrastructure Complete Implementation Cost

Considering the added qualitative cost of ICT objectives explained in Chapter 3, Figure 4.3 illustrates the cost per GB trend [26, 39]. This figure illustrates a 60% price decrease per gigabyte per year [26].

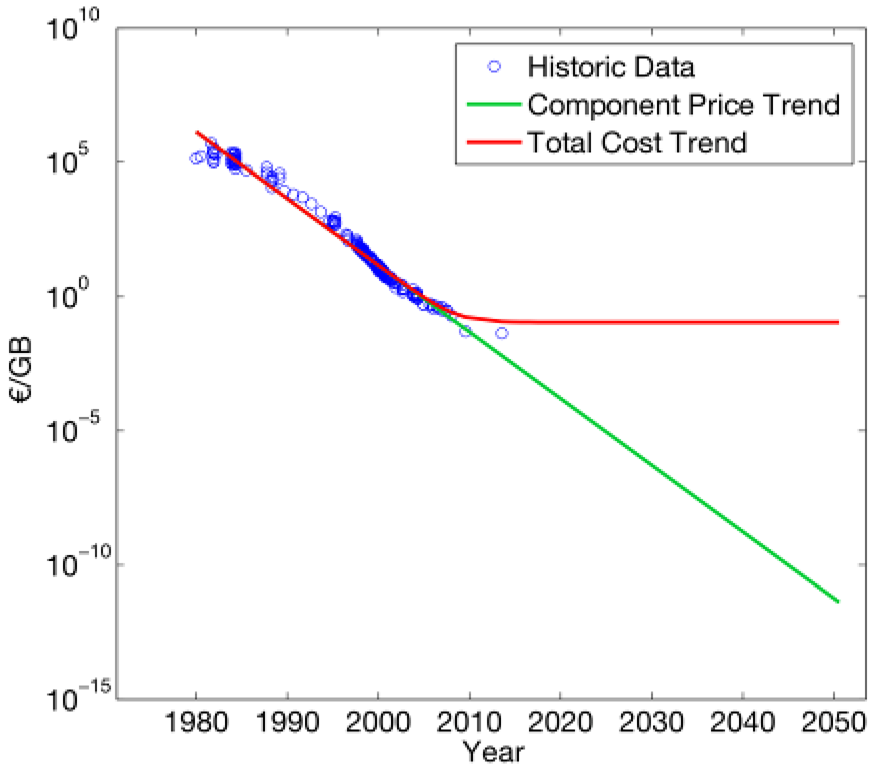


Figure 4.3: Data Storage Projected Cost Trend for a Specific Domain-ICT Interaction Considering the Impacts of ICT Objectives Qualitative Costs - *Energy Market ICT Infrastructure and Generation Domain Interaction*

The blue dots present the historical data, the green line illustrates the physically quantitative component price trend based on historical data and the red line presents the total implementation cost of ICT components considering the added qualitative cost of ICT objectives. Historically, the cost of physically quantitative ICT components has dominated the total cost; however, this cost has become inexpensive at different time horizons and the added qualitative cost of ICT objectives has dominated the total cost and flattened the curve. Figure 4.4 presents the projected bandwidth price based on the historical data [41], considering the added qualitative cost of ICT objectives.

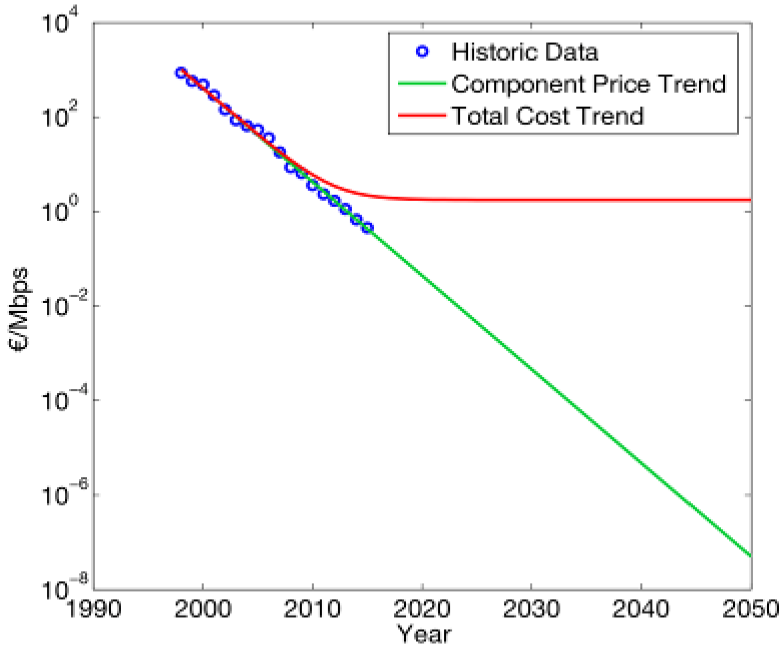


Figure 4.4: Bandwidth Projected Cost Trend for a Specific Domain-ICT Interaction Considering the Impacts of ICT Objectives Qualitative Costs - *Energy Market ICT Infrastructure and Generation Domain Interaction*

Furthermore, Figure 4.5 presents the projected computational power price based on the historical data [42, 46], considering the added qualitative cost of ICT objectives.

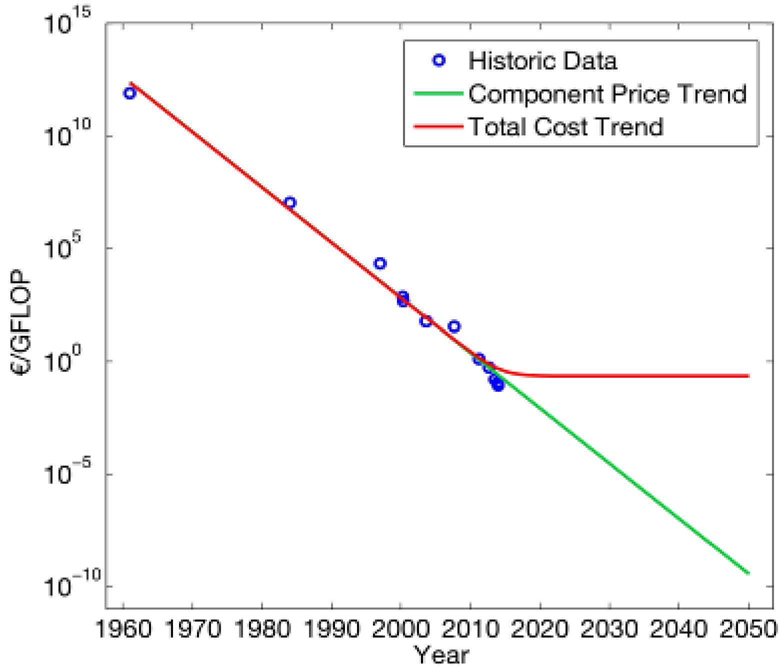


Figure 4.5: Computational Power Projected Cost Trend for a Specific Domain-ICT Interaction Considering the Impacts of ICT Objectives Qualitative Costs - *Energy Market ICT Infrastructure and Generation Domain Interaction*

In Section 4.1, the cost trends of three physically quantitative ICT components were investigated. It was presented that how much these three ICT components will cost at different time horizons. It is noticeable that the cost of ICT infrastructure includes the cost of physically quantitative ICT components plus the added qualitative cost of ICT objectives. Therefore, the cost of ICT infrastructure can be *varied* for different domain-ICT interactions. For example, by considering the *Energy Market Management and Trading Control* and *Generation* Domain interaction it can be presented how the cost of implementing this ICT infrastructure can be calculated.

Addressing the qualitative ICT objective costs defined in Chapter 3, a set of coefficients K can be introduced, where the coefficients take a value in the range of $0 \leq K \leq 10$.

These coefficients are designed such that a value of $K = 0$ leads to no increase in the marginal costs of a physically quantitative ICT component, and a coefficient of $K = 10$ for any qualitative ICT objective leads to a 100% increase in the marginal price

Separate coefficient K for each of the four qualitative ICT objectives, resilience, maintenance & support, privacy & cyber security, and interoperability, can be defined as $K_R, K_M, K_P,$ and K_I respectively. Since these coefficients are interaction dependent, thus:

$$K_R(j), j \in [1, M],$$

$$K_M(j), j \in [1, M],$$

$$K_P(j), j \in [1, M],$$

$$K_I(j), j \in [1, M]. \qquad E4.3$$

These coefficients are applied to the present day physically quantitative ICT components costs in order to determine an additive ICT objective marginal cost. In this case, the additive cost of bandwidth, data storage, and computational power, respectively are: $Q_{BW}, Q_{ST},$ and Q_{CP}. It is important to note that these values are dependent on the qualitative ICT objective K coefficients, but only utilize the quantitative ICT component costs for the present day, interval $i = 1$. Furthermore, these Qs are only dependent on the relevant domain-ICT interaction $Z(j)$. Hence:

$$Q_{BW}(j) = [(K_R(j)/10) + (K_M(j)/10) + (K_P(j)/10) + (K_I(j)/10)]P_{BW}(1) \qquad E4.4$$

$$Q_{ST}(j) = [(K_R(j)/10) + (K_M(j)/10) + (K_P(j)/10) + (K_I(j)/10)]P_{ST}(1) \qquad E4.5$$

$$Q_{CP}(j) = [(K_R(j)/10) + (K_M(j)/10) + (K_P(j)/10) + (K_I(j)/10)]P_{Cp}(1) \qquad E4.6$$

Table 4.4: Physically Quantitative ICT Components Costs

Time \ ICT Components	Data Storage_P_{ST} (€/GB)	Bandwidth_P_{BW} (€/Mbps)	Computational Power_P_{CP} (€/GFLOP)
Present (2014)	4.32E-02	6.77E-01	8.64E-02
2020	1.15E-04	4.32E-02	7.92E-03
2030	3.82E-07	4.61E-04	2.88E-05
2040	1.22E-09	4.82E-06	1.01E-07
2050	4.32E-12	5.04E-08	3.60E-10

Table 4.4 illustrates the cost of physically quantitative ICT components at different time horizons.

Furthermore, in order to consider the impacts of qualitative ICT objectives for this domain-ICT interaction, each of the four qualitative ICT objectives has been assigned with a coefficient (K). This coefficient presents the qualitative

Table 4.5: ICT Objectives Qualitative Cost Impacts - *Energy Market ICT Infrastructure and Generation Domain Interactions*

ICT Objectives	**Resilience (K_R)**	**Maintenance and Support (K_M)**	**Privacy and Cyber Security (K_P)**	**Interoperability (K_I)**

impact of that ICT objective on the cost of implementing that ICT infrastructure. According to the formulas E4.4-4.6 the cost of quantitative ICT components presented in Tables 4.1-4.3 at interval $i = 1$ are multiplied by these coefficients. In this case, three additional qualitative costs have been calculated.

Cost Impacts (0-10)	1.0	5.0	10.0	10.0		
Objectives Cost Impacts on Data Storage (Q_{ST})	0.0043	0.0216	0.0432	0.0432	**0.1123**	**Additional ICT Qualitative Cost**
Objectives Cost Impacts on Bandwidth (Q_{BW})	0.0677	0.3384	0.6768	0.6768	**1.7597**	
Objectives Cost Impacts on Computational Power (Q_{CP})	0.0086	0.0432	0.0864	0.0864	**0.2246**	

Now, in order to calculate the resultant marginal costs, both the physically quantitative ICT component costs P and the qualitative ICT objective costs Q can be combined together. In this case, the total marginal costs of bandwidth, data storage, and computational power will be: C_{BW}, C_{ST}, and C_{CP} respectively.

These total marginal cost estimates C have both time-dependence and domain-ICT interaction dependence, yielding:

$$C_{BW}\ (i,j), i\ \in [1,N], j\ \in [1,M],$$

$$C_{ST}\ (i,j), i\ \in [1,N], j\ \in [1,M],$$

$$C_{CP}\ (i,j), i\ \in [1,N], j\ \in [1,M]. \qquad E4.7$$

where:

$$C_{BW}\ (i,j) = P_{BW}(i) + Q_{BW}(j)$$

$$C_{ST}\ (i,j) = P_{ST}(i) + Q_{ST}(j)$$

$$C_{CP}\ (i,j) = P_{CP}(i) + \ Q_{CP}(j) \qquad E4.8$$

By adding these costs to the cost of physically quantitative ICT components the both quantitative and qualitative cost trends for implementing an ICT infrastructure can be analysed (Table 4.6):

Table 4.6: ICT Combined Qualitative and Quantitative Cost Trends for Implementing an ICT Infrastructure - *Energy Market ICT Infrastructure and Generation Domain Interaction*

Time \ ICT Components	Data Storage_C_{ST} (€/GB)	Bandwidth_C_{BW} (€/Mbps)	Computational Power_C_{CP} (€/GFLOP)
Present (2014)	0.1555	2.4365	0.3110
2020	0.1124	1.8029	0.2326
2030	0.1123	1.7601	0.2247
2040	0.1123	1.7597	0.2246
2050	0.1123	1.7597	0.2246

At this point of methodology, in order to extend the domain-ICT interaction mapping (Figure 3.6), it is essential to account the impacts of the projected cost trends of the physically quantitative ICT components, as well as implementation of the considered qualitative ICT objectives. This extended mapping will attempt to provide a quantitative estimate of the costs of implementing an ICT infrastructure within a power system domain. According to Figure 3.6, there are 13 interactions between ICT infrastructure and power system domains. The next following sub-sections describe the total cost of implementing different ICT infrastructures within various power system domains.

Since the total marginal per unit costs for implementing ICT infrastructure are time dependents; therefore, it is also essential to characterize not only these marginal costs over the relevant time intervals, but also to model the quantities purchased during the time intervals. In this case, variable E will be used to define a purchase quantity.

For each of the 13 domain-ICT interactions $Z(j)$, there will be a required total purchase amount for each of the three quantifiable ICT components. In this case, by defining superscript t the total required purchase quantity by 2050 can be indicated, yielding the set of variables as follows:

$$E^t{}_{BW}\,(j), j \in [1, M],$$

$$E^t{}_{ST}\,(j), j \in [1, M],$$

$$E^t{}_{CP}\,(j), j \in [1, M]. \qquad E4.9$$

These E^ts represent the total quantity of a physically quantifiable ICT component to be purchased by 2050. These purchases are expected to occur incrementally over the relevant time period, according to the time intervals determined by the set of $L(i)$. Therefore, a purchasing model must be formulated, where for each of the i time intervals; a certain percentage of the total physically quantitative ICT component requirement E^t is purchased during that interval. In this case, a purchasing schedule is modelled as:

$$D(i), i \in [1, N], \qquad E4.10$$

where:

$$\sum_{i=1}^{N} D(i) = 1. \qquad E4.11$$

Therefore, for the three physically quantitative ICT components, the amount of the component purchase is time interval i for a specific domain-ICT interaction j is:

$$E_{BW}(i,j) = D(i){E^t}_{BW}(j), i \in [1,N], j \in [1,M],$$

$$E_{ST}(i,j) = D(i){E^t}_{ST}(j), i \in [1,N], j \in [1,M],$$

$$E_{CP}(i,j) = D(i){E^t}_{CP}(j), i \in [1,N], j \in [1,M]. \qquad E4.12$$

Figure 4.6 illustrates the percentage purchased chart. According to this figure, a typical exponential model has been taken into consideration in order to estimate the share of purchased quantitative ICT components for each ICT infrastructure. As illustrated in Figure 4.6 the percentage purchased exponentially increase at different time horizons. The exponential characteristics have been modified to model an investment strategy where asset investment is deferred, but once the large-scale uptake of technology begins, the growth is very rapid.

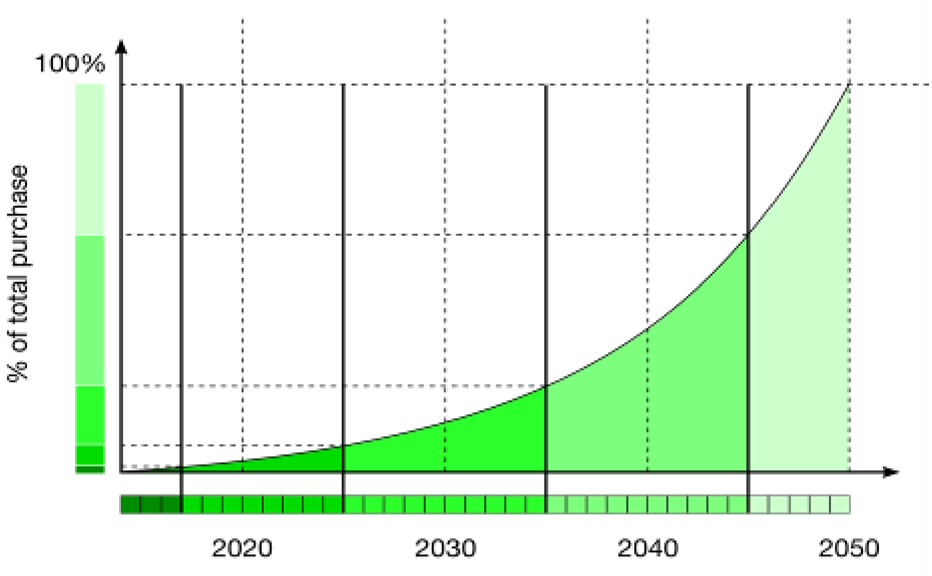


Figure 4.6: Exponential Purchase Trend

Table 4.7 presents the percentage purchased as well as the total purchased ICT components at different intermediate time horizons. Since, the purchase trend is exponential; therefore, great share of ICT components will be purchased closer to the 2050 time horizon, when the prices of physically quantitative ICT components are relatively cheaper due to the deflationary nature of ICT components costs when compared to the present time.

Table 4.7: Exponential Purchase

Exponential Purchase Trend

	Present	2020	2030	2040	2050
Purchase Percentage	0.55%	7.30%	22.77%	40.93%	28.45%
Total Purchased	0.55%	7.85%	30.62%	71.55%	100%

At this point of methodology, the defined physically quantitative ICT component purchase quantities $\mathrm{E_{BW}(i,j)}, \mathrm{E_{BW}(i,j)}$, and $\mathrm{E_{BW}(i,j)}$, can be used along the estimated marginal costs $\mathrm{E_{BW}(i,j)}, \mathrm{E_{BW}(i,j)}$, and $\mathrm{E_{BW}(i,j)}$ to form the total cost estimates. The total cost T for any of the three ICT components - considering the impacts of qualitative ICT objectives - for time interval i for domain-ICT interaction j is:

$$T_{BW}(i,j) = E_{BW}(i,j)\, C_{BW}(i,j), i \in [1,N], j \in [1,M],$$

$$T_{ST}(i,j) = E_{ST}(i,j)\, C_{ST}(i,j), i \in [1,N], j \in [1,M],$$

$$T_{CP}(i,j) = E_{CP}(i,j)\, C_{CP}(i,j), i \in [1,N], j \in [1,M]. \qquad E4.13$$

In this case, the total costs of the ICT components – including the qualitative impacts of ICT objectives – for domain-ICT interaction j over the entire time horizon to 2050 are:

$$T_{BW}(j) = \sum_{i=1}^{N} T_{BW}(i,j),\ j \in [1,M],$$

$$T_{ST}(j) = \sum_{i=1}^{N} T_{ST}(i,j),\ j \in [1,M],$$

$$T_{CP}(j) = \sum_{i=1}^{N} T_{CP}(i,j),\ j \in [1, M]. \qquad E4.14$$

Finally, the total cost of ICT infrastructure implementation for domain-ICT interaction j up to 2050 is estimated as:

$$T(j) = T_{BW}(j) + T_{ST}(j) + T_{CP}(j) \qquad E4.15$$

More details regarding the cost of implementing different ICT infrastructure in different power system domains can be found in accompanying spreadsheet.

4.2.1 Energy Market Management and Trading Control X Generation Domain Interaction (Z_1)

Coreso [47] has developed tools to obtain and analyse various incoming data and also compare the results with previous predictions and share this information with other TSOs. In this case it is essential to consider two-day-ahead, day-ahead and intraday congestion forecasts for the market analysis through an IT platform.

Merging single two-day ahead files provided by each TSO every day can create the Day 2 Ahead Congestion Forecast (D2CF) [47]. Furthermore, it is essential to collect unique security analysis data of the European grid on a day-ahead basis every hour. In this case, TSOs can submit their Day Ahead Congestion Forecasting (DACF) files [47]. Also, in order to perform the analysis close to real time, TSOs should submit their Intraday Congestion Forecast Files (IDCFs). These files can be automatically collected every 15 minutes [47].

It is expected that all 41 ENTSO-E TSOs [48] will participate in this monitoring task. By assuming that the size of these congestion forecasting files will be not more that 5MB, the total required data storage over 36 years from 2014 can be calculated as:

*<u>Day 2 Ahead Congestion Forecast (D2ACF):</u> 5MB * 365days * 41ENTSO-E TSOs * 36years = 2,693.7GB*

*<u>Day Ahead Congestion Forecast (DACF):</u> 5MB * 24hours * 365days * 41ENTSO-E TSOs * 36years = 64,648.8GB*

*<u>Intra Day Congestion Forecast Files (IDCFs):</u> 5MB * 4 * 24hours * 365days * 41ENTSO-E TSOs * 36years = 258,595.2GB*

E_{ST}: *<u>Total required storage over 36 years</u> =* ***325,937.7GB***

Furthermore, the required bandwidth over the 36 years can be calculated as follows:

*<u>Total required bandwidth over 36 years:</u> 32,5937,700MB / (8760hours * 60 hours * 60secs) = 10.3Mbps*

In order to consider an appropriate safety margin, the amount of bandwidth can be considered *3* times bigger*, hence:*

E_{BW}: *<u>Total required bandwidth over 36 years x</u>**<u>3</u>** =* ***31.0Mbps***

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS)****,* which can meet the computational requirements for analysing these data.

4.2.2 Energy Market Management and Trading Control X DER Domain Interaction (Z_2)

According to [49], the European Wind Energy Association (EWEA) has predicted 600GW of installed capacity for wind energy by 2050. The average size of single wind turbine can be assumed to be 5MW. In this case, there will be 120,000 wind turbines in Europe by 2050. If they transmit 12 bit [50] of data at a resolution of 1 second; therefore the total required data storage over the 36 years will be:

E_{ST}: *<u>Total required storage over 36 years per substation</u>: 12bit * 60secs * 60mins * 24hours * 365days * 36years * 32 condition monitoring * 120,000WT =* ***6,090,202.3GB***

Furthermore, the required bandwidth over the 36 years can be calculated as follows:

*<u>Total required bandwidth over 36 years:</u> 6,090,202,331.54MB / (8760hours * 60 hours * 60secs) = 193.1Mbps*

In order to consider an appropriate safety margin, the amount of bandwidth can be considered *100* times bigger in order to facilitate communication in the market platform*, hence:*

E_{BW}: *<u>Total required bandwidth over 36 years x</u>**<u>100</u>** =***19,311.9Mbps***

In order to be conservative, the safety factor has been considered 100 in this domain-ICT interaction in order to reflect the importance of real time communications in electricity market platform, specifically for the DERs such as wind power. In this case, the requirements for transferring huge amount of data at real time can be taken into consideration.

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS)***, which can meet the computational requirements for analysing these data.

4.2.3 Energy Market Management and Trading Control X Customer Premises Domain Interaction (Z_3)

In order to consider the role of the end-users in the electricity market, it is essential to investigate the number of smart meters in future. According to [51], it is anticipated that 170-180 million smart meters will be installed in EU by 2020. However, the potential number of smart meters in EU is 250 million. The data collection can be performed at the intervals of 5-15 minutes [52].

According the [52], based on the 15 minutes intervals, a single electricity meter can generate less than 1.5MB data per year. In this case, the total required data storage over the 36 years from now will be:

E_{ST}: *Total required data storage over 36 years: 250million * 1.5MB * 36years =* ***13,183,593.75GB***

Furthermore, the required bandwidth over the 36 years can be calculated as follows:

*Total required bandwidth over 36 years: 13,183,593,750MB / (8760hours * 60 hours * 60secs) = 418.04Mbps*

In order to consider an appropriate safety margin, the amount of bandwidth can be considered *100* times bigger in order to facilitate communication in the market platform*, hence:*

E_{BW}: *Total required bandwidth over 36 years x**100** =**41,804.9Mbps***

In order to be conservative, the safety factor has been considered 100 in this domain-ICT interaction in order to reflect the importance of real time communications in electricity market platform, specifically for the end-users in order to fine-tune their position in the market. In this case, the requirements for transferring huge amount of data at real time can be taken into consideration.

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS),*** which can meet the computational requirements for analysing these data.

4.2.4 Weather Observation and Forecasting X Generation Domain Interaction (Z_4)

For weather observation and forecasting, 10 to 20 terabytes of data can be collected per day [53]. This will be 2.25 billion weather data points, 15 times per hour [53]. In order to consider the cost of this ICT infrastructure in the generation domain, we have assumed that 10 terabytes of data will be collected per day. In this case, the total required data storage over the 36 years from now can be calculated as follows:

E_{ST}: <u>*Total required data storage over 36 years:*</u> *10,240GB * 365days * 36years =* ***134,553,600GB***

Furthermore, the required bandwidth over the 36 years can be calculated as follows:

<u>*Total required bandwidth over 36 years:*</u> *137,838,600,000MB / (8760hours * 60 hours * 60secs) = 4,266.6Mbps*

In order to consider an appropriate safety margin, the amount of bandwidth can be considered *3* times bigger*, hence:*

E_{BW}: <u>*Total required bandwidth over 36 years x**3***</u> = ***12,800Mbps***

Also, the computational power for this ICT infrastructure will be [54]:

- Computational Power for weather prediction: 100 teraFLOPS
- Computational Power for very rapid weather prediction: 100 petaFLOPS
- Computational Power for instantaneous weather prediction: 100 exaFLOPS

In this case we have assumed this amount will be E_{CP}: ***100 exaFLOPS (100,000,000,000).***

4.2.5 Weather Observation and Forecasting X DER Domain Interaction (Z_5)

According to [58, 59], PMUs were first introduced in the UK in 2011 and by 2012 there were 20 PMUs transmitting data to a PDC at National Grid. Assuming for simplicity that these are all Arbiter PMUs where each packet is 50bytes [60]. As of 2014 there are 40 PMUs transmitting data to a PDC at National Grid. In this case, it is predicted that over the next 6 years to 2020 the number of PMUs will be 100 [57, 58]. By 2030, every substation will have 1 PMU and then 4 PMUs per substation by 2050.

According to the [59], for *20* PMUs the required data storage per year is as follows:

1.43TB a year of rolling storage + 0.286TB a year of archived data

Since the number of UK primary substations is about 6,000; therefore, the total required storage over the 36 years from now in the UK will be:

*UK Total required storage over 36 years: 300 * 1.43TB * 36years + 80 * 0.286TB * 35 = 18,889,728GB*

As explained in the previous sections, in order to estimate the required data storage in the EU, the EU/UK ratio is assumed to be *9.05* based on the electricity generation data from Eurostat [56].

E_{ST}: *Total required storage over 36 years: 9.05 * 18,889,728GB =* ***170,952,038GB***

Furthermore, the required bandwidth over the 36 years for UK can be calculated:

*UK required bandwidth over 36 years: 170,952,038,000MB/ (8760hours * 60 hours * 60secs) = 598.98Mbps*

In this case, the total required bandwidth for EU will be:

*Required bandwidth for 36 years: 9.05 * 598.98Mbps = 5,420.85Mbps*

In order to consider an appropriate safety margin, the amount of bandwidth can be considered 3 times bigger*, hence:*

E_{BW}: *Total required bandwidth over 36 years x**3*** = ***16,262.56Mbps***

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS),*** which can meet the computational requirements for analysing these data.

4.2.6 Asset Maintenance and Management/GIS X Transmission Domain Interaction (Z_6)

Based on [54], around 81 condition-monitoring parameters per substation can be collected. The maximum measurement resolution for online transformer monitoring is 12bit at 10 KHz [50]. It has been assumed that for the asset maintenance and management requirements, the required measurement resolution can be 12bit at 1 second. In this case, the required data storage over the 36 years from now can be calculated as follows:

*<u>Total required storage over 36 years per substation</u>: 12bit * 60secs * 60mins * 24hours * 365days * 36years * 81 condition monitoring = 1,027.72 GB*

According to [55], the number of high voltage substation in the UK is 400. Therefore, the total required data storage for this ICT infrastructure in UK will be:

*1027.72 GB * 400substations = 411,088GB*

At this point, it is essential to extrapolate this number in order to obtain the total required data storage for the EU. According to the Eurostat [56], the total electricity generation for EU-28 in 2012 was 3,294,590 GWh. Also, the total electricity generation for UK in 2012 was 363,837 GWh. Therefore, the EU/UK ratio can be assumed to be ***9.05*** [56]. In this case the total required storage will be:

E_{ST}: *<u>Total required storage over 36 years:</u> 9.05 * 411,088GB =* ***3,720,346.4GB***

Furthermore, the required bandwidth over the 36 years for UK can be calculated:

*<u>UK required bandwidth over 36 years:</u> 411,088,000MB / (8760hours * 60 hours * 60secs) = 13.03Mbps*

In this case, the total required bandwidth for EU will be:

*Required bandwidth for 36 years: 9.05 * 13.03Mbps = 117.97Mbps*

In order to consider an appropriate safety margin, the amount of bandwidth can be considered 3 times bigger*, hence:*

E_{BW}: *Total required bandwidth over 36 years x**3*** = ***353.91Mbps***

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS),*** which can meet the computational requirements for analysing these data.

4.2.7 Asset Maintenance and Management/GIS X Distribution Domain Interaction (Z_7)

Based on [54], around 81 condition-monitoring parameters per substation can be collected. The maximum measurement resolution for online transformer monitoring is 12bit at 10 KHz [50]. It has been assumed that for the asset maintenance and management requirements, the required measurement resolution can be 12bit at 1 second. In this case, the required data storage over the 36 years from now can be calculated as follows:

*<u>Total required storage over 36 years per substation</u>: 12bit * 60secs * 60mins * 24hours * 365days * 36years * 81 condition monitoring = 1,027.72 GB*

According to [55], the number of primary substation in the UK is about 6,000. Therefore, the total required data storage for this ICT infrastructure in UK will be:

*1,027.72 GB * 6,000substations = 6,166,320GB*

At this point, it is essential to extrapolate this number in order to obtain the total required data storage for the EU. According to the Eurostat [56], the total electricity generation for EU-28 in 2012 was 3,294,590 GWh. Also, the total electricity generation for UK in 2012 was 363,837 GWh. Therefore, the EU/UK ratio can be assumed to be ***9.05*** [56]. In this case the total required storage will be:

E_{ST}: *<u>Total required storage over 36 years:</u> 9.05 * 6,166,320GB =* ***55,805,196GB***

Furthermore, the required bandwidth over the 36 years for UK can be calculated:

*<u>UK required bandwidth over 36 years:</u> 6,166,320,000MB / (8760hours * 60 hours * 60secs) = 195.53Mbps*

In this case, the total required bandwidth for EU will be:

*<u>Required bandwidth for 36 years:</u> 9.05 * 195.53Mbps = 1,769.57Mbps*

In order to consider an appropriate safety margin, the amount of bandwidth can be considered 3 times bigger*, hence:*

E_{BW}: *Total required bandwidth over 36 years x**3** = **5,308.71Mbps***

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS),*** which can meet the computational requirements for analysing these data.

4.2.8 Asset Maintenance and Management/GIS X DER Domain Interaction (Z_8)

According to [49], the European Wind Energy Association (EWEA) has predicted 600GW of installed capacity for wind energy by 2050. The average size of single wind turbine can be assumed to be 5MW. In this case, there will be 120,000 wind turbines in Europe by 2050. According to [57], there are about 32 condition monitoring parameters for a wind turbine including vibration monitoring, gearbox oil temperature, etc. If they transmit 12 bit [50] of data at a resolution of 1 second; therefore, the total required data storage over the 36 years will be:

E_{ST}: *Total required storage over 36 years per substation: 12bit * 60secs * 60mins * 24hours * 365days * 36years * 32 condition monitoring * 12,0000WT = **6,090,202.33GB***

Furthermore, the required bandwidth over the 36 years can be calculated as follows:

*Total required bandwidth over 36 years: 6,090,202,331.54MB / (8760hours * 60 hours * 60secs) = 193.11Mbps*

In order to consider an appropriate safety margin, the amount of bandwidth can be considered *3* times bigger*, hence:*

E_{BW}: *Total required bandwidth over 36 years x**3** = **579.35Mbps***

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS)**),* which can meet the computational requirements for analysing these data.

4.2.9 WAMS X Transmission Domain Interaction (Z_9)

According to [57, 58], PMUs were first introduced in the UK in 2011 and by 2012 there were 20 PMUs transmitting data to a PDC at National Grid. Assuming for simplicity that these are all Arbiter PMUs where each packet is 50bytes [59]. As of 2014 there are 40 PMUs transmitting data to a PDC at National Grid. In this case, it is predicted that over the next 6 years to 2020 the number of PMUs will be 100 [57, 58]. By 2030, every substation will have 1 PMU and then 4 PMUs per substation by 2050.

According to the [59], for *20* PMUs the required data storage per year is as follows:

<u>1.43TB a year of rolling storage + 0.286TB a year of archived data</u>

Since the number of UK high voltage substations is about 400; therefore, the total required storage over the 36 years from now in the UK will be:

*<u>UK Total required storage over 36 years</u>: 80 * 1.43TB * 36years + 80 * 0.286TB * 35 = 5,037,260.8GB*

As explained in the previous sections, in order to estimate the required data storage in the EU, the EU/UK ratio is assumed to be *9.05* based on the electricity generation data from Eurostat [56].

E_{ST}: *<u>Total required storage over 36 years</u>: 9.05 * 5,037,260.8GB =* ***45,587,210.24GB***

Furthermore, the required bandwidth over the 36 years for UK can be calculated:

<u>UK required bandwidth over 36 years:</u> *5,037,260,800MB/ (8760hours * 60 hours * 60secs) = 159.73Mbps*

In this case, the total required bandwidth for EU will be:

<u>Required bandwidth for 36 years:</u> *9.05 * 159.73Mbps = 1,445.56Mbps*

In order to consider an appropriate safety margin, the amount of bandwidth can be considered 3 times bigger*, hence:*

E_{BW}: <u>*Total required bandwidth over 36 years x**3***</u> = ***4,336.68Mbps***

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS),*** which can meet the computational requirements for analysing these data.

4.2.10 WAMS X Distribution Domain Interaction (Z_{10})

According to [58, 59], PMUs were first introduced in the UK in 2011 and by 2012 there were 20 PMUs transmitting data to a PDC at National Grid. Assuming for simplicity that these are all Arbiter PMUs where each packet is 50bytes [60]. As of 2014, there are 40 PMUs transmitting data to a PDC at National Grid. In this case, it is predicted that over the next 6 years to 2020 the number of PMUs will be 100 [57, 58]. By 2030, every substation will have 1 PMU and then 4 PMUs per substation by 2050.

According to the [59], for *20* PMUs the required data storage per year is as follows:

<u>*1.43TB a year of rolling storage + 0.286TB a year of archived data*</u>

Since the number of UK primary substations is about 6000; therefore, the total required storage over the 36 years from now in the UK will be:

<u>UK Total required storage over 36 years</u>*: 300 * 1.43TB * 36years + 80 * 0.286TB * 35 = 18,889,728GB*

As explained in the previous sections, in order to estimate the required data storage in the EU, the EU/UK ratio is assumed to be *9.05* based on the electricity generation data from Eurostat [56].

*<u>Total required storage over 36 years</u>: 9.05 * 18,889,728GB =* ***170,952,038GB***

Furthermore, the required bandwidth over the 36 years for UK can be calculated:

E_{ST}: *<u>UK required bandwidth over 36 years:</u> 170,952,038,000MB/ (8760hours * 60 hours * 60secs) = 598.98Mbps*

In this case, the total required bandwidth for EU will be:

*<u>Required bandwidth for 36 years:</u> 9.05 * 598.98Mbps = 5,420.85Mbps*

In order to consider an appropriate safety margin, the amount of bandwidth can be considered 3 times bigger*, hence:*

E_{BW}: *<u>Total required bandwidth over 36 years x**3**</u> =* ***16,262.56Mbps***

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS),*** which can meet the computational requirements for analysing these data.

4.2.11 Advanced SCADA/EMS X Transmission Domain Interaction (Z_{11})

According to the description of WAMS in Chapter 3, this ICT infrastructure can be realized as a supplement to the SCADA infrastructure. The PMUs take sample data at a rate of up to 50 measurements per second. In this case, it can be assumed that the advanced SCADA/EMS infrastructure can collect data per second. In this case, the total required data storage over the 36 years will be:

E_{ST}: *<u>Total required storage over 36 years</u> = Total required storage over 36 years by WAMS / 50 = 45,587,210.2GB / 50 =* ***911,744.2GB***

Furthermore, the required bandwidth over the 36 years for UK can be calculated:

UK required bandwidth over 36 years = UK required bandwidth over 36 years by WAMS / 50 = 1,445.56 Mbps / 50 = 28.91Mbps

In order to consider an appropriate safety margin, the amount of bandwidth can be considered 3 times bigger*, hence:*

E_{BW}: *Total required bandwidth over 36 years x**3** = **86.73Mbps***

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS),*** which can meet the computational requirements for analysing these data.

4.2.12 Advanced SCADA/EMS X Distribution Domain Interaction (Z_{12})

According to the description of WAMS in Chapter 3, this ICT infrastructure can be realized as a supplement to the SCADA infrastructure. The PMUs take sample data at a rate of up to 50 measurements per second. In this case, it can be assumed that the advanced SCADA/EMS infrastructure can collect data per second. In this case, the total required data storage over the 36 years will be:

E_{ST}: *Total required storage over 36 years = Total required storage over 36 years by WAMS / 50 = 170,952,038.4GB / 50 =* ***3,419,040.76GB***

Furthermore, the required bandwidth over the 36 years for UK can be calculated:

UK required bandwidth over 36 years = UK required bandwidth over 36 years by WAMS / 50 = 5,420.85Mbps / 50 = 108.4Mbps

In order to consider an appropriate safety margin, the amount of bandwidth can be considered 3 times bigger*, hence:*

E_{BW}: *Total required bandwidth over 36 years x**3** =* ***325.2Mbps***

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS),*** which can meet the computational requirements for analysing these data.

4.2.13 AMI and Business Services X Distribution Domain Interaction (Z_{13})

According to [51], it is anticipated that 170-180 million smart meters will be installed in EU by 2020. However, the potential number of smart meters in EU is 250 million. The data collection can be performed at the intervals of 5-15 minutes [52].

According the [52], based on the 15 minutes intervals, a single electricity meter can generate less than 1.5MB data per year. In this case, the total required data storage over the 36 years from now will be:

E_{ST}: *Total required data storage over 36 years: 250million * 1.5MB * 36years =* ***13,183,593.75GB***

Furthermore, the required bandwidth over the 36 years can be calculated as follows:

*Total required bandwidth over 36 years: 13,183,593,750MB / (8760hours * 60 hours * 60secs) = 418.04Mbps*

In order to consider an appropriate safety margin, the amount of bandwidth can be considered *3* times bigger*, hence:*

E_{BW}: *Total required bandwidth over 36 years x**3*** = ***1,254.14Mbps***

Also, the computational power can be considered as E_{CP}: ***1PetaFLOPS (1,000,000 GFLOPS),*** which can meet the computational requirements for analysing these data.

4.3 Domain-ICT Interaction Total Cost

In the previous section the total required purchase quantities of the three quantitative ICT components were calculated for each of the 13 domain-ICT interactions $Z(j)$ by 2050, $E^t{}_{BW}\ (j), E^t{}_{ST}\ (j), E^t{}_{CP}\ (j)$.

By considering to the amount of the purchased ICT component at time interval i for a specific domain-ICT interaction$j$: $E_{BW}(i,j), E_{ST}(i,j), E_{CP}(i,j)$,along the estimated marginal costs, the total costs of the ICT components – including the qualitative impacts of ICT objectives – for domain-ICT interaction j over the entire time horizon up to 2050 can be calculated. Please refer to formulas E14.12 and E14.13. Finally, the total cost of ICT infrastructure implementation for domain-ICT interaction$j$,$T(j)$, can be estimated according to formulas E4.14 and E4.15.

For illustration purposes, Table 4.8 represents the cost calculation for the *Z_{13}: AMI and Business Services x Customer Premises*. The Z_{13} domain-ICT interaction has been selected since it is the interaction introduced just prior to 4.3. The cost calculation for the rest of the domain-ICT interactions can be found in the Excel spreadsheet tool named: *'Chapter 4_ICT Infrastructures Cost'*, tabs *Z_1- Z_{13}* accompanied with this report.

Table 4.8a: Qualitative ICT Objectives Cost Impacts for Domain-ICT Interaction Z_{13}

ICT Objectives	Resilience (K_R)	Maintenance and Support (K_M)	Privacy and Cyber Security (K_P)	Interoperability (K_I)		
Cost Impacts (0-10)	2.0	10.0	10.0	2.0		
Objectives Cost Impacts on Data Storage	0.0086	0.0432	0.0432	0.0086	**0.1037**	Additional ICT Qualitative Cost (€/GB)_Q_{ST}
Objectives Cost Impacts on Bandwidth	0.1354	0.6768	0.6768	0.1354	**1.6243**	Additional ICT Qualitative Cost (€/Mbps)_P_{BW}
Objectives Cost Impacts on Computational Power	0.0173	0.0864	0.0864	0.0173	**0.2074**	Additional ICT Qualitative Cost (€/GFLOPS)_Q_{CP}

Table 4.8b: ICT Qualitative and Quantitative Cost Trends at Different Time Horizons for Domain-

Time / ICT Components	Data Storage (€/GB)_C_{ST}	Bandwidth (€/Mbps)_C_{BW}	Computational Power (€/GFLOP)_C_{CP}
Present (2014)	0.1469	2.3011	0.2938
2020	0.1038	1.6675	0.2153
2030	0.1037	1.6248	0.2074
2040	0.1037	1.6243	0.2074
2050	0.1037	1.6243	0.2074

Table 4.8c: Total ICT Infrastructure Implementation Cost for Domain-ICT Interaction Z_{13}

Total Required Data Storage (GB)_E_{ST}	**Required Data Storage (GB) at Present**	**Required Data Storage (GB) by 2020**	**Required Data Storage (GB) by 2030**	**Required Data Storage (GB) by 2040**	**Required Data Storage (GB) by 2050**		
1.32E+07	7.31E+04	9.62E+05	3.00E+06	5.40E+06	3.75E+06		
Cost (€)	1.07E+04	9.99E+04	3.11E+05	5.59E+05	3.89E+05	1.37E+06	**Total Data Storage Cost (€)_T_{ST}**

Total Required Bandwidth (Mbps)_E_{BW}	**Required Bandwidth (Mbps) at Present**	**Required Bandwidth (Mbps) by 2020**	**Required Bandwidth (Mbps) by 2030**	**Required Bandwidth (Mbps) by 2040**	**Required Bandwidth (Mbps) by 2050**		
1254.1470	6.9515	91.5462	285.5748	513.2975	356.7771		
Cost (€)	15.9963	152.6552	463.9964	833.7618	579.5201	2045.9298	**Total Bandwidth Cost (€)_T_{BW}**

Total Required Computational Power (GFLOPS)_E_{CP}	**Required Computational Power (GFLOPS) at Present**	**Required Computational Power (GFLOPS) by 2020**	**Required Computational Power (GFLOPS) by 2030**	**Required Computational Power (GFLOPS) by 2040**	**Required Computational Power (GFLOPS) by 2050**		
1.00E+06	5.54E+03	7.30E+04	2.28E+05	4.09E+05	2.84E+05		
Cost (€)	1.63E+03	1.57E+04	4.72E+04	8.49E+04	5.90E+04	2.08E+05	**Total Computational Power Cost (€)_T_{CP}**
						1.58E+06	**Total ICT Infrastructure Qualitative and Quantitative Components Cost (€)_T**

Chapter 5: Scenario Assessment

The relationship between the ICT infrastructure, components and objectives was analysed in Stage 1 of the adopted methodology. It was clearly demonstrated how the relationship could have an impact on the cost of implementing ICT infrastructures in power system domains. This chapter comprises stage 2 of the adopted methodology, and presents the primary results that describe the impact and costs of ICT in relation to the five future scenarios selected in WP1 of the e-Highway2050 project [11]. Within each of the five scenarios, both the necessity of the various ICT infrastructures for enabling the scenario, as well as the cost quantification provided by the domain-ICT cost projection analysis are simultaneously considered. The five e-highway 2050 scenarios and the domain-ICT cost projection analysis serve as inputs to this stage of the adopted methodology.

In this manner, an in-depth analysis of the five scenarios was made and the summary is presented in Section 5.1. An analysis of potential benefits of smart grids implementations as related to the different scenarios was performed and consequently an inventory of benefits selected for inclusion in the present study is presented in Section 5.2. The quantification of each potential benefit was estimated based on clearly justifiable assumptions based on published national and regional studies, consequently, justified assumptions are presented in order to scale the quantification to the pan-European level. Where quantifications were available from different sources with regard to the same benefit category, the most justifiable quantification was considered. Therefore, the result of this intermediary stage was an inventory of potential benefits and their extreme quantification at the horizon 2050. These findings are presented in Section 5.3. Using the quantification of benefits identified previously, an estimation of the benefits was determined for each scenario, as a proportion of the extreme quantification of the potential benefits, based on the specifications of each scenario. It is important to note that the uptake of technology can also follow a range of trends. For example, the trend used in the analysis presented in Chapter 4 was based on exponential variation. The exponential characteristics from Chapter 3 were modified to model an investment strategy where asset investment is deferred, but once the large-scale uptake of technology begins, the growth is very rapid. In order to account for uncertainties regarding future developments of power grids, an additional trend were considered in this analysis. Another possibility is to assume that this trend is linear, modelling a steady uptake of ICT investments up to 2050. Therefore, with the modified cost trends and the linear technology deployment strategies described above, a new case has to be investigated in order to project the cost of ICT in 2050. The results of this analysis are presented in Section 5.4. Having these costs and the quantification of potential benefits for each of the five scenarios, the cost-benefit analysis can then take shape. This is summarized in Section 5.5.

5.1 e-Highway2050 Scenarios

Since all five scenarios established in WP1 [11] cover a wide range of possibilities for the future pan-European power system, the role of ICT infrastructures will be varied for each scenario. At this stage of methodology, it is essential to describe the scenarios specifications briefly in order to illustrate the impacts of ICT on each scenario. The detailed specification of each scenario was used in the assessment of potential benefits from different ICT infrastructure. These five scenarios are [11]:

- Big and Market (x-10)
- Large Fossil Fuel with CCS & NUC (x-13)
- Large Scale RES & No Emissions (x-5)
- 100% RES (x-7)
- Small and Local (x-16)

5.1.1 Big and Market (x-10)

In this scenario the CO_2 costs are high due to the existence of a global carbon market. Europe is fully committed to meet its 80-95% GHG reduction orientation by 2050 but it relies mainly on a market-based strategy [11].

Moreover, in this scenario, there is a special interest on large-scale centralized solutions, especially for RES deployment and storage. Public attitude towards deployment of RES technologies is indifferent in the EU, while acceptance of nuclear and shale gas, as energy sources, is positive since being preferred to decentralize local solutions. Electrification of transport, heating and industry are considered to occur mainly at centralized (large scale) level. Only a minor shift towards 'greener' behaviours is experienced in this scenario compared to present practices [11].

5.1.2 Large Fossil Fuel with CCS & NUC (x-13)

In this scenario, a global agreement for climate mitigation is achieved and Europe is fully committed to its target of 80-95% GHG reduction. Thus, CO_2 costs are high due to the existence of a global carbon market.

Europe is mainly following a non-RES strategy to reach this target. Acceptance of nuclear and shale gas, as energy sources is positive. Nuclear and fossil fuel plants with CSS play critical roles in achieving the 80-95% GHG targets without large scale RES deployment. There is a low focus on development of RES and storage solutions.

Electrification of transport, heating and industry are considered to occur mainly at centralized (large scale) level. Energy efficient options (including DSM and flexibility of EV use) are deployed only at medium level, mainly aiming at reducing energy demand. No further flexibility is needed since variable generation from PV and wind is low.

The energy strategy is deployed from a top-down approach at EU level with coordinated trans-national approaches based on a strong framework for policy and incentives, supporting market operation. In this case, Electricity exchanges with outside Europe are low.

5.1.3 Large Scale RES & No Emissions (x-5)

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

Similarly, a high priority is given to the development of centralized storage solutions (pumped hydro storage, compressed air, etc.), which accompanies the large-scale RES deployment. Decentralized storage solutions are considered to be insufficient. Nuclear technology as a centralized technology is included in this Scenario. However, no development in new nuclear technologies is assumed: the current level of deployment is maintained according to standard decommissioning rates for present nuclear plants up to 2050.

Electrification of Transport, Heating and Industry are considered to occur both at centralized (large scale) and decentralized (domestic) level. However, the political focus is mainly on the supply side. A low increase in energy efficient solutions is foreseen (including DSM and flexibility of EV use).

5.1.4 100% RES (x-7)

In this scenario, the global community has not succeeded in reaching a global agreement for climate mitigation. Yet, Europe is fully committed to its target of 80-95% GHG reduction and the CO_2 costs in EU are high due to these strict climate mitigation targets.

The strategy to achieve this target has a higher ambition than the other scenarios: it bases Europe's energy system entirely (100%) on renewable energy. To reach this target, both large scale and small-scale options are used: offshore wind parks in the North Sea and Baltic Seas and the Desertec project in North Africa, combined with EU- wide deployment of de-centralized RES (including CHP and Biomass) solutions.

Neither nuclear nor fossil fuels with CCS are used in this Scenario. Thus, both centralized storage solutions (pumped hydro storage, compressed air, etc.) and de-centralized solutions are needed to balance the variability in terms of renewable energy generation

On the consumer side, a marked increase in energy efficiency (including DSM and flexibility of EV use) is also needed. Electrification of transport, heating and industry are considered to occur both at centralized (large scale) and de-centralized (domestic) level and these solutions will reduce resulting energy demand as well as provide complementary flexibility and storage to account for variability of RES production from PV and wind.

5.1.5 Small and Local (x-16)

In this Scenario, the global community has not succeeded in reaching an agreement for climate mitigation. Yet, Europe is fully committed to meet its target of 80-95% GHG reduction. Compared to the other scenarios, the European member states have chosen a bottom-up strategy mainly based on small-scale/local solutions to reach this target.

Common agreements/rules for transnational initiatives regarding the operation of an internal EU market, EU wide security of supply and coordinated use of interconnectors for transnational energy exchanges do not exist. The focus is rather on local solutions dealing with de-centralized generation and storage and smart grid solutions at transmission and mainly on a distribution level.

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

According to the scenarios brief specifications, the considered ICT systems will have varied relevance and impacts. For instance, the role of ICT in the ‘Big and Market’ scenario (x-10) can be different as compared to the ‘Small and Local’ scenario (x-16). Thus, this stage should result in an analysis, which attempts to quantify the cost of a given ICT system (for example PMU deployment), within each of the scenarios. Taking PMU deployment as an ICT infrastructure example, the requirements for bandwidth and storage will emerge from high data-sampling rates and consequently large volumes of stored data. This must be weighed against the potential improvements to system operation, through improved situational awareness and greater knowledge of network stability.

5.2 Benefits Enabled through ICT

In order to consider the role of ICT infrastructures in the scenarios, a range of potential benefits that ICT can bring into future power systems are described in this section. The most significant benefits taken into consideration in this study can be listed as follows:

- Improved asset utilization
- Electricity loss reduction
- Electricity cost saving
- Improved Quality of Service
- Reduced CO_2 emissions

It is important to note that these benefits and their related sub-benefits have been selected according to several international studies published recently [61-67]. A description of each potential benefit is provided in the following subsections, and the references related to each sub-benefit have been cited.

5.2.1 Improved Asset Utilization

The ICT infrastructures can utilize the latest technologies to enable better asset maintenance and management. This utilization can be performed in two different ways: the short-term focuses on the day-to-day operations and the log-term focuses on the considerably long asset management process [61]. This benefit refers to the network point of view, both at transmission and distribution level.

In today's power system grid, the optimized real-time asset utilization is not typically available [61] specifically within the distribution network. In this case, the ability of adjust individual asset loadings is limited. At present the utilization of transformers at distribution substations is about 40% and at the transmission substations is around 50% [61]. Furthermore, condition-based maintenance (CBM) is a challenging task for the maintenance engineers, since they are facing with the lack of asset condition information. At present, the asset management is time-based rather than condition-based [61].

By integrating ICT in future power systems, the ability of controlling essential assets will increase significantly and asset failure rates can be reduced. In this case, the communication systems and advanced algorithms that analyse and diagnose asset condition will bring more observability in future power systems. Therefore, improved asset utilization can benefit operators, planners, and engineers to improve operational and asset management processes for a relatively small incremental cost. Therefore, the transmission and distribution (T&D) capital saving can increase and the transmission transfer capability can be enhanced without building additional transmission capacity [62].

In order to assess this benefit, during the analysis it was divided into a range of sub-benefits:

- Savings due to T&D investments and reduced capital costs [63]
- Automated Network Management (ANM) [63]
- Microgeneration [63]
- Avoided network reinforcement as a result of DSR [67]

5.2.2 Electricity Loss Reduction

Electricity losses are an unavoidable part of power systems. These losses can be results of technical inefficiencies within transmission and distribution networks, or non-technical losses, related to the diversion of electricity flow delivered to each consumer [68]. By integrating ICT in future power systems, the transmission and distribution networks can be more efficient; therefore, the network losses can be reduced. In this case, the increase in variable RI^2 - network losses – will be mitigated due to the improved load factor [67]. Furthermore, the value of customer minutes lost can be reduced [67].

Therefore, this benefit was divided into three sub-benefits during the analysis:

- The theft of electricity [63]
- Losses at distribution level [63]
- Losses reduced through the DSR [67]

5.2.3 Electricity Cost Saving

Comparing to the previous two benefits, this benefit takes into account the consumer side. ICT can reduce the power outages and cutting energy waste, thus saving money on customers' energy bills [62].

Future smart grids can help meet the demand for electricity while limiting the requirements to invest in new power plants. Furthermore, by rolling out smart meters within Europe, near real-time energy usage information and the ability to manage electricity usage can be provided to the consumers' level. In this case, they can save money and reduce their bills. Moreover, smart meters can eliminate the need for meter reading and the usage information can be transmitted directly to the utility for accurate billing. In this case the expenses to energy producers can be reduced and the need to costly standby power plants can decrease.

In order to perform the analysis, this benefit was be divided into a range of sub-benefits grouped in two categories:

- AMI:

- Efficient network investment [63]
- Time varying rates [65]
- Implementation of smart metering and remote meter reading [63]

- Business Services:

- Pre-payment cost to serve [63]
- Customer service overheads [63]
- Debt management [63]

5.2.4 Improved Quality of Service

By applying ICT in the future pan-European power system, the voltage quality performance of the grid can be enhanced and the voltage dips and voltage and frequency deviations can be reduced [64]. Furthermore, the loading of stressed assets will be reduced and their lives can be extended. Outage Management Systems (OMS) can greatly reduce outage duration [61]. Extended outages can be costly and cause a loss of revenue to supply companies and generators. In this case, advanced OMS can significantly help to detect, locate, diagnose, and isolate the outages more quickly. And finally, advanced Distribution Management Systems (DMS) can assist OMS to reconfigure system feeders to reduce the number of consumers affected by the outages in order to increase reliability, security and efficiency. In this case, better demand/generation connections can be facilitated [63].

Therefore, this benefit was divided into the following sub-benefits:

- Quality of supply [63]
- Outage Management Systems (OMS) [63,65]
- Fault location and isolation [65]

5.2.5 Reduced CO_2 Emissions

Future power systems can help to reduce damages as a result of lower Green House Gases (GHGs) emissions by consuming lower electricity from intelligent appliances and also lower T&D losses from optimized T&D network and also the integration of DERs in the power grid close to the load centre [65]. Furthermore, the reduced losses can enable a reduction in generation for a given load and this can result in reducing environmental emission [61]. Therefore, reduction in carbon emission can be considered as a benefit triggered by smart grids [63]. It important to note that it is a challenging task to distinguish between the benefits enabled exclusively through ICT, against the overall benefits related to the reduced CO_2 emission resulting from smart grids. Therefore, this benefit has not been taken into consideration with regard to the procedure for quantifying benefits.

5.2.6 Maximum Benefits Quantification

At this stage of methodology, it is essential to quantify the benefits described in previous sections. A benefit inventory was made based on several international studies published recently. Where the analysis was country-specific, the quantification was converted and scaled to the European level. According to [63,67,68], as part of the UK Smart Metering Implementation program, the Department of Energy and Climate Change (DECC) and Energy Network Association (ENA) have been investigating the cost and benefits of the energy industry of rolling out smart meters from 2014 onwards. It should be emphasized here that the benefits were components of an overall cost-benefit analysis and therefore the benefits quantification took into account investment in all assets, not only ICT. However, in order to derive the benefits of ICT for this study, there are two possible approaches: first, the ICT can be viewed as enabler of all benefits, as without ICT the whole system would not have had the maximum functionalities, and second, the pro rata approach, where the benefits are viewed as proportional to the investment effort in ICT only. We have assumed that the benefits enabled by the ICT infrastructures are proportional to the investment in ICT. However, it is important to note that ICT acts as an enabler technology that without deploying it in future power systems it won't be possible to achieve to the overall power system benefits. The benefits calculated in the studies used as literature for this analysis took into account the overall investment in smart grids. Therefore, calculations were necessary for each of the benefits listed previously.

It should be noted that these calculations were performed with a pro rata of 10% of benefits, denoted below ICT share. The values calculated below are per year, with the values calculated at the 2050 horizon, and are considered to be the maximum potential benefit. Each value considered, retrieved from the references indicated below, were selected from the best case scenario of each analysis. Furthermore, when multiple values were available for the same benefit in different literature sources, the maximum quantified benefit was selected for this study. According to the above descriptions and Table 5.1,

$H = 15$ sub-benefits enabled thorough ICT are taken into consideration. These benefits have been scaled to the European level, based on the EU/UK ratio identified in the previous chapter. Furthermore, the benefits are calculated based on the pro rata of 10%. This assumption is based on the premise that 10% of investments in smart grid technology is associated with novel ICT infrastructure. In this case, the maximum annual benefit enabled through ICT is denoted by:

$$B^{*}(\mathrm{k}), \forall k \in 1 \dots H, \quad E5.1$$

Improved Asset Utilization _ Savings due to avoided network reinforcement as result of DSR:

According to [67,68], the avoided cost of reinforcement due to improved load factor and asset utilization in the UK would be **£14.6875M** per year. In order to scale this value to European size, it is possible to use the EU/UK ratio, 9.05 assumed in Chapter 5 [56]. Also, it has been assumed that the exchange between Euro and GBP will be the as the current rate, which is: 1.22. Therefore, ICT monetary savings for Europe can be:

$B^{*}(1)$: *£14.6875M * 1.22 (Euro/GBP ratio) * 9.05 (EU/UK ratio) * 1,000,000 (million) * 0.1 (ICT share)* = **16.2 M€/y**

Improved Asset Utilization _ Savings due to avoided network reinforcement as result of ANM:

According to [68], the DNOs can save **£136M** on network reinforcements from ANM in the UK. In this case, the ICT monetary savings for Europe can be estimated as:

$B^{*}(2)$: *£136M * 1.22 (Euro/GBP ratio) * 9.05 (EU/UK ratio) * 1,000,000 (million) * 0.1 (ICT share)* = **150 M€/y**

Improved Asset Utilization _ Savings due to avoided network reinforcement as result of Microgeneration:

According to [63], using the assumption that in 2020, there will be around 1 million microgeneration devices in the UK power system, the cost savings is

£0.12 per year per meter. In this case, considering a deployment of 250 million meters in Europe by 2050 and maintaining the same number of microgeneration devices, the ICT monetary savings for Europe can be estimated as:

$B^*(3)$: *£0.12 * 1.22 (Euro/GBP ratio) * 250,000,000 (meters) * 0.1 (ICT share) =* **3.66 M€/y**

Electricity Loss Reduction _ Savings due to reduction of losses through reduction of Theft:

The implementation of smart metering can reveal existing theft and allow the power network to combat it. According to DECC [63], **£0.2** per meter per year can be saved. Therefore, ICT monetary savings for Europe can be:

$B^*(4)$: *£0.2 * 1.22 (Euro/GBP ratio) * 250,000,000 (meters) * 0.1 (ICT share) =* **6.1 M€/y**

Electricity Loss Reduction _ Savings due to reduction of losses at distribution level:

According to [67], **£0.5** per meter per year can saved at distribution level. In this case, the total savings due to reduction of losses at distribution level can be calculated as follows:

$B^*(5)$: *£0.5 * 1.22 (Euro/GBP ratio) * 250,000,000 (meters) * 0.1 (ICT share) =* **15.3 M€/y**

Electricity Loss Reduction _ Savings due to reduction of losses at transmission level:

Based on [67], the reduction in transmission network losses by employing smart grid technologies can result in **£2.4125M** savings in the UK per year. Therefore, ICT monetary savings for Europe can be estimated as:

$B^*(6)$: *£2.4125M * 1.22 (Euro/GBP ratio) * 9.05 (EU/UK ratio) * 1,000,000 (million) * 0.1 (ICT share) =* **2.66 M€/y**

Electricity Loss Reduction _ Savings due to reduction of network losses through DSR:

Based on [67], the savings due to reduction of network losses through DSR is **£1.94M** for the UK per year. Therefore, ICT monetary savings for Europe can be:

$B^*(7)$: *£1.94M * 1.22 (Euro/GBP ratio) * 9.05 (EU/UK ratio) * 1,000,000 (million) * 0.1 (ICT share)* = **2.15 M€/y**

Electricity Cost Saving _ AMI _ Efficient network investment due to use of smart metering data:

The total benefit is **£4.4M** per annum once the smart metering has been rolled out [63]. In this case, the ICT monetary savings for Europe can be:

$B^*(8)$: *£4.4M * 1.22 (Euro/GBP ratio) * 9.05 (EU/UK ratio) * 1,000,000 (million) * 0.1 (ICT share)* = **4.86 M€/y**

Electricity Cost Saving _ AMI _ due to time varying rates:

In future power systems, it is expected that the electricity tariffs will be more dynamic; therefore, by rolling out advanced metering infrastructures, based on [65], each customer can save **$19.98** per year. Therefore, ICT monetary savings for Europe can be estimated as:

$B^*(9)$: *$19.98 * 0.72 (Euro/Dollars ratio) * 250,000,000 (meters) * 0.1 (ICT share)* = **360 M€/y**

Electricity Cost Saving _ AMI _ due to remote meter readings:

Two benefits should be taken into consideration for remote metering [63]. One is avoided meter reading, which was quantified at **£6** per meter per year in the UK [63]. Also, [63] took into account avoided site visit. This benefit avoids special visits to read the meters or ad hoc safety inspections. Avoiding these benefits can bring an extra **£0.75** benefit per meter per year [63]. In this case, the total ICT monetary savings for Europe will be:

$B^{*}(10)$: *£6.75 * 1.22 (Euro/GBP ratio) * 250,000,000 (meters) * 0.1 (ICT share) =* **206 M€/y**

Electricity Cost Saving _ Improved Business Services _ customer service overheads:

Based on [63], the savings due to customer service overheads is **£2.2** per meter per year. Therefore, ICT monetary savings for Europe can be:

$B^{*}(11)$: *£2.2 * 1.22 (Euro/GBP ratio) * 250,000,000 (meters) * 0.1 (ICT share) =* **67.1 M€/y**

Electricity Cost Saving _ Improved Business Services _ debt management:

The assumed benefit for debt management is **£2.2** per meter per year [63]. Therefore, ICT monetary savings for Europe can be:

$B^{*}(12)$: *£2.2 * 1.22 (Euro/GBP ratio) * 250,000,000 (meters) * 0.1 (ICT share) =* **67.1 M€/y**

Quality of Service _ Savings due to improvement of quality of supply:

The assumed benefit for improvement of quality of supply is **£4.53** per DNO in the UK [68]. Since there are 14 DNOs in the UK, the ICT monetary savings for Europe can be extrapolated as:

$B^{*}(13)$: *£4.53 * 14 (UK DNOs number) * 1.22 (Euro/GBP ratio) * 9.05 (EU/UK ratio) * 1,000,000 (million) * 0.1 (ICT share) =* **70 M€/y**

Quality of Service _ Savings due to improvement of outage management:

The assumed benefit from outage management improvement is **£0.5M** per year in the UK [68]. Therefore, ICT monetary savings for Europe can be estimated as:

$B^{*}(14)$: *£0.5M * 1.22 (Euro/GBP ratio) * 9.05 (EU/UK ratio) * 1,000,000 (million) * 0.1 (ICT share) =* **0.552 M€/y**

Quality of Service _ Savings due to improvement of fault location and isolation:

The assumed benefit due to improvement of fault location and isolation is **$40.14** per customer per year [65]. Therefore, ICT monetary savings for Europe can be:

$B^{*}(15)$: *$40.14 * 0.72 (Euro/Dollars ratio) * 250,000,000 (meters) * 0.1 (ICT share) =* **723 M€/y**

Table 5.1 summarizes the maximum quantification estimated for each benefit and sub-benefit. In the next section, these benefits will be weighted based on the specification of each e-Highway2050 scenario. It should be noted that employing ICT infrastructures in power grids may enable other benefits, but as the advancements of technology in the future cannot be foreseen, a limited range of benefits can be accounted for at present time.

Benefits	Sub-benefits	Power System Total Monetary Savings (M€/year) at 2050	ICT Monetary Savings (M€/year) at 2050 (10% pro rata Total Benefit)_B*(k)
Improved Asset Utilization	Savings due to avoided network reinforcement as result of:		
	DSR	162	16.2
	ANM	1500	150
	Microgeneration	36.6	3.66
Electricity Loss Reduction	Savings due to reduction of losses through reduction of:		
	Theft	61	6.1
	Losses at distribution level	153	15.3
	Losses at transmission level	26.6	2.66
	Network losses through DSR	21.5	2.15
Electricity Cost Saving (consumer related)	Savings due to AMI:		
	Efficient network investment due to use of smart metering data	48.6	4.86
	Time varying rates	3600	360
	Remote meter readings	2060	206
	Savings due to Improved business services:		
	Customer service overheads	671	67.1
	Debt management	671	67.1
Quality of Service	Savings due to improvement of:		
	Quality of supply	700	70
	Outage management	5.52	0.552

Table 5.1: ICT Maximum Benefits

	Fault location and isolation	7230	723

5.3 Scenario-Specific Analysis

In Section 5.1 the specifications of the e-Highway 2050 scenarios were reviewed. At this step, the interaction between each ICT infrastructure and the scenarios will be assessed, where the potential benefits of ICT implementation will be considered, in order to analyse the ICT infrastructure deployment within the context of each scenario.

In the previous chapters the general domain-ICT interaction table was investigated. It was demonstrated how different ICT infrastructure can have impact on the power system domains. However, the role of ICT in different power system domains can be varied based on the specifications of each scenario. In this section, the five domain-ICT interaction tables will be introduced for each scenario in order to illustrate the role of different ICT infrastructure in power system domains. It is noticeable that at this point of methodology, only those ICT infrastructures that can have greater impact on the scenarios will be introduced and their impacts will be weighted in the next section.

According to Chapter 3, $R = 6$ ICT infrastructures are introduced in this study. Furthermore, $S = 5$ e-Highway2050 scenarios have been taken into consideration. As described above, at this point of methodology the impacts of those ICT infrastructures that have major role in providing 15 sub-benefits will be taken into consideration and assigned with a weighting factor, $W(r, s)$. These weighting factors are both scenario and ICT interaction dependent, thus:

$$W(r, s), r \in [1, R], s \in [1, S], \qquad E5.2$$

where: $0 \leq W(r, s) \leq 1$

This is designed such that a value of $\mathrm{W} = 0$ leads to no impact on the annual benefit from an ICT infrastructure for each scenario, and $\mathrm{W} = 1$ for any scenario leads to 100% impact in the annual benefits from a specific ICT interaction. The methodology permits the sum of $W(r, s)$ weighting factors for a given row in Table 5.2 to be different than 1, and the only constraint is that each individual $W(r, s)$weighting factor must be between 0 and 1.

In this case, the maximum annual value for each sub-benefit will be:

$$B(k,s) = \frac{\sum_{r=1}^{R} W(r,s)}{R} B^{*}(\mathrm{k}), k \ \in [1,H], s \ \in [1,S]. \qquad E5.3$$

Therefore, the scenario dependent maximum annual benefits can be calculated as follows:

$$B^{Max}(s) = \sum_{k=1}^{H} B(k,s)\,, s \ \in [1,S]. \qquad E5.4$$

5.3.1 Big and Market Scenario (x-10)

According to the specification of this scenario, the decisions are made from the market-based strategy. Also, large-scale centralized solutions such as RES play an important role in this scenario. Therefore, the role of "Energy Market Management and Trading Control" and "Weather Observation and Forecasting" ICT infrastructure can be significant in this scenario. Also, nuclear energy is preferred to the decentralized solution; thus, the role of "Advanced SCADA/EMS" and "WAMS" as two different ICT infrastructures can be major.

Since this is a market driven scenario, the electricity consumers can also play significant impact. Hence, the domain-ICT interaction table for this

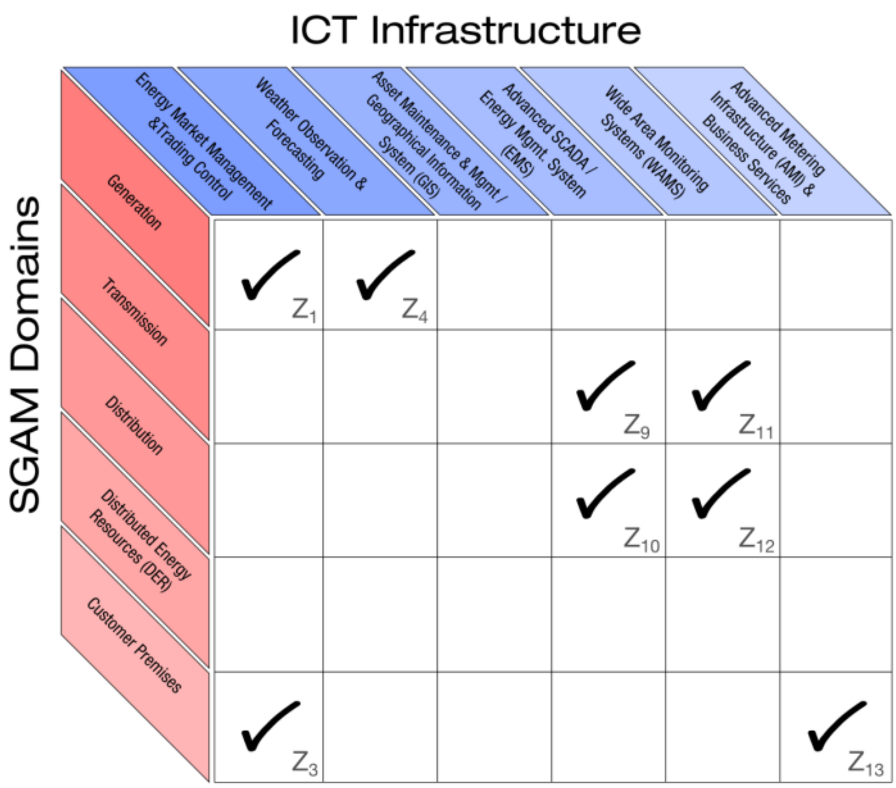


Figure 5.1: Domain-ICT Interactions, Scenario x-10

scenario can be presented as follows:

In the previous section the maximum ICT benefits were quantified. Based on the specification of each scenario and according to the domain-ICT interaction table the benefits of ICT for each e-Highway2050 scenario can be calculated by assigning different weightings (0-1) to each benefit. Table 5.2 illustrates the ICT benefits for the Big and Market scenario. As, it is a market-based scenario, the benefits of DSR, smart meters deployment, and time varying rates will be high. Furthermore, the savings due to the ANM and transmission and distribution losses will be significant as well, compared to other benefits. The values of the weights were assumed based on the estimated interaction between each ICT infrastructure and the scenario-specific benefits and on the scenario particulars. For example, the Big and Market scenario will enable improved asset utilization through market mechanisms, by demand response, but WAMS will play a more crucial role in enabling ANM. Therefore, a weight of 0.9 was assigned to the later. As DSR is enabled by AMI at customer level, a weight of 0.5 was assigned to this ICT infrastructure for the X-10 scenario.

Table 5.2: ICT Benefits, Scenario x-10

		ICT Infrastructure Impact Weights (0-1)							
Benefits	**Sub-benefits**	**Energy Market Management & Trading Control**	**Weather Observation and Forecasting**	**Asset Maintenance and Management/ GIS**	**Advanced SCADA/EMS**	**WAMS**	**AMI and Business Services**	**ICT Monetary Savings (M€/year)**	**Benefit Total Savings (M€/year)**
Improved Asset Utilization	Savings due to avoided network reinforcement as result of:								
	DSR	0.4					0.5	2.43	47.6
	ANM	0.1			0.8	0.9		45	
	Microgeneration	0.1	0.1					0.122	
Electricity Loss Reduction	Savings due to reduction of losses through reduction of:							0	
	Theft						0.2	0.203	3.96
	Losses at distribution level				0.6	0.6		3.05	
	Losses at transmission level				0.7	0.9		0.71	
	Network losses through DSR							0	
Electricity Cost Saving (consumer related)	Savings due to AMI:							0	
	Efficient network investment due to use of smart metering data						0.5	0.405	126
	Time varying rates	0.9					0.8	102	
	Remote meter readings						0.5	17.2	
	Savings due to Improved business services:							0	
	Customer service overheads						0.3	3.36	
	Debt management						0.3	3.36	
Quality of Service	Saving due to improvement of:							0	
	Quality of supply		0.3				0.4	8.17	165
	Outage management				0.5	0.4	0.4	0.12	
	Fault location and isolation				0.5	0.4	0.4	157	

B^{Max} (s): 343	**Total ICT Benefit (M€/year)**

5.3.2 Large Fossil Fuel with CCS and Nuclear Scenario (x-13)

According to the specification of this scenario, Europe is mainly following the non-RES strategy; therefore, the role of "Energy Market Management and Trading Control" infrastructure in generation domain will be significant. Furthermore, the share of large fossil fuels power plants with CCs and also nuclear will be significant. In this case, the "Asset Maintenance and Management/GIS" ICT infrastructure plays an important role in both generation and distribution domains. "Advanced SCADA/EMS" and "WAMS" can play major role in the transmission domain. Hence, the domain-ICT interaction table for this scenario can be presented as follows:

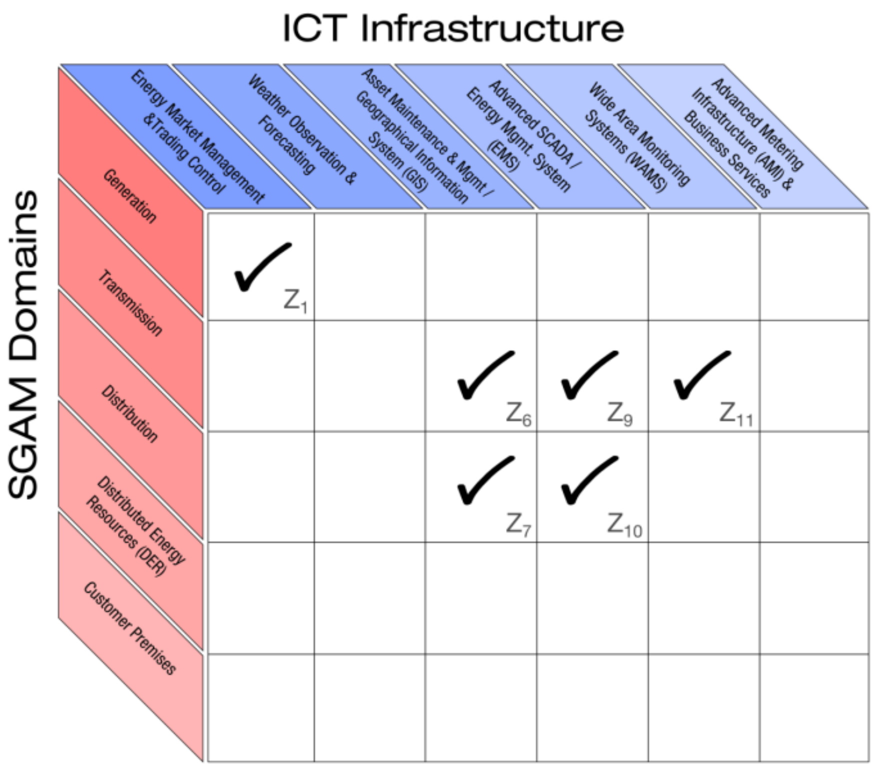


Figure 5.2: Domain-ICT Interactions, Scenario x-13

Following the same reasoning presented for scenario X-10, the ICT impact weights were assigned for this scenario also. Table 5.3 illustrates the ICT benefits for the Large Fossil Fuel with CCS and Nuclear scenario. Since the asset management and maintenance, alongside advanced SCADA/EMS infrastructures play significant role; therefore, the savings due to the outage management, fault location and isolation, theft and ANM are significantly higher compare to other benefits.

Table 5.3: ICT Benefits, Scenario x-13

		ICT Infrastructure Impact Weights (0-1)							
Benefits	**Sub-benefits**	**Energy Market Management & Trading Control**	**Weather Observation and Forecasting**	**Asset Maintenance and Management/ GIS**	**Advanced SCADA/EMS**	**WAMS**	**AMI and Business Services**	**ICT Monetary Savings (M€/year)**	**Benefit Total Savings (M€/year)**
Improved Asset Utilization	Savings due to avoided network reinforcement as result of:								
	DSR	0.2						0.541	35.6
	ANM			0.8	0.3	0.3		35	
	Microgeneration							0	
Electricity Loss Reduction	Savings due to reduction of losses through reduction of:							0	
	Theft			0.2			0.5	0.712	0.8
	Losses at distribution level							0	
	Losses at transmission level			0.2				0.0888	
	Network losses through DSR							0	
Electricity Cost Saving (consumer related)	Savings due to AMI:							0	
	Efficient network investment due to use of smart metering data							0	17.2
	Time varying rates							0	
	Remote meter readings						0.5	17.2	
	Savings due to Improved business services:							0	
	Customer service overheads							0	
	Debt management							0	
Quality of Service	Saving due to improvement of:							0	
	Quality of supply							0	157
	Outage management			0.2	0.5	0.4		0.101	
	Fault location and isolation			0.4	0.5	0.4		157	

B^{Max} (s): 210	**Total ICT Benefit (M€/year)**

5.3.3 Large Scale RES and No Emissions Scenario (x-5)

According to the specification of this scenario, RES play major role. In this case, “Energy Market Management and Trading Control” infrastructure have key impacts on both generation and DER domains. Furthermore, “Weather Observation and Forecasting” can play vital role in this scenario.

“Asset Maintenance and Management/GIS” and “Advanced SCADA/EMS” ICT infrastructure can have major impacts on the transmission and DER domains, since a huge amount of electricity should be transported from long distances, such as North Sea, to the load centres. In this case, “WAMS” play

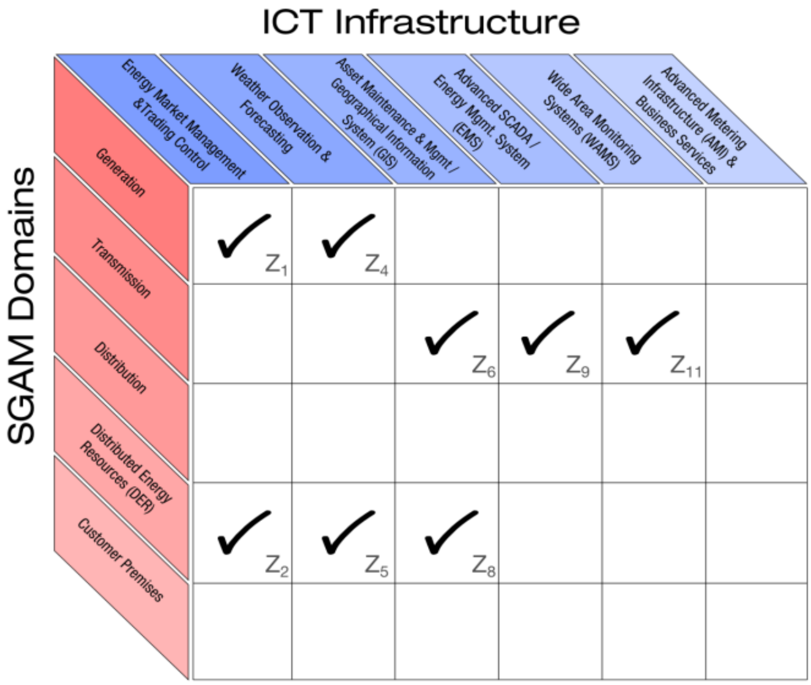


Figure 5.3: Domain-ICT interactions, Scenario x-5

major role in the transmission domain.

Table 5.4 illustrates the ICT benefits for the Large Fossil Fuel with CCS and Nuclear scenario. Although this scenario represents large scale RES; therefore, the role of microgeneration has been considered. However, it has been assigned with a relatively low weighting factor. In this case the benefits from ANM and DSR are higher.

Table 5.4: ICT Benefits, Scenario x-5

Benefits	Sub-benefits	ICT Infrastructure Impact Weights (0-1): Energy Market Management & Trading Control	Weather Observation and Forecasting	Asset Maintenance and Management/ GIS	Advanced SCADA/EMS	WAMS	AMI and Business Services	ICT Monetary Savings (M€/year)	Benefit Total Savings (M€/year)
Improved Asset Utilization	Savings due to avoided network reinforcement as result of:								
	DSR	0.3		0.4	0.5			3.24	56.3
	ANM	0.7		0.2	0.6	0.6		52.6	
	Microgeneration	0.2	0.2	0.1	0.2	0.2		0.549	
Electricity Loss Reduction	Savings due to reduction of losses through reduction of:							0	
	Theft							0	0.516
	Losses at distribution level							0	
	Losses at transmission level			0.4	0.3	0.3		0.444	
	Network losses through DSR			0.2				0.716	
Electricity Cost Saving (consumer related)	Savings due to AMI:							0	
	Efficient network investment due to use of smart metering data							0	0
	Time varying rates							0	
	Remote meter readings							0	
	Savings due to Improved business services:							0	
	Customer service overheads							0	
	Debt management							0	
Quality of Service	Saving due to improvement of:							0	
	Quality of supply		0.2			0.3		5.84	54.1
	Outage management			0.5	0.4			0.0828	

	Fault location and isolation					0.4		48.2		
									B^{Max} (s): 111	**Total ICT Benefit (M€/year)**

5.3.4 100% RES Scenario (x-7)

This is the most extreme e-Higwhay2050 scenario. According to the specification of this scenario, RES play significant role. In order to achieve to this target both centralized and decentralized RES should be taken into consideration. Also, energy efficiency including DMS is also needed. Therefore, most of the ICT infrastructure play key role in different power system domains.

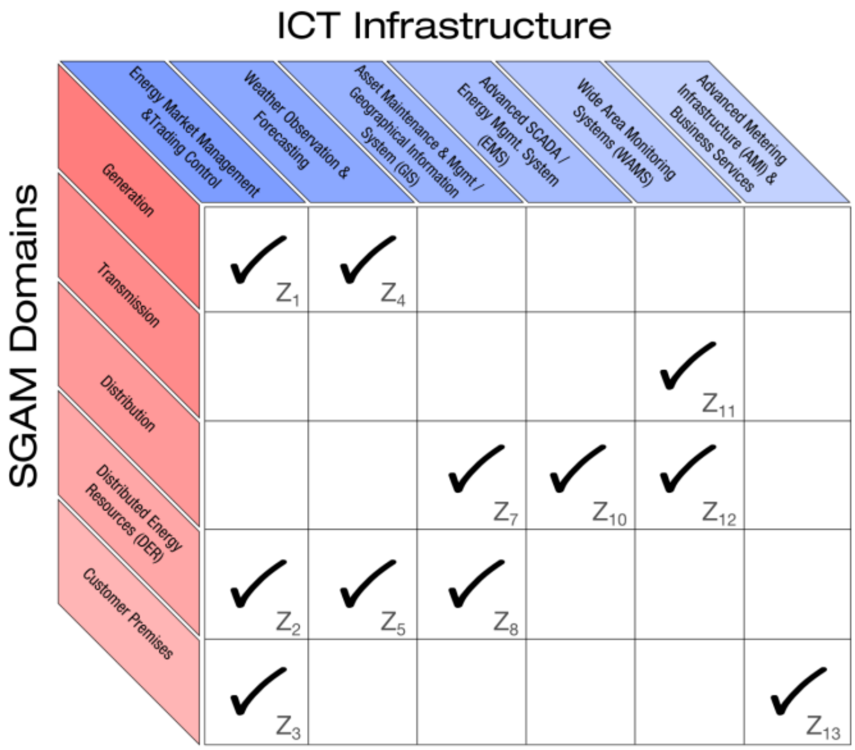


Figure 5. 4: Domain-ICT Interactions Scenario x-7

Table 5.5 illustrates the ICT benefits for the 100% RES scenario. In this scenario the efficiency is very high (as it results from Figure 1.4). Therefore, the savings from reduction of theft, losses in transmission and distribution levels, and also network losses through DSR are high. Furthermore, the benefits coming from microgeneration, DSR are large as well. The ICT infrastructures that are estimated to enable savings due to loss reduction in a 100% RES scenario are mainly Advanced SCADA/EMS, WAMS and AMI. Therefore the weights of these ICT infrastructures were chosen as shown in Table 5.5. Furthermore, improved asset utilization through the use of the

Asset Maintenance and Management/GIS ICT infrastructure is considered to be very high in this scenario.

		ICT Infrastructure Impact Weights (0-1)							
Benefits	**Sub-benefits**	**Energy Market Management & Trading Control**	**Weather Observation and Forecasting**	**Asset Maintenance and Management/ GIS**	**Advanced SCADA/EMS**	**WAMS**	**AMI and Business Services**	**ICT Monetary Savings (M€/year)**	**Benefit Total Savings (M€/year)**
Improved Asset Utilization	Savings due to avoided network reinforcement as result of:								
	DSR	0.9		0.9			0.8	7.03	31.7
	ANM			0.7			0.2	22.5	
	Microgeneration	0.9	0.9	0.9			0.9	2.2	
Electricity Loss Reduction	Savings due to reduction of losses through reduction of:							0	
	Theft						0.7	0.712	6.68
	Losses at distribution level				0.6	0.7	0.4	4.32	
	Losses at transmission level				0.7	0.8	0.2	0.755	
	Network losses through DSR				0.9	0.9	0.7	0.895	
Electricity Cost Saving (consumer related)	Savings due to AMI:							0	
	Efficient network investment due to use of smart metering data						0.7	0.567	124
	Time varying rates	0.7					0.7	83.9	
	Remote meter readings						0.7	24	
	Savings due to Improved business services:							0	
	Customer service overheads						0.7	7.83	
	Debt management						0.7	7.83	
Quality of Service	Saving due to improvement of:							0	
	Quality of supply					0.6	0.1	8.17	80.5
	Outage management			0.3	0.5		0.1	0.0828	
	Fault location and isolation			0.3		0.2	0.1	72.3	

Table 5.5: ICT Benefits, Scenario x-7

B^{Max} (s): 243	Total ICT Benefit (M€/year)

5.3.5 Small and Local Scenario (x-16)

According to the specification of this scenario, the EU member states have chosen the strategy mainly based on the small and local solutions dealing with decentralized generation, storage, and smart grid solutions mainly on the distribution level. Therefore, "Energy Market Management and Trading Control" play major role only in the customer premises domain. Furthermore, the "Weather Observation and Forecasting" ICT infrastructure has an impact on the DER domain. Moreover, the impacts of the "Asset Maintenance and Management/GIS" infrastructure on the distribution and DER domains will be major. "Advanced SCADA/EMS" infrastructure within distribution level play significant role, while the "WAMS" has major impacts on both transmission and distribution domains. Finally, the "AMI and Business Services" ICT

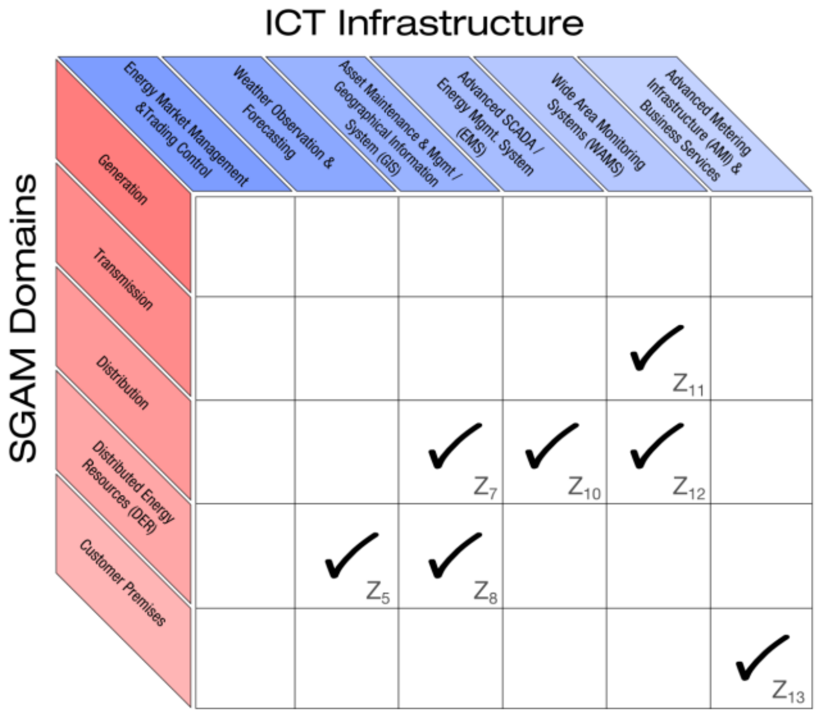


Figure 5. 5: Domain-ICT Interactions Scenario x-16

infrastructure play an important role in this scenario.

Table 5.6 illustrates the ICT benefits for the Small and Local scenario. Since this scenario is considering decentralized solution; therefore, the benefits from DSR, microgeneration, and reduction of losses in distribution level are very high. Furthermore, the savings due to AMI and business services have been assigned with high weights.

Table 5.6: ICT Benefits, Scenario x-16

		ICT Infrastructure Impact Weights (0-1)							
Benefits	**Sub-benefits**	**Energy Market Management & Trading Control**	**Weather Observation and Forecasting**	**Asset Maintenance and Management/ GIS**	**Advanced SCADA/E MS**	**WAMS**	**AMI and Busines s Services**	**ICT Monetary Savings (M€/year)**	**Benefit Total Savings (M€/year)**
Improved Asset Utilization	Savings due to avoided network reinforcement as result of:								
	DSR							0	3.66
	ANM							0	
	Microgeneration		0.5	0.5				3.66	
Electricity Loss Reduction	Savings due to reduction of losses through reduction of:								
	Theft							0	23.1
	Losses at distribution level			0.7	0.2	0.3		18.3	
	Losses at transmission level				0.3	0.6		2.4	
	Network losses through DSR	0.2			0.7	0.2		2.36	
Electricity Cost Saving (consumer related)	Savings due to AMI:								
	Efficient network investment due to use of smart metering data						0.9	4.37	8.74
	Time varying rates		0.3				0.9	432	
	Remote meter readings						0.9	185	
	Savings due to Improved business services:								
	Customer service overheads						0.7	47	
	Debt management						0.7	47	
Quality of Service	Saving due to improvement of:								
	Quality of supply		0.4					28	679
	Outage management			0.3			0.7	0.552	
	Fault location and isolation			0.3			0.6	650	
									B^{Max} (s): 714 **Total ICT Benefit**

(M€/year)

5.4 Cost Projection Hypothesis for the e-Highway2050 Scenarios

In the previous chapter, the cost trends of three physically quantitative ICT components were investigated. It was presented how much these three quantitative ICT components will cost at different time horizons. According to these projections based on historical data, the cost of ICT components will be extremely cheap. However, it is essential to note that there are other external costs that can have major influence in the future cost of ICT deployments, such as price of electricity for cooling devices, cost of expert human resources, etc. According to Figure 4.6, the share of purchased quantitative ICT components for each ICT infrastructure will exponentially increase at intermediate time horizons, where in each successive time period, the rate of ICT deployment is increasing. This strategy permits more ICT infrastructure to be purchased closer to the 2050 time horizon, which will enable significant cost savings due to the deflationary nature of ICT components costs. However, at this point of methodology, a new linear purchasing curve has been taken into consideration in order to illustrate different future purchasing strategies and highlight the comparative cost differences between different strategies that might be adopted in the deployment of ICT infrastructures in future power systems.

By considering the linear purchasing curve, a significant share of required ICT components will be purchased closer to present time at much higher prices. However, by considering the exponential curve, a greater share of required ICT components can be purchased in future up to 2050, as and when the prices are relatively cheaper. The assumption made for linear purchasing is that the rate of purchasing doesn’t change over the time up to 2050. Figure 5.6 presents the linear purchasing trend.

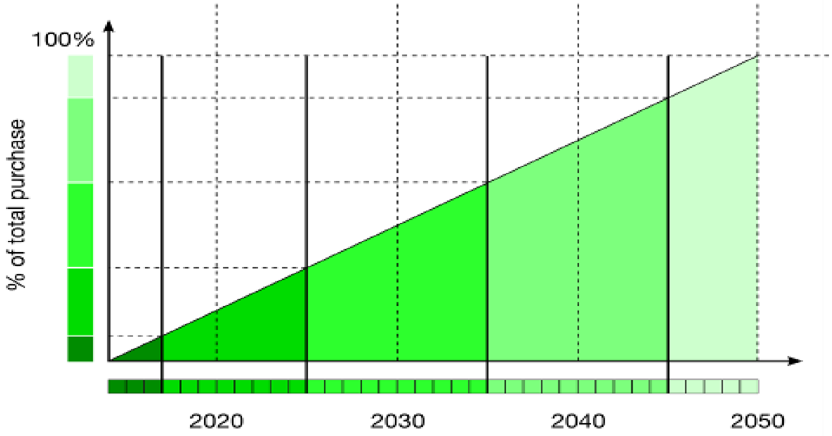


Figure 5.6: Linear Purchasing Curve

Table 5.7 presents the percentage and total purchased ICT components at different intermediate time horizons.

Table 5.7: Linear Purchase Trend

Linear Purchase Trend

	Present	2020	2030	2040	2050
Purchase Percentage	8.33%	22.22%	27.78%	27.78%	13.89%
Total Purchased	8.33%	30.55%	58.33%	86.11%	100%

Therefore, in order to present the impacts of different purchasing strategies, two assumptions have been considered:

- **Exponential Purchase:** It was assumed in Chapter 4 that the significant share of required ICT components would be purchased at cheap prices when compared to linear purchase assumption. Therefore, it is expected that the cost of implementing ICT infrastructures will be cheaper.
- **Linear Purchase:** Since the ICT components purchasing curve has been assumed to be linear, therefore, it is expected that the cost of implementing ICT infrastructures will be higher compare to the previous assumption.

According to the five scenarios descriptions and the role of each ICT infrastructure in different scenarios (Figures 5.1-5.5), the cost of implementing ICT infrastructure for different scenarios at each power system domain based on the above two assumptions can be calculated. The results of this section have been included in the accompanying spreadsheet.

5.5 Summary of Costs and Benefits for the e-Highway2050 Scenarios

In chapter 4, the cost of implementing ICT infrastructure for different power system domains was analysed. In the costing presented in Chapter 4, the purchasing curve was assumed to be exponential. In the previous section, the purchasing curve was also assumed to be linear in order to analyse different approaches in smart grid investments.

At this point of methodology, it is possible to calculate the cost of implementing ICT infrastructures in different e-Highway2050 scenarios based on the domain- ICT interaction table for each scenario and compare them with the benefits associated with that scenario. We are assuming that the benefits from implementing ICT infrastructure are cumulative. The ICT benefits at present are relatively low compared to the benefits at future time horizons. As shown in Figure 5.7, the ICT purchases at each time step follow the

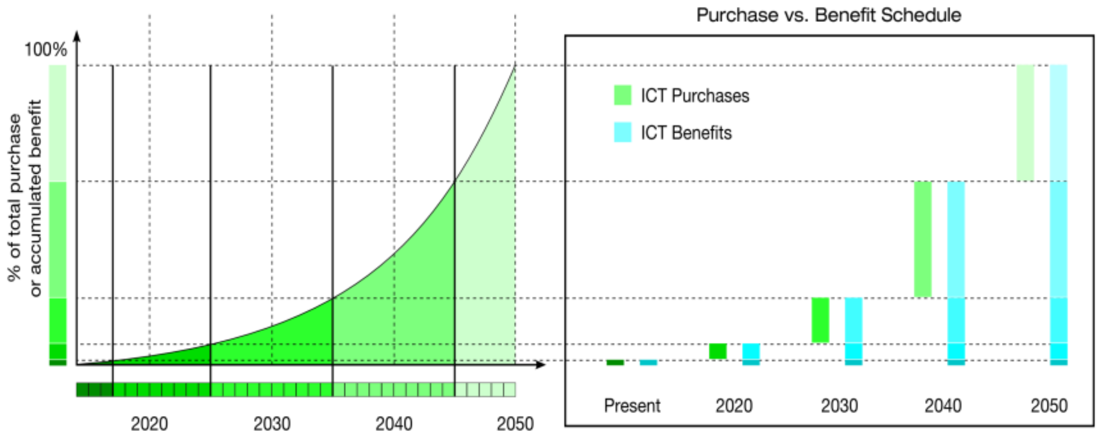


Figure 5.7: ICT Purchases vs. Benefits

purchasing trend, whereas the benefits enabled by ICT are accumulating over the years.

The benefit presented for each scenario (Tables 5.2-5.6) was the maximum annual benefit at 2050. In order to compare the costs of implementing ICT infrastructures with the benefits enabled exclusively through ICT within a scenario, it is essential to calculate the benefits from today up to 2050. While the costs of purchasing the ICT infrastructure are incurred incrementally, it is reasonable to expect the positive benefits of ICT infrastructure development to be cumulative. In this case, we have assumed that the benefits are cumulative and exponentially increase over the time (Figure 5.7). Therefore, while the incremental purchase plan was defined by $D(i)$, it has been assumed that the model for the accumulation of benefits $A(i)$ is similar to the physically quantitative ICT components exponential purchasing curve introduced in Chapter 4; therefore, the total benefits percentages at different time steps are the same as the values in Table 4.7:

$$A(i) = \sum_{1}^{i} D(i), i \in [1, N]. \qquad E5.5$$

The estimated benefits U for a given scenario s during time interval i can be defined by combining the scenario-specific maximum annual benefit$B^{Max}(s)$, the benefit accumulation model $A(i)$, and the interval lengths $L(i)$.

$$U(i, s) = L(i)\, A(i) B^{Max}(s), i \in [1, N], s \in [1, S]. \qquad E5.6$$

Considering all N time intervals yields the estimate of the total benefit V for a given scenario s as:

$$V(s) = \sum_{i=1}^{N} U(i, s),\ s \in [1, S]. \qquad E5.7$$

5.5.1 ICT Infrastructures Implementation Cost and Benefits for Scenario x-10

According to the domain-ICT interactions for the Big and Market Scenario, Figure 5.1, both the total cost of implementing ICT infrastructures over 36 years for both linear and exponential purchasing strategies can be calculated. As illustrated in Figure 5.1, based on the specification of this scenario there are 8 interactions between power system domains and ICT infrastructures. For illustration purposes, the first interaction *Z_1: Energy Market Management and Trading Control x Generation* has been represented in Table 5.8a. In this case, the complete implementation cost of ICT infrastructures for both exponential and linear purchasing strategies can be calculated for the rest of the interactions, Table 5.8b.

Additionally, the total cumulative benefit over 36 years has been calculated (according to E5.7 and Table 4.7) and compared with the total cost of implementing ICT infrastructure associated with this scenario (Table 5.9). This procedure has been applied to all the scenarios and more detailed calculations can be found in the attached interactive Excel tool accompanying the Task 3.2.8 report.

Table 5.8a: Cost calculation for Z_1 Domain-ICT interaction for scenario x-10 considering both exponential and linear purchasing strategies

	Total Required Data Storage (GB)_E_{ST}	**Required Data Storage (GB) at Present**	**Required Data Storage (GB) by 2020**	**Required Data Storage (GB) by 2030**	**Required Data Storage (GB) by 2040**	**Required Data Storage (GB) by 2050**		
Chapter 4 Analysis	**3.26E+05**	1.81E+03	2.38E+04	7.42E+04	1.33E+05	9.27E+04		
	Cost (€)	2.81E+02	2.68E+03	8.34E+03	1.50E+04	1.04E+04	3.67E+04	**Total Data Storage Cost (€)_T_{ST}**
Linear Purchase	**3.26E+05**	2.72E+04	7.24E+04	9.05E+04	9.05E+04	4.53E+04		
	Cost (€)	4.22E+03	8.14E+03	1.02E+04	1.02E+04	5.08E+03	3.78E+04	**Total Data Storage Cost (€)_T_{ST}**

	Total Required Bandwidth (Mbps)_E_{BW}	**Required Bandwidth (Mbps) at Present**	**Required Bandwidth (Mbps) by 2020**	**Required Bandwidth (Mbps) by 2030**	**Required Bandwidth (Mbps) by 2040**	**Required Bandwidth (Mbps) by 2050**		
Chapter 4 Analysis	**31.0063**	0.1719	2.2633	7.0603	12.6902	8.8206		
	Cost (€)	0.4187	4.0805	12.4270	22.3308	15.5214	54.7785	**Total Bandwidth Cost (€)_T_{BW}**
Linear Purchase	**31.0063**	2.5839	6.8903	8.6128	8.6128	4.3064		
	Cost (€)	6.2955	12.4223	15.1598	15.1559	7.5779	56.6115	**Total Bandwidth Cost (€)_T_{BW}**

	Total Required Computational Power (GFLOPS)_E_{CP}	**Required Computational Power (GFLOPS) at Present**	**Required Computational Power (GFLOPS) by 2020**	**Required Computational Power (GFLOPS) by 2030**	**Required Computational Power (GFLOPS) by 2040**	**Required Computational Power (GFLOPS) by 2050**		
Chapter 4 Analysis	**1.00E+06**	5.54E+03	7.30E+04	2.28E+05	4.09E+05	2.84E+05		
	Cost (€)	1.72E+03	1.70E+04	5.12E+04	9.19E+04	6.39E+04	2.26E+05	**Total Computational Power Cost (€)_T_{CP}**
Linear Purchase	**1.00E+06**	8.33E+04	2.22E+05	2.78E+05	2.78E+05	1.39E+05		
	Cost (€)	2.59E+04	5.17E+04	6.24E+04	6.24E+04	3.12E+04	2.34E+05	**Total Computational Power Cost (€)_T_{CP}**
							2.62E+05	**Exponential Purchase Total ICT Infrastructure Qualitative and Quantitative Components Cost (€)_T**
							2.71E+05	**Linear Purchase Total ICT Infrastructure Qualitative and Quantitative Components Cost (€)_T**

Table 5.8b: Total costs of implementing ICT infrastructures over 36 years for both exponential and linear purchasing strategies for scenario x-10 considering all the relevant domain-ICT interactions

	Z1	**Z3**	**Z4**	**Z9**	**Z10**	**Z11**	**Z12**	**Z13**	**Total**
Scenario x10 Cost (Exponential Purchase) (M€)	0.262	1.78	875	0.404	0.752	7.42	27	1.58	914

Scenario x10 Total Cost (Linear Purchase) (M€)	0.271	1.84	954	0.415	0.771	7.59	27.6	1.63	994

Table 5.9: Scenario x-10 ICT Infrastructures Costs and Benefits

	Cost Over 36 Years (M€) - Exponential Purchase	Cost Over 36 Years (M€) - Linear Purchase	Benefits Over 36 Years (M€)_ V(s)
Big and Market Scenario x-10	914	994	5430

Both the exponential and linear costs have been estimated based on the specifications of scenario x-10 and relevant ICT infrastructures introduced in Figure 5.1. These values are based on the cost of implementing ICT infrastructure considering based on the physical ICT components cost and qualitative cost of ICT objectives for each ICT infrastructure. As presented, if the purchasing behaviour is linear, the cost of implementing ICT infrastructures for this scenario is higher compare to the exponential curve, where great share of ICT will be purchased close to 2050 time horizon at cheaper prices.

It is important to note that the as calculated in Chapter 4, the cost of implementing the *Weather Forecasting and Observation* ICT infrastructure is very expensive. Compared to other ICT infrastructures, the application of this ICT infrastructure is not only for energy sector. Other sectors such as agriculture, entertainment, construction, transportation, retailing, and municipalities are making benefits from this infrastructure [69]. Normally, governmental agents can fund such an expensive ICT infrastructure. In this case, it has been assumed that the share of power system for this ICT infrastructure for all scenarios is 10%.

Since the benefits per year have been calculated for each scenario; therefore, it is possible to calculate the payback period relative to the 2050 time horizon. This metric can be called *2050 relative payback period.* The 2050 relative payback period is a financial metric for evaluating the consequences of investments relative to the 2050 time horizon. Since we have calculated the maximum annual benefit for 2050 for each scenario;

therefore, it is possible to calculate the number of years that we can get the benefits from 2050:

$$2050\ Relative\ Payback\ Period\ Years = \frac{Costs\ Over\ 36\ Years\ (\text{M€}) - Benefits\ Over\ 36\ Years(\text{M€})}{Maximum\ Annual\ Benefits\ \ (\text{M€/year})} \quad 5.8$$

Therefore, the required years for returning the investments for exponential purchase for scenario x-10 relative to 2050 are:

$$\frac{914 - 5430}{343} = -13.2\ Years \quad 5.9$$

Therefore, the ICT investments for this scenario can be recovered 13 years before 2050. This is because of the specification of this scenario, which is a market led scenario. Furthermore, the traditional payback period can be calculated relative to the present time. In this case, the traditional payback period for this scenario is: (2050 – 2014) + (–13.2) = **22.8 years.**

5.5.2 ICT Infrastructures Implementation Cost and Benefits for Scenario x-13

In this case, for the Large Fossil Fuel with CCS and Nuclear Scenario (x-13), both the linear and exponential total cost of implementing ICT infrastructures over 36 years have been presented in Table 5.10. Furthermore, the total benefit over 36 years has been calculated.

Table 5.10: Scenario x-13 ICT Infrastructures Costs and Benefits

Large Fossil Fuel with CCS and Nuclear Scenario x-13	Cost Over 36 Years (M€) - Exponential Purchase	Cost Over 36 Years (M€) - Linear Purchase	Benefits Over 36 Years (M€)_V(s)
	16.3	16.7	3330

Both the exponential and linear costs have been estimated based on the specifications of scenario x-13 and relevant ICT infrastructures introduced in Figure 5.2. These values are based on the cost of implementing ICT infrastructure considering based on the physical ICT components cost and qualitative cost of ICT objectives for each ICT infrastructure. As presented, if the purchasing behaviour is linear, the cost of implementing ICT infrastructures for this scenario is higher compare to the exponential curve, where great share of ICT will be purchased close to 2050 time horizon at cheaper prices.

Therefore, the required years for returning the investments for exponential purchase for scenario x-13 relative to 2050 are:

$$\frac{16.3 - 3330}{210} = -15.8\, Years \qquad 5.10$$

Hence, the ICT investments for this scenario can be recovered about 16 years before 2050. This is because of the specification of this scenario, in which renewable energy does not play significant role in this scenario and the efficiency is low. Furthermore, the traditional payback period can be calculated relative to the present time. In this case, the traditional payback period for this scenario is: (2050 – 2014) + (–15.8) = **20.2 years.**

5.5.3 ICT Infrastructures Implementation Cost and Benefits for Scenario x-5

In this case, for the Large Scale RES Scenario (x-5), both the linear and exponential total cost of implementing ICT infrastructures over 36 years have been presented in Table 5.11. Furthermore, the total benefit over 36 years has been calculated.

Table 5.11: Scenario x-5 ICT Infrastructures Costs and Benefits

Large Scale RES and No Emission Scenario x-5	Cost Over 36 Years (M€) - Exponential Purchase	Cost Over 36 Years (M€) - Linear Purchase	Benefits Over 36 Years (M€)_V(s)
	9630	10500	1760

Both the exponential and linear costs have been estimated based on the specifications of scenario x-5 and relevant ICT infrastructures introduced in Figure 5.3. These values are based on the cost of implementing ICT infrastructure considering based on the physical ICT components cost and qualitative cost of ICT objectives for each ICT infrastructure. As presented, if the purchasing behaviour is linear, the cost of implementing ICT infrastructures for this scenario is higher compare to the exponential curve, where great share of ICT will be purchased close to 2050 time horizon at cheaper prices.

Therefore, the required years for returning the investments for exponential purchase for scenario x-5 relative to 2050 are:

$$\frac{9630 - 1760}{111} = 70.9\,Years \qquad 5.11$$

Hence, the ICT investments for this scenario can be recovered about 71 years after 2050. This is because of the specification of this scenario, in which centralized RES play significant role in this scenario. Furthermore, the traditional payback period can be calculated relative to the present time. In this case, the traditional payback period for this scenario is: (2050 – 2014) + 70.9 = **106.9 years.**

5.5.4 ICT Infrastructures Implementation Cost and Benefits for Scenario x-7

In this case, for the 100% RES Scenario (x-7), both the linear and exponential total cost of implementing ICT infrastructures over 36 years have been presented in Table 5.12. Furthermore, the total benefit over 36 years has been calculated.

Table 5.12: Scenario x-7 ICT Infrastructures Costs and Benefits

100% RES Scenario x-7	Cost Over 36 Years (M€) - Exponential Purchase	Cost Over 36 Years (M€) - Linear Purchase	Benefits Over 36 Years (M€)_V(s)
	9640	10500	3860

Both the exponential and linear costs have been estimated based on the specifications of scenario x-7 and relevant ICT infrastructures introduced in Figure 5.4. These values are based on the cost of implementing ICT infrastructure considering based on the physical ICT components cost and qualitative cost of ICT objectives for each ICT infrastructure. As presented, if the purchasing behaviour is linear, the cost of implementing ICT infrastructures for this scenario is higher compare to the exponential curve, where great share of ICT will be purchased close to 2050 time horizon at cheaper prices.

Therefore, the required years for returning the investments for exponential purchase for scenario x-7 relative to 2050 are:

$$\frac{9640-3860}{243} = 23.8\,Years \qquad 5.12$$

Hence, the ICT investments for this scenario can be recovered about 24 years after 2050. This is because of the specification of this scenario, in which RES play significant role in this scenario. Furthermore, the traditional payback period can be calculated relative to the present time. In this case, the traditional payback period for this scenario is: (2050 – 2014) + 23.8 = **59.8 years.**

Small and Local Scenario x-16	Cost Over 36 Years (M€) - Exponential Purchase	Cost Over 36 Years (M€) - Linear Purchase	Benefits Over 36 Years (M€)_V(s)

5.5.5 ICT Infrastructures Implementation Cost and Benefits for Scenario x-16

In this case, for the Small and Local Scenario (x-6), both the linear and exponential total cost of implementing ICT infrastructures over 36 years have been presented in Table 5.13. Furthermore, the total benefit over 36 years has been calculated.

	8770	9560	11300

Table 5.13: Scenario x-16 ICT Infrastructures Costs and Benefits

Both the exponential and linear costs have been estimated based on the specifications of scenario x-16 and relevant ICT infrastructures introduced in Figure 5.5. These values are based on the cost of implementing ICT infrastructure considering based on the physical ICT components cost and qualitative cost of ICT objectives for each ICT infrastructure. As presented, if the purchasing behaviour is linear, the cost of implementing ICT infrastructures for this scenario is higher compare to the exponential curve, where great share of ICT will be purchased close to 2050 time horizon at cheaper prices.

Therefore, the required years for returning the investments for exponential purchase for scenario x-16 relative to 2050 are:

$$\frac{8770 - 11300}{714} = -3.5\,Years \quad 5.13$$

Hence, the ICT investments for this scenario can be recovered about 3.5 years before 2050. This is because of the specification of this scenario, in which a high degree of electrification is considered to be occurring mainly at de-centralized level and the efficiency is high. Furthermore, the traditional payback period can be calculated relative to the present time. In this case, the traditional payback period for this scenario is: (2050 – 2014) + (-3.5) = **32.5 years.**

Chapter 6: Conclusion

The methodology proposed in this report attempts to address the impacts of ICT infrastructure on the pan-European power system up to the 2050 time horizon and consists of three stages. The objective of Stage 0 is to identify and characterize the power system domains from the SGAM. Furthermore, the three core quantitative ICT components and four qualitative ICT objectives, which are relevant to this analysis, are classified. These act as inputs for the subsequent steps.

In order to analyse the impact of ICT on future power systems, thirteen ICT infrastructures that could have impacts on the five power system domains are introduced in Stage 1. Furthermore, these ICT infrastructures are mapped to the power system domains based on their specifications. The cost trends of the most physically quantifiable ICT components: data storage, bandwidth, and computational power are projected based on historical data. Furthermore, the impacts of the qualitative ICT objectives: interoperability, resilience, cyber security and privacy, and maintenance are assessed in this study. To yield an accurate estimate, the impacts of the qualitative ICT objectives are designed in this methodology to directly modify the marginal costs for the ICT components. This means that the ICT objectives qualitative costs are added to the ICT components marginal costs. Finally, the five e-Highway 2050 scenarios, potential benefits from ICT deployments, and the domain-ICT cost projection analysis serve as inputs to Stage 2 in order to perform the cost-benefit analysis.

In Chapter 3, a range of performance improvements alongside technological limitations have been predicted for the three most physically quantifiable ICT components up to 2020. Bandwidth is increasing at rates between 20% up to 60% depending on where it is measured; however, the capital expenditures only rose by 2.6% over the past five years. A conservative projection for hard disk drives is to maintain a 20% annual areal density increase from 2010 instead of 40%, because the future areal densities is approaching thermal fluctuation limits. Furthermore, the clock frequency can be changed at compound annual growth rate of average 4%. The clock frequency has stayed relatively similar over that past since the wires that connecting the transistors have now become the dominant delay, and also cooling issue has negative impacts on the future developments of processors.

On the other hand, by estimating the cost trends of these core quantitative ICT components in Chapter 4, it has been realized that the cost of these ICT components will drastically decrease over the 36 years from now up to 2050. For instance, it can be identified that the bandwidth price has declined by 61% from 1998 up to 2010. However, the added qualitative cost of ICT objectives will dominate the total cost of implementing an ICT infrastructure. In Chapter 4, it has been shown that the costs of implementing ICT infrastructures for the 13 domain-ICT interactions are different, since the role of each ICT infrastructure in different power system domain is diverse. For instance, the total required data storage over the 36 years from now up to 2050 for the *weather forecasting and observation* and distributed energy resources domain interaction is estimated to be around 171 Petabyte, comparing with the total required data storage for the *AMI/business services* and *customer premises* interaction, which is estimated to be around 13 Petabyte.

In Chapter 5 the cost-benefit analysis for the five e-Highway2050 scenarios has been performed. The benefits were extracted from literature and a smart grid benefit inventory was made based on several international studies. The quantification was converted and scaled to the European level for the purpose of this study. Assuming a 10% investment in ICT from the overall investment to create smart grid, a pro rata benefit share from ICT of 10% has been used in calculation, denoted as ICT share. According to the specifications of each scenario, the related costs for implementing relevant ICT infrastructures and the benefits enabled though ICT are compared. As it was expected, the costs and benefits are different for each scenario due to the scenarios specifications. For instance, the maximum annual benefit enabled through ICT for the small *and local scenario (x-16)* was estimated at 714M€**,** the higher value obtained amongst the five scenarios. In this scenario there is a high focus on deployment of de-centralized storage and RES and the electrification of transport, heating and industry is considered to occur mainly at de-centralized level, and the energy efficiency has been assumed to be high in this scenario.

Furthermore, both the 2050 relative payback period and the traditional payback period are calculated for each scenario based on the ICT infrastructure investments and benefits. Three of the scenarios are estimated to achieve full traditional payback even before 2050 due to incremental investments which would lead to partial benefits before full ICT deployments. These scenarios are x-*13, x-10*, and *x-16* (with the traditional payback periods of 20.02, 22.8, and 32.5 years respectively relative to the present time). The other two scenarios, *x-7* and *x-5*, where the role of renewable energy sources is significant, have the traditional payback periods of 59.8 and 106.9 years respectively, which means that the ICT investments would be recovered after the year 2050 (approximately 2073 and 2120 respectively). Table 6.1 displays the comparison between the five scenarios with regard to the payback period associated with the implementation of ICT infrastructure. It is important to note that this comparison is not indicative of the general cost-benefit analysis associated with the full-scenario implementation, but only predicts the payback period for the implementation of an ICT infrastructure that has been justifiably associated with each scenario.

Table 6.1: Five e-Highway2050 Scenarios Comparison

All estimations were made based on scientific assumptions, historical data, technical literature and observed trends. Therefore, the report is accompanied by spreadsheets that allow the investigation of ICT impacts based on custom assumptions of interested parties.

Rank	**Scenario**	**2050 Relative Payback Period (years)**	**Traditional Payback Period Relative to the Present Time (years)**
1	Large Fossil Fuel with CCS and Nuclear Scenario x-13	-15.8	**20.2**
2	Big and Market Scenario x-10	-13.2	**22.8**
3	Small and Local Scenario x-16	-3.5	**32.5**
4	100% RES Scenario x-7	23.8	**59.8**
5	Large Scale RES Scenario x-5	70.9	**106.9**

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