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D6.1

KPIs and assessment procedure

Magnitude

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D6.1 – KPIs and assessment procedure

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Executive Summary

The present report is a public deliverable (D6.1) of the MAGNITUDE H2020 funded European project. The MAGNITUDE project aims to develop business and market mechanisms, as well as supporting coordination tools to provide flexibility to the European electricity system, by enhancing the synergies between electricity, heating/cooling and gas systems. The overall goal is to support the cost-effective integration of renewable energy sources into the electricity system and to enhance the security of supply.

Seven real-life case studies of multi-energy systems (MES) of different sizes and technological features located in seven European countries are used to provide the data foundation for the assessment and for the modelling activities taking place in different Work Packages (WP) in the project.

This deliverable aims at identifying the key performance indicators that can be used to evaluate and assess the performance of the combined system modules for the evaluation of the entire systems under study and monitor the MAGNITUDE improvements.

The work presented in this deliverable lists the most relevant and important set of KPIs that have been selected to qualify and measure the performance of all activities happening inside MAGNITUDE: from the technical (technology and systems) to the market layers but also on the project level, considering cost effectiveness, carbon content, curtailment reduction and security of supply. To tackle the problem's scalability, the KPIs are categorized in different layers to reflect assessment across system levels: MES internal KPIs, MES output KPIs, MES aggregation KPIs, Services and Market KPIs, Project level general KPIs; and furthermore they are grouped depending on the specific project target or benefit that they are addressing (with regard to the project call). The table below (Table 3 in the document) lists the identified targets and benefits that the KPIs selected in this deliverable are trying to address.

Project targets and benefits
Increased flexibility potential from MES operation in a synergetic MES environment
Increased sustainability, security of supply and quality of service in electricity supply and grid operation
Increase of generation and utilisation of renewable energy
Provision of cost-effective MES flexibility in the electrical power system
Create market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (directly or through aggregators)

In total, an initial number of 71 KPIs had been identified to be relevant to MAGNITUDE analysis. These KPIs were taken from related literature and research work and have been either adapted or modified in order to fulfil and match MAGNITUDE processes and activities. There are several studies in the literature that have been trying to quantify, measure and assess flexibility services, multi-energy systems operation and related cost-benefit analysis. A long list of potential KPIs was initially created and a first scanning of these KPIs was performed by distributing a KPIs questionnaire (see APPENDIX 2) and afterwards statistically analysing the results of the questionnaire to measure the importance of each of the proposed KPIs (Section 3). According to this analysis, the most important KPIs were selected based on two criteria: number of votes and homogeneity of answers – understood as the fact that the respondents tended to attribute similar importance to given criteria.

This initial picking of KPIs, coming directly from the questionnaire analysis is a significant input to the final list of KPIs and corresponds to the first part of a hybrid approach to select the MAGNITUDE KPIs list. The second part of KPIs selection is based on a qualitative search and internal communication among project partners throughout the relevant KPIs already identified in the literature. The metrics that were directly relevant to MAGNITUDE goals, objectives and assessment requirements were internally decided to be part of the final list of MAGNITUDE KPIs.

Finally, 37 KPIs have been selected as representative for MAGNITUDE contents, aims and objectives. These KPIs are listed in Section 4 of this document.

Eventually, the methods to evaluate these 37 KPIs are described and defined in Section 5 of this document. These MAGNITUDE KPIs shall be the basis according to which it is possible to evaluate MAGNITUDE's progress towards its objectives on the different system levels to ensure the consistency and the traceability of the improvements. The methods to evaluate the specified KPIs can be used across system levels and also for the baselines and forecast scenarios to be defined as the project evolves.

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List of Acronyms

Abbreviation / Acronym	Description
ADP	Abiotic Depletion Potential
API	Application Programming Interface
CHP	Combined Heat and Power
COP	Coefficient of Performance
CS	Case study
DH	District Heating
EHP	Electric Heat Pumps
EMS	Energy Management Systems
ENS	Energy not Supplied
EN	Electricity Network
FESR	Fuel Energy Savings Ratio
FF	Flexibility Factor
GHGs	Greenhouse gases
KPIs	Key Performance Indicators
MES	Multi Energy Systems
OC	Optimal Control
WP	Work Package
PBITDA	Operating profit before payment of interest, tax, depreciation and amortization
TES	Thermal Energy Storage
RES	Renewable Energy Resources
ROI	Return on Investment
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
n.a	Not available

1 Introduction

1.1 Purpose of the report

This report is a public deliverable (Deliverable D6.1) of the MAGNITUDE project. The MAGNITUDE project aims to develop business and market mechanisms, as well as supporting coordination tools to provide flexibility to the European electricity system, by enhancing the synergies between electricity, heating/cooling and gas systems. In particular, MAGNITUDE's goal is to identify possible flexibility options to support the cost-effective integration of Renewable Energy Sources (RES) and the decarbonisation of the energy system, and to enhance the security of supply.

To achieve its goals, MAGNITUDE will:

- Provide technological and operational tools to enable the provision of flexibility to the electricity system by Multi-Energy Systems (MES).
- Develop enhanced business and market mechanisms and identify potential regulatory evolutions to exploit the full potential value of the flexibility provided.
- Validate the project results on seven real life case studies of multi-energy systems of different sizes and technological features (including key "cross-sector" technologies), located in seven European countries (Austria, Denmark, France, Italy, Spain, Sweden, United Kingdom) with different regulations, support schemes, and geopolitical characteristics.
- Propose recommendations and contribute to the definition of policy strategies in a pan-European perspective and spread the project achievements towards stakeholders in the electricity, heat and gas sectors to raise awareness and foster a higher collaboration.

MAGNITUDE addresses the challenge to bring under a common framework, technical solutions, market design and business models, to ensure that its results can be integrated in the overall ongoing policy discussion in the energy field.

The aim of Deliverable 6.1 is to identify the key performance indicators that can be used to evaluate and assess the performance of the combined system modules for the evaluation of the entire systems under study and monitor the MAGNITUDE improvements.

In MAGNITUDE, multi energy systems (MES) take into account single (or coupling) technologies as well as aggregation of technologies (as shown in Figure 1). MES are arranged in an architecture enabling them to interact via the market aggregation platform, with the multi-energy systems managed by EMS (Energy Management Systems) and without EMS (single "unmanaged" technology) in a way that enables aggregation activities. At the same time, the aggregation platform is interacting with the electricity markets. For the sake of simplicity, aggregation of technologies is represented by the energy management layer, which is supposed to regulate the power of technologies managed and has also the ability to interact with the external environment (aggregation platform and the other stakeholders).

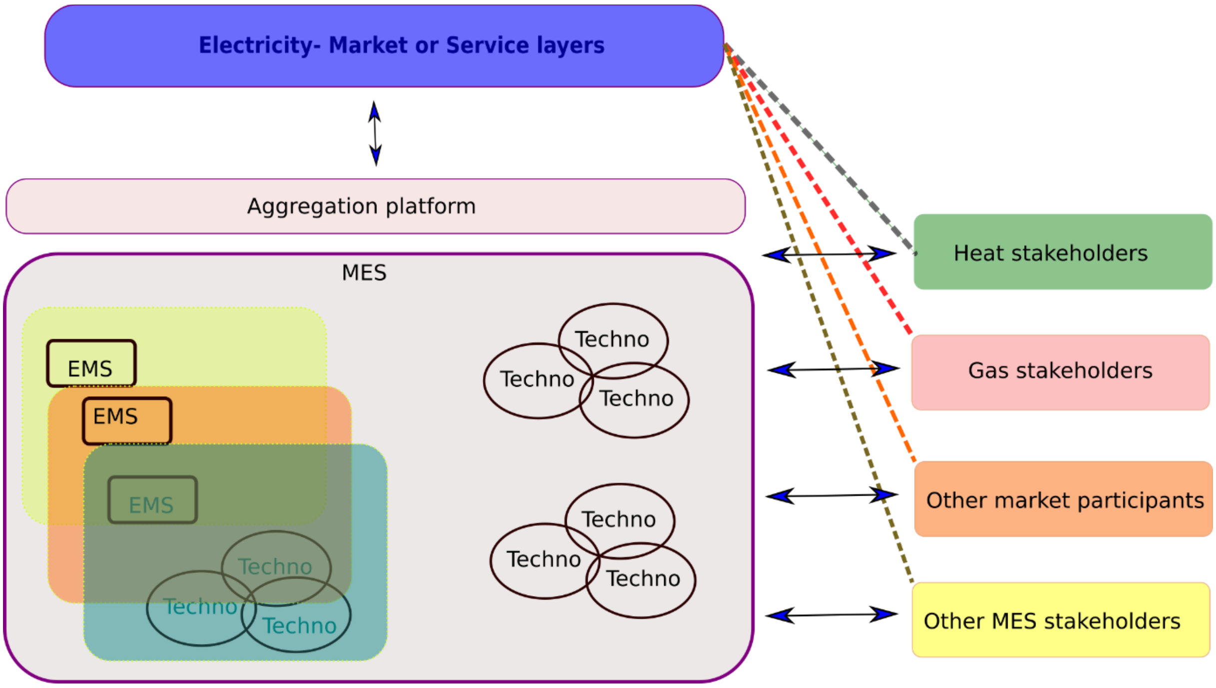

Figure 1: MES in MAGNITUDE (as identified and described in WP4)

The main characteristics and coupling technologies forming the MES and the sector coupling involved in MAGNITUDE are described in the project public deliverable D1.1 "Cartography of the flexibility services provided by heating/cooling, storage and gas technology and systems to the electricity system" [1]. The technologies used in the different case studies (CS) are listed in Table 1.

Table 1: Existing technologies in the MAGNITUDE case studies

Existing technologies in the case studies
Biomass boilers
Gas boilers
Steam turbines
Gas engines
Gas turbines
Chillers
Electrical energy storage
Thermal energy storage
Heat pump
Electrical boiler
Anaerobic digestion
Electricity network

District heating network
Gas network

Additionally, the technological characteristics of the CSs are translated into capability of the CSs to provide flexibility services towards the electricity grid. MAGNITUDE public deliverable D3.1 "Benchmark of markets and regulations for electricity, gas and heat and overview of flexibility services to the electricity grid" [2] examines the most relevant services, which are presented in Table 2.

Table 2: Identified services to be provided by MES flexibility in MAGNITUDE

Identified services to the electricity grid
FCR - Frequency Containment Reserve aFRR - automatic Frequency Restoration Reserve mFRR - manual Frequency Restoration Reserve ID - Intraday energy market DA - Day Ahead energy market ReD - Re-Dispatching or congestion management mechanism Cap - Capacity requirement mechanism

MAGNITUDE aims to achieve particular benefits by integrating and jointly operating electricity heating, cooling and gas networks. These benefits are also regarded as the project targets and are outlined in Table 3. A comprehensive set of corresponding KPIs will be defined in this report to help us to capture the deployment merit of a MAGNITUDE solution and measure the performance of the developed business and market mechanisms.

Table 3: Project targets and benefits

Project targets and benefits
Increased flexibility potential from MES operation in a synergetic MES environment
Increased sustainability, security of supply and quality of service in electricity supply and grid operation
Increase of generation and utilisation of renewable energy
Provision of cost-effective MES flexibility in the electrical power system
Create market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (directly or through aggregators)

There is a need for assessing how the MAGNITUDE solutions meet the project targets and for comparing the different solutions proposed. KPIs should answer the following basic questions by quantifying the technical, economic, social and environmental performance of processes inside MAGNITUDE.

- How effective are the decisions made throughout the project? Decision examples include the selection of the coupling technologies, the configurations of the MES components, the operational strategies, the associated controls, etc...
- Which is the most appropriate service to address a particular need?
- How does the service improve the project targets?
- Which is the most suitable MES architecture to deliver this service?
- What are the technical and economic implications for different configurations and controls? How does flexibility change?

From the abovementioned questions it can be realised that KPIs should reflect assessment across system levels (components and technologies, MES and EMS, aggregation platform, overall system configuration, proposed services and markets). Therefore, KPIs are categorized into the following layers (Figure 2):

- **MES internal KPIs:** KPIs expressing the ability to deliver flexibility through the components forming a MES. They are the basically coupling component specific KPIs and parameters e.g. conversion efficiencies, utilisation factors. They should take the range of operation into consideration with special focus on flexibility, which can be reflected by ramp rate, ramp magnitude and ramp frequency.
- **MES output KPIs**: KPIs measuring performance of a MES offering a flexibility option within a specific configuration and control function (illustrated by the technical use cases).
- **MES aggregation KPIs:** KPIs measuring the performance of the aggregation platform which is built with the aim to aggregate flexibilities available by innovative utilization of the cross-energy carrier synergies.
- **Services and market KPIs**: KPIs measuring performance of the (aggregated) MES, providing a service inside a market structure, KPIs measuring the performance of the proposed innovative market options to increase synergies between energy systems.
- **Project level general KPIs:** KPIs measuring the performance of different services with respect to project targets

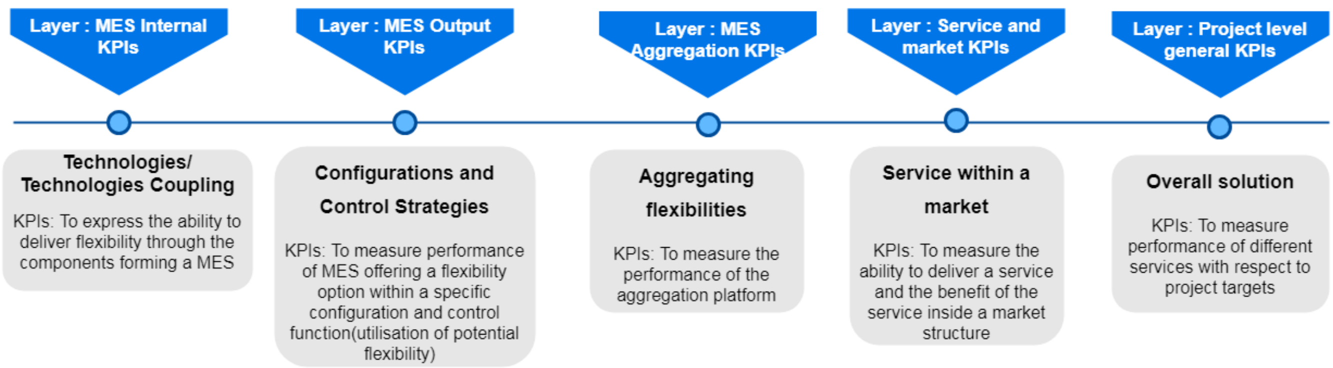

Figure 2: KPI assessment across system levels with different layers.

The KPIs can also be divided into four categories, including technical, economic, environmental and socio-political KPIs. Therefore, in the next sections, the study of KPIs follows the structure presented in Figure 3.

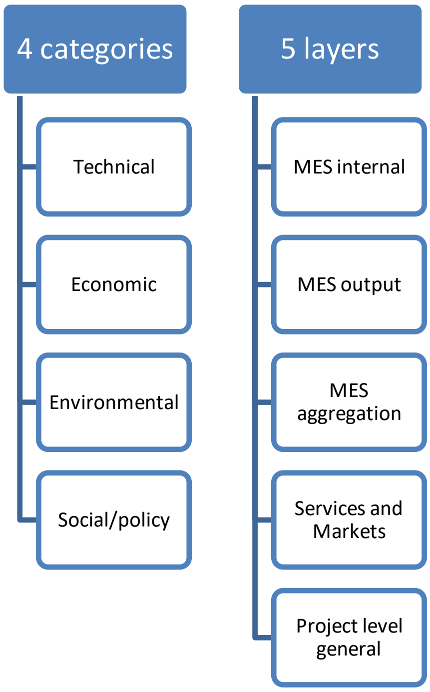

Figure 3: Categories of KPIs distinguished in this report

1.2 Organization of the report

The adopted methodology is presented in Section 2. Section 3 summarizes the feedback of survey and the results of analysis, which can demonstrate the preferred KPIs per layer and will be used to support the final list of the KPIs to be selected. Afterwards, the final list of the selected KPIs is presented in Section 4 and the methods to evaluate the selected KPIs are presented in Section 5. Finally, conclusions are given in Section 6.

2 Methodology to select the most relevant KPIs

This chapter introduces the methodology applied to identify the most relevant KPIs. It also summarizes the pool of the relevant KPIs collected in the energy field.

2.1 Methodology

Overall, there is a rich literature body on the appropriate strategies for the selection of the right KPIs' set. Due to its complex nature but also importance for various parties, the selection of an appropriate set of KPIs is a vital process. From the perspective of the MAGNITUDE project it should involve organizations or their representatives responsible for the flexibility solutions, parties affected by the flexibilities options, and experts from the respective fields operating as advisors and assessors of analysis outcome. The methodology adopted in this task is mainly based on literature review, survey, and internal discussion and communication within MAGNITUDE. The literature review will generate the pool of KPIs; and the survey will provide important assistance regarding KPI selection. However, since the partners involved in the work package (WP) in charge of the KPIs definition and the WP leaders have a better understanding about the purpose of KPIs and the objectives of the project, their comments and feedback are considered to be more important, based on which the final KPI list will be determined .

The methodology applied in this report consists of the following steps:

1) creating a KPI pool by identifying and collecting the most relevant KPIs from the literature , which can measure the performance of:
   - Services and markets with respect to MAGNITUDE general project targets listed in Table 3.
   - Different use cases (control functions and flexibility options) to deliver the same service
   - Different MES (with respect to coupled technologies and configurations)
2) formulating a questionnaire, collecting feedback from partners and outside world. Based on the analysis of obtained data, a preliminary list of relevant KPIs is generated. The purpose of the questionnaire is to make an informal filtering of the initial pool, forming a draft list, assisting us in the determination of the final list,
3) organizing internal discussion within the WP in charge of the KPIs definition, namely WP6 to revisit the KPI literature pool and further extend the draft KPI list to properly address MAGNITUDE requirements,
4) further extending the list by asking for comments and interacting with
   - other project WPs, where the technical analysis is done and their performance needs to be measured (namely WP3, WP4 and WP5)[1] – since the finally selected KPIs have to be approved and accepted by those WPs and integrated into their internal specifications,

[1] In WP3 market designs and business models for cross system integration are proposed and defined, for the identified flexibility services in the considered countries. WP4 is in charge of the simulation and the optimization of the integrated energy systems, defining the technical specifications for the flexibility products. Finally, WP5, is building the tools for the multi-energy aggregation, bundling flexibilities to market products and performing control strategies on the pool level.

- all MAGNITUDE WP leaders to guarantee that MAGNITUDE's aims and objectives are properly addressed.

5) for the final list of the selected KPIs, detailed definition and specification of the methods to evaluate these KPIs.

From the steps described above, it is clear that there is a strong interdependence between the KPIs identification from the literature, final selection of representative KPIs and the actual technical processes and activities happening inside MAGNITUDE but carried out by different partners. Therefore, interactions between WP6 and the other WPs, is of paramount importance for the selection of appropriate metrics.

The whole process can be graphically presented in Figure 4.

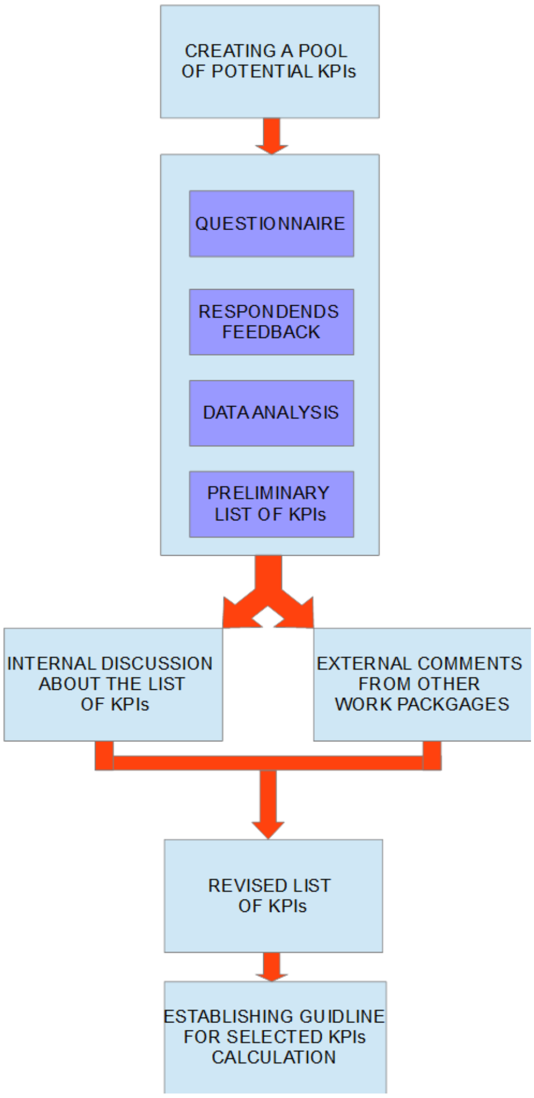

Figure 4: Flowchart of applied procedure in this research

2.2 Potential KPIs from the literature

The benefits that the MAGNITUDE project anticipates to achieve will be quantified by a set of corresponding KPIs. These indicators will facilitate a qualitative and quantitative indication of the impact of the project. KPIs should assess performance in all systems and levels in MAGNITUDE, therefore KPIs are categorized in the different layers that have been defined in Section 2.1.

The set of potential KPIs (which were later included in the questionnaire) was created based on the literature review [3] [4] [5] [6] [7], internal discussion with MAGNITUDE partners, and expert knowledge of the project members involved in this deliverable.

Based on literature review, a total of 71 potential KPIs have been collected, based on which the questionnaire was created. Furthermore, the KPIs have been grouped in homogeneous clusters depending on the described MAGNITUDE benefits addressed. A brief summary is shown in Table 4 and Table 5 and the details are presented in Appendix 1. The numbers in the tables below represent the amount of KPIs found for each cluster per category.

Table 4: Potential KPIs collected from literature according to different categories

Benefits	Technical	Economic	Environmental	Social/policy
Increased flexibility potential from MES operation in a synergetic MES environment	19	0	1	0
Increased sustainability, security of supply and quality of service in electricity supply and grid operation	14	1	2	1
Increase of generation and utilisation of renewable energy	2	0	0	0
Provision of cost-effective MES flexibility in the electrical power system	4	7	0	0
Creating market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (directly or through aggregators	8	10	0	3

Table 5: Potential KPIs collected from literature according to different layers

Benefits	MES internal	MES output	MES aggregation	Services and market	Project level general
Increased flexibility potential from MES operation in a synergetic MES environment	9	11	5	9	6
Increased sustainability, security of supply and quality of	1	9	2	15	14

Benefits	MES internal	MES output	MES aggregation	Services and market	Project level general
service in electricity supply and grid operation					
Increase of generation and utilisation of renewable energy	0	2	0	2	2
Provision of cost-effective flexibility in the electrical power system	0	6	3	18	15
Creating market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (directly or through aggregators)	0	4	11	22	18

3 Questionnaire analysis

3.1 Aim

The KPI pool contains 71 KPIs (see APPENDIX 1 - Full KPIs list from the literature (prior to the final selection)). The objective of the questionnaire is to perform an initial filtering of the KPIs and a draft selection, by screening a certain number of KPIs per category. Therefore, it was proposed that 5 KPIs from “technical” category, 5 from “economic” category, 3 from “environmental” category, and 3 from “social/policy” category should be selected from the questionnaire analysis. The questionnaire that was distributed can be found in APPENDIX 2 - Questionnaire. This questionnaire contains a smaller number of KPIs compared to the KPI pool, both because the KPIs literature survey and the processes and activities inside MAGNITUDE were still on going at the time that the questionnaire was distributed, and because the questionnaire shall not be tedious to a respondent.

Based on the feedback of the questionnaire, the most important KPIs are identified according to the number of votes, the mean value of votes (which ranged from 0 to 7) and the standard deviation of votes. The Coefficient of Variation (CV) is used to replace the mean of votes and stand deviation which is defined as the ratio of the standard deviation σ to the mean μ (Equation (1)).

$$CV = \frac{\sigma}{\mu} \tag{1}$$

The Coefficient of Variation is a measure which shows the extent of variability in relation to the mean of the population and in our case exhibits the overall agreement of respondents with regard to the KPI importance. Combined with the total score, it can be used to select KPIs. The following procedure is applied to find the most relevant KPIs:

- Results from questionnaires are first checked for consistency and potential errors.
- The number of votes collected by given KPI, the mean of the scores and the standard deviation of the scores are computed and the Coefficient of Variation is calculated.
- The number of votes and CVs is normalized to (0-1) within the category which is being currently investigated.
- For each KPI a Z value is calculated which is equal to: “vote” + (1-CV). The goal is to find the top (here top five) highest values of the Z value. This objective ensures that the selected KPIs are in the same time characterized by 1) maximal number of respondents who selected them, and also 2) the lowest value of the Coefficient of Variation (which combines the mean value and standard deviation of the scores). This means that the questionnaire respondents are uniform about the given KPI importance.
- Selection of the most important KPIs is based on the Z value (calculated as presented above). This is conducted by 1) selecting the top five values of objective function without category distinction, and 2) selecting the top five values of objective function in “technical” category, the top five in “economic” category, the top three in “environmental” category, and the top three in “social/policy” category. In each selection, we distinguish different weights for the respondents, i.e. researchers (MAGNITUDE research partners or others), MAGNITUDE industrial partners and the remaining respondents were assigned a value of “3”, “2”, and “1” respectively. Since the questionnaire KPIs are all extracted from existing literatures, we assigned higher weight to the researchers’ responses based on the fact that they have possibly more knowledge on academically dealing with metrics and the assessment of energy systems. Accordingly, we emphasized the

influence of MAGNITUDE industrial partners by consulting and employing their opinions based on current practices and applications. For the other respondents, we perceived them having less significant roles as they are not directly involved in the MAGNITUDE project and may not have a good understanding of the objectives of the project.

3.2 Statistical assessment of the results

After the collection of potential KPIs, the questionnaire is created. In the questionnaire the KPIs are divided based on their categories and layers. It also collects basic information about the respondent (its role and potential relation to the MAGNITUDE project). This is summarized as:

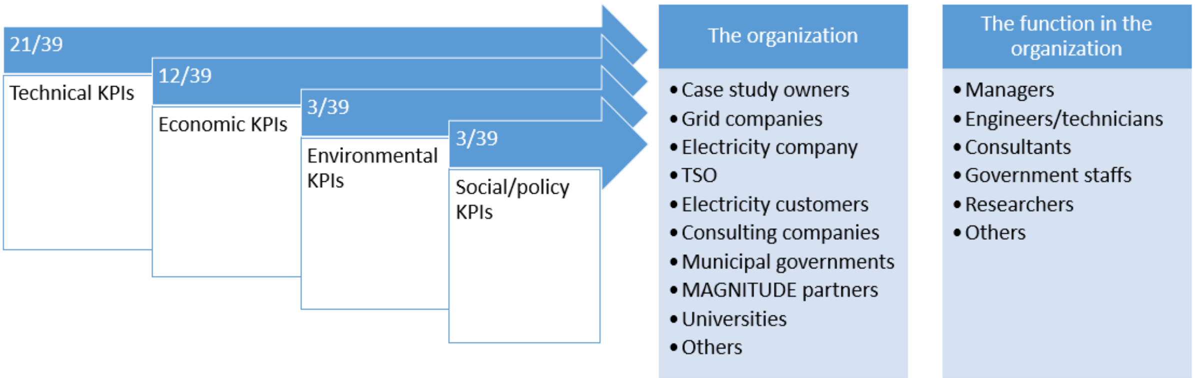

Figure 5: The summary of KPI categories, question numbers, stakeholders, and their roles

After the feedback of questionnaire is received, the following analysis is done.

3.2.1 Reliability

The reliability, as a measurement instrument, is to analyze the questionnaire accuracy and quality to investigate all the key performance indicators to the combined systems and MAGNITUDE project.

Joppe [8] defines reliability as*: "…The extent to which results are consistent over time and an accurate representation of the total population under study is referred to as reliability and if the results of a study can be reproduced under a similar methodology, then the research instrument is considered to be reliable. (p. 1)"*. Embodied in this citation is the idea of replicability or repeatability of results or observations. This is especially important if the measure is to be used on an on-going basis to detect change.

Kirk and Miller [9] identify three types of reliability referred to in quantitative research, which relate to: (1) the degree to which a measurement, given repeatedly, remains the same (2) the stability of a measurement over time; and (3) the similarity of measurements within a given time period (pp. 41-42).

One of the most popular reliability statistics in use today is Cronbach's alpha [10]. Cronbach's alpha determines the internal consistency or average correlation of items in a survey instrument to gauge its reliability, that is, how closely related a set of items are as a group.

Cronbach's alpha can be written as a function of the number of test items and the average inter-correlation among the items. Below, for conceptual purposes, the formula for the standardized Cronbach's alpha is shown as Equation (2):

$$\alpha = \frac{N \cdot \acute{c}}{\acute{v} + (N-1) \cdot \acute{c}} \tag{2}$$

Here *N* is equal to the number of items, *c-bar* is the average inter-item covariance among the items and *v-bar* equals the average variance.

The alpha coefficient ranges in value from 0 to 1 and may be used to describe the reliability of factors extracted from dichotomous (that is, questions with two possible answers) and/or multi-point formatted questionnaires or scales (i.e., rating scale: 1 = poor, 5 = excellent). The higher the score, the more reliable the generated scale is. Nunnaly [11] has indicated 0.7 to be an acceptable reliability coefficient but lower thresholds are sometimes used in the literature.

3.2.2 Total Votes

The total votes, which represent how many respondents choose the specific KPI, were counted. Literally, the more votes to a specific KPI the more important that KPI is. The votes include the KPI perception of different stakeholders who play different roles with respect to the MAGNITUDE project. Beside the unweighted counts, the different weights will also be applied to the stakeholders and their votes in order to distinguish the unequal influences of them.

3.2.3 Means and Standard Deviations

The means, or the mathematical expectation of all the KPI candidates' scores are calculated, specifically, the sum of the values divided by the number of KPI candidates. The values are the voted KPI candidates' values by the respondents, excluding the non-voted ones. Similarly, the number just includes the voted KPI candidates. The mean value shows the average importance level of each KPI candidate. The higher the value, the more important is the voted KPI.

The standard deviations, represented by σ, measure the amount of variation of dispersion of all the answers. A lower standard deviation indicates that the data points tend to be closer to the mean of the set. In our case, a lower standard deviation shows that the voted KPI scores are clustered closely around the mean, i.e. different respondents give more or less similar scores to the specific KPI candidate. A higher standard deviation shows that a big variation within different respondents' evaluation on the specific KPI candidate.

3.2.4 Z factor

From the analysis described above, obviously, the KPI with higher vote, higher mean and lower standard deviation are more preferable. To reduce the dimension, we bring in the Coefficient of Variation, as shown in Section 3.1. Distributions with CV<1 are considered as low-variance, while those with CV>1 are considered as high-variance.

Based on these variables, the objective function Z factor is developed as Equation (3):

$$Z = N_{vote} + (1 - N_{CV}) \tag{3}$$

Here, N_{vote} represents the normalized numbers of votes, and. N_{CV} represents the normalized Coefficient of Variation ("min-max" normalization was performed[2]).

[2] "min-max" normalization linearly transforms *x* variable to *y =(x-min)/(max-min) where: max and min are minimal values observed in the set of xs*

By maximizing the Z factor, we can determine the selected KPIs both with maximal number of votes and with minimal variance of preferences.

3.3 Questionnaire reliability

Prior to the statistical analysis of the obtained results, the questionnaire is tested with regard to its reliability. The procedure described in Section 3.2.1 has been applied. The results are as follows. The 39 observed variables (KPIs) were used to run on Cronbach's alpha analysis. The following statements obtained from the statistical software SPSS[3] show the statistical result in Table 6.

Table 6: The reliability test result of the questionnaire

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	Number of Items
0.718	0.744	39

The alpha coefficient for the 39 items/questions, which correspond to the four categories of the questionnaire (i.e. technical, economic, environmental, and social/policy KPIs), was 0.718. It suggests that the items have relatively high internal consistency. Thus, the designed questionnaire has a relatively good reliability level, and therefore, we have accepted the questionnaire as valid and proceeded to the statistical analysis of the questionnaire outcome.

3.4 Descriptive analysis

22 questionnaires were received from different respondents, among which 39% are from MAGNITUDE partners (among the 16 partners of the MAGNITUDE project), followed by 17% from case study representatives (among the 7 case studies of the MAGNITUDE project). Meanwhile, 50% of the respondents are working as engineers/technicians and 40% are researchers (Figure 6 and Table 7). Lastly, two of the case study representatives are also MAGNITUDE partners.

[3] Statistical Package for the Social Sciences

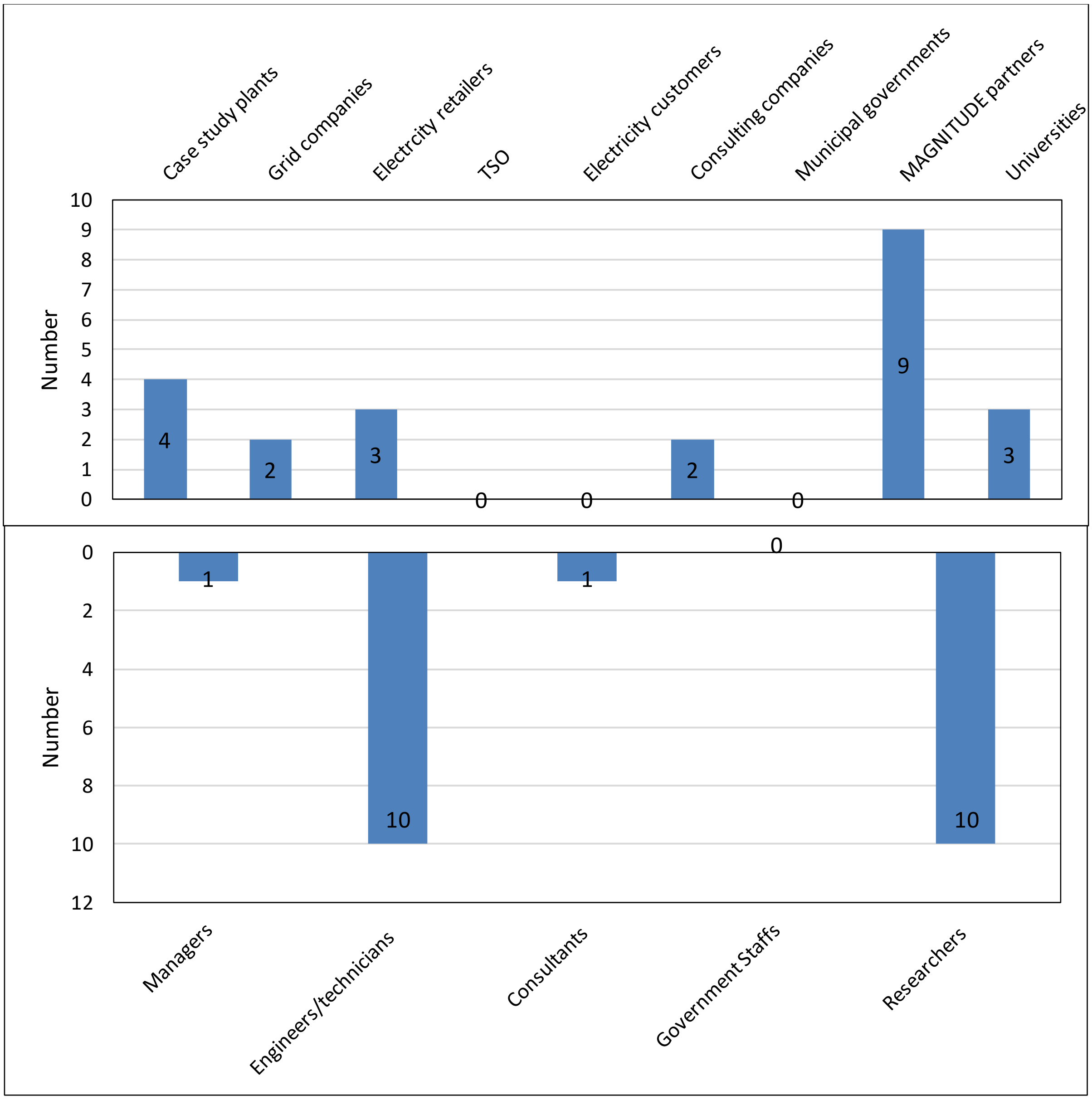

Figure 6: The distribution of respondents' types of organizations and roles from the questionnaire

Table 7: Numbers of types of organizations and roles from 22 questionnaires received

	Managers	Engineers, technicians	Consultants	Government Staffs	Researchers
Case study plants		4			
Grid companies		2			1
Electricity retailers	1	2			
TSO					
Electricity customers					
Consulting companies		1	1		
Municipal governments		1			

	Managers	Engineers, technicians	Consultants	Government Staffs	Researchers
MAGNITUDE partners		1			7
University					3

For the descriptive analysis of each variable/KPI candidate, we list their histogram distributions according to the categories (Figure 7 to Figure 10). The histograms show the Coefficient of Variations (the standard deviation divided by the mean) and vote counts of each variable. From the figures, some KPI candidates show relatively high vote count and low coefficient of variation, e.g. energy efficiency, ramp rate, availability factor, market price of provided energy and services, GHG emission, Abiotic depletion potential, etc. However, some show the contrary results, e.g. system minutes lost, duration and frequency of interruptions per customer, revenue for the network operator from the service, fuel energy saving ratio, and reduction of the number of communication channels. From the analysis above, the former KPI candidates are much more preferable than the latter ones because they indicates: 1) more respondents confirm their significance, and 2) the confirmation among respondents are of higher consistency.

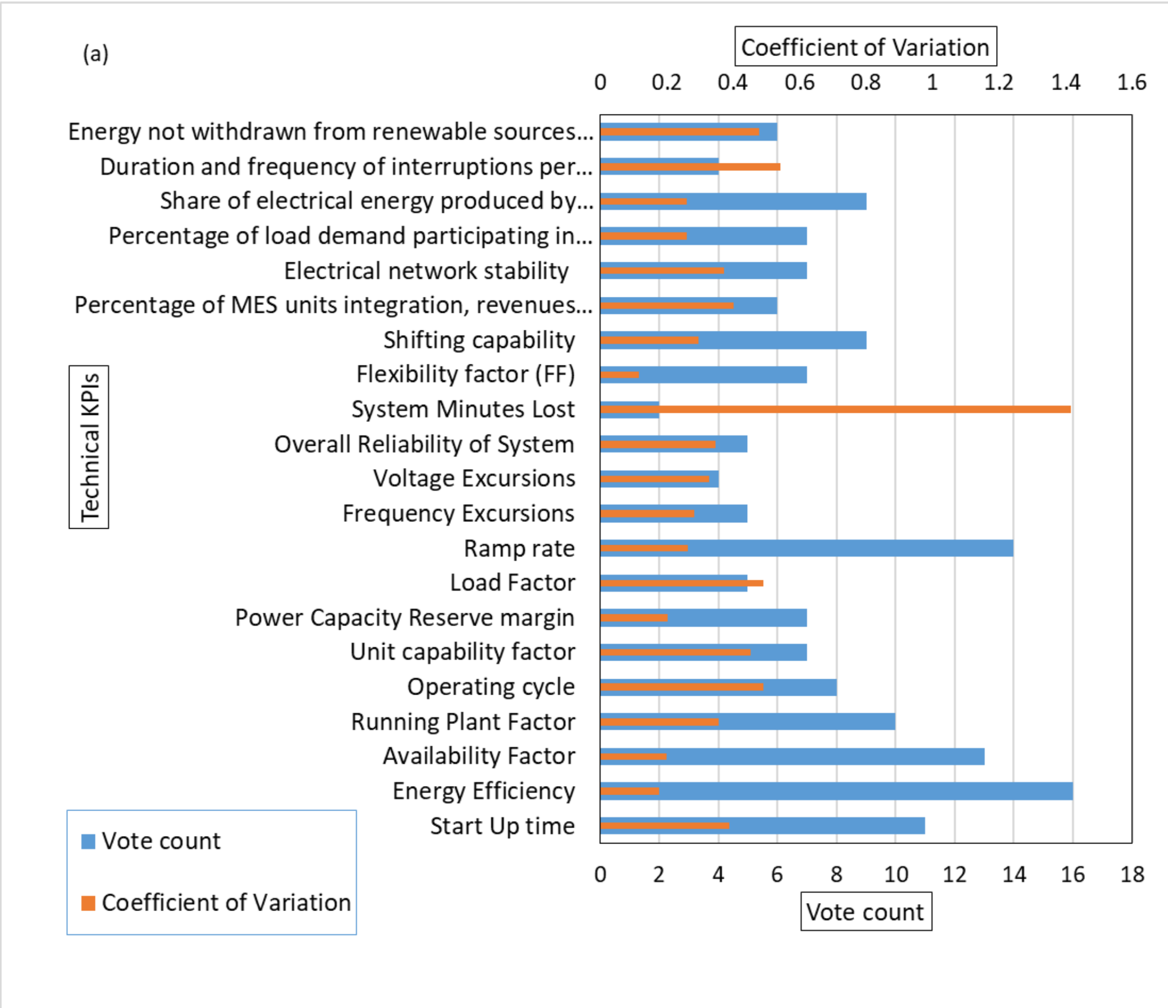

Figure 7: The descriptive analysis of vote count and coefficient of variation for technical KPIs

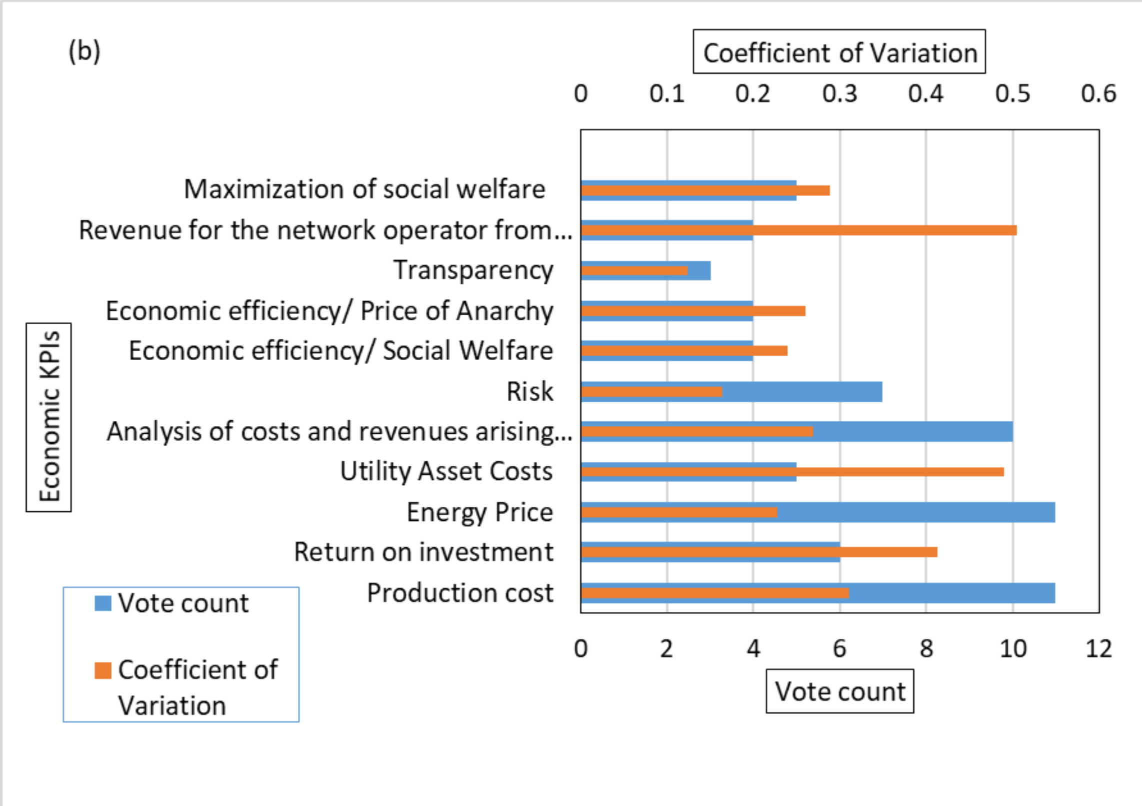

Figure 8: The descriptive analysis of vote count and coefficient of variation for economic KPIs

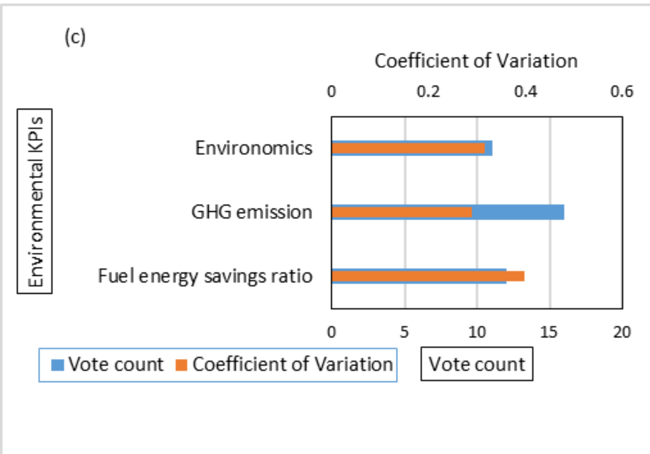

Figure 9: The descriptive analysis of vote count and coefficient of variation for environmental KPIs

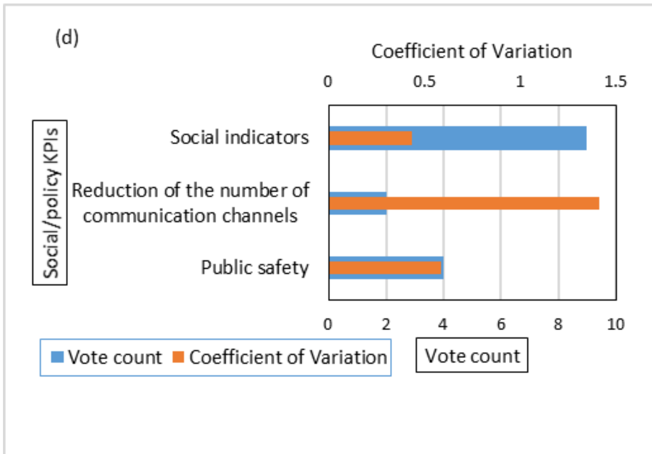

Figure 10: The descriptive analysis of vote count and coefficient of variation for social/policy KPIs

3.5 Standard deviation, average and number count

The scatter plot in Figure 11 shows the coefficient of variation and number of counts for 39 variables (KPIs) which could be selected in the questionnaire. The presented values have been normalized to [0..1] based on observed maximal and minimal values. The KPIs characterized by a high number of counts and low value of CV are considered as representative ones / important for the project. The results presented on the scatter plot are later used in Section 4 to find the most relevant KPIs.

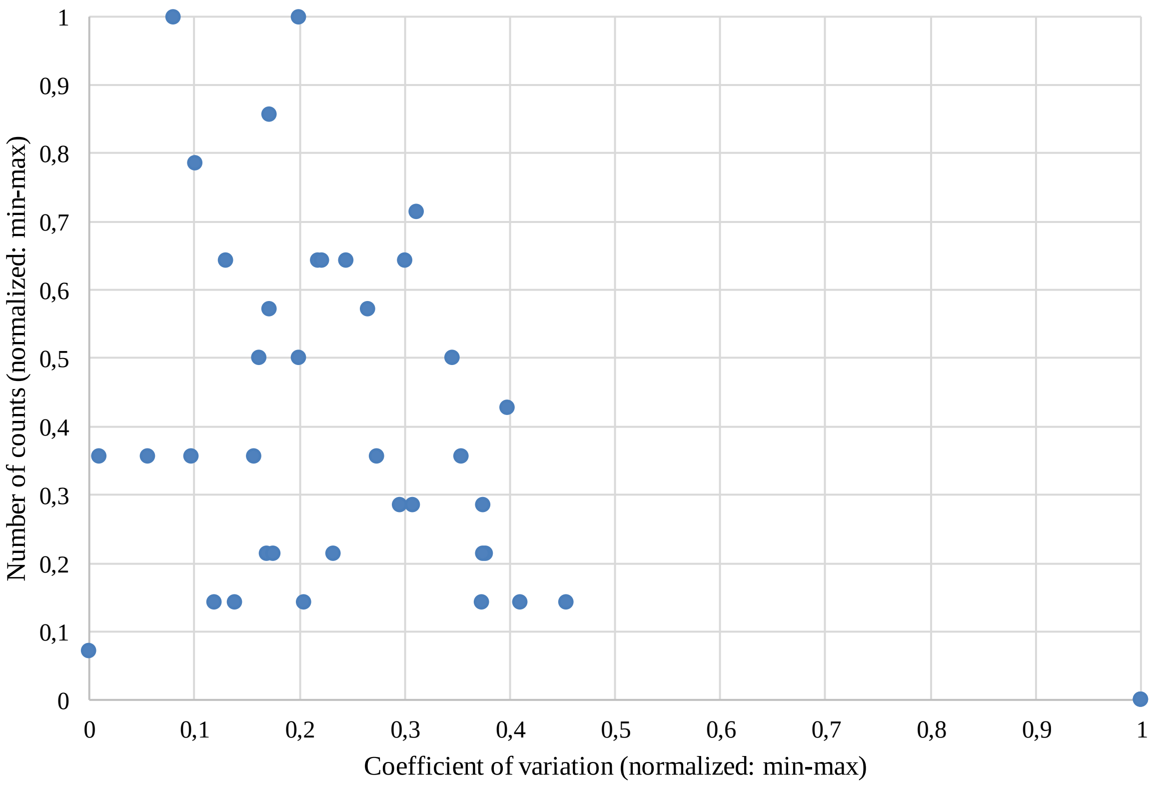

Figure 11: Variables' coefficient of variation average and count (see Appendix 3 for KPIs decoding).

3.6 Questionnaire results - KPIs collection

Based on the procedure presented in Sections 2.1 and 3.2, the following results have been obtained.

3.6.1 KPIs not divided into categories

To distinguish the five most important KPIs, an analysis is performed on the whole set of potential candidates. Table 8 summarizes the statistical parameters of the questionnaire results.

Table 8: Summary results of statistical parameters

No.	KPI	Count	AVG	STD	CV	Normalized objective
1	Start Up time	11	4.6	1.8	38.9%	1.4
2	Energy Efficiency	16	5.9	1.1	17.9%	2.0
3	Availability Factor	13	5.6	1.1	20.0%	1.7
4	Running Plant Factor	10	4.6	1.6	35.8%	1.4
5	Operating cycle	8	4.5	2.2	49.0%	1.1
6	Unit capability factor	7	4.6	2.1	45.3%	1.1
7	Power Capacity Reserve margin	7	5.6	1.1	20.4%	1.3
8	Load Factor	5	3.4	1.7	49.2%	0.9

9	Ramp rate	14	5.5	1.5	26.4%	1.7
10	Frequency Excursions	5	5.8	1.6	28.3%	1.1
11	Voltage Excursions	4	5.8	1.9	32.9%	1.0
12	Energy not supplied	5	5.0	1.7	34.6%	1.0
13	System Minutes Lost	2	3.5	4.9	141.4%	0.0
14	Flexibility factor (FF)	7	5.9	0.7	11.8%	1.4
15	Power Shifting capability	9	4.9	1.5	29.7%	1.4
16	Percentage of MES units' integration, revenues for the aggregator	6	4.8	1.9	40.2%	1.1
17	Electrical network stability	7	5.7	2.1	37.4%	1.2
18	Percentage of load demand participating in market-like schemes for demand flexibility	7	5.1	1.3	26.2%	1.2
19	Share of electrical energy produced by renewable sources	9	5.9	1.5	26.1%	1.4
20	Duration and frequency of interruptions per customer	4	5.0	2.7	54.2%	0.8
21	Energy not withdrawn from renewable sources due to congestion and/or security risk	6	4.8	2.3	47.9%	1.0
22	Energy Conversion plant profitability	11	5.4	1.8	33.6%	1.5
23	Production cost	11	5.5	1.7	31.1%	1.5
24	Return on investment	6	5.2	2.1	41.4%	1.1
25	Market price of provided energy and services	11	5.6	1.3	22.8%	1.6
26	Utility Asset Costs	5	5.0	2.4	49.0%	0.9
27	Costs and revenues arising from system operation	10	5.6	1.5	26.9%	1.5
28	Operational failure risk	7	5.0	0.8	16.3%	1.3
29	Economic efficiency/ Social Welfare	4	6.3	1.5	24.0%	1.0
30	Economic efficiency/ Price of Anarchy	4	5.8	1.5	26.1%	1.0
31	Transparency	3	4.7	0.6	12.4%	1.1
32	Revenue for the network operator from the service	4	3.8	1.9	50.5%	0.8
33	Maximization of social welfare	5	6.2	1.8	28.9%	1.1
34	Fuel energy savings ratio	12	5.1	2.0	39.8%	1.5
35	GHG emission	16	5.6	1.6	28.9%	1.9
36	Generated pollutant element	11	4.7	1.5	31.5%	1.5
37	Public safety and acceptability	4	4.5	2.6	58.8%	0.8
38	Reduction of the number of communication channels	2	1.5	2.1	141.4%	0.0
39	Abiotic depletion potential	9	5.0	2.2	43.6%	1.3

Based on the results in Table 8, it is found that the most important KPIs are the energy efficiency followed by GHG emissions. The top five KPIs are presented in Table 9. The selected KPIs are characterized by the lowest coefficient of variation and highest number of votes (Count) both normalized and presented as objective (Normalized objective).

Table 9: Five most important KPIs

No.	Chosen KPIs
1	Energy Efficiency
2	GHG emission
3	Ramp rate
4	Availability Factor
5	Market price of provided energy and services

As a part of our analysis, different weights can be assigned to the score provided by each participant according to his/her role. Based on expert opinions, “3”, “2”, and “1” were assigned to researchers (inside and outside MAGNITUDE), other MAGNITUDE partners and the remaining participants. The group marked as “researchers” were attributed with the highest weight of their votes as they are simultaneously most often working with different metrics (KPIs) or the assessment of energy systems as well as were directly involved in the project. Lower values were respectively assigned to MAGNITUDE partners and remaining participants as their involvement in the project might be smaller than that of researchers or might be limited to specific tasks. The results based on the weighted score show a small change in the hierarchy of the KPIs, which is presented in Table 10. The final selected KPIs remain the same ones.

Table 10: Five most important KPIs (weighted)

No.	Chosen KPIs
1	Energy Efficiency
2	GHG emission
3	Availability Factor
4	Ramp rate
5	Market price of provided energy and services

3.6.2 KPIs divided into categories

In the second part of the analysis the five most important KPIs have been distinguished from each category (technical, economic, environment and social/policy). The results of this analysis are as follows.

3.6.2.1 Technical KPIs

The questionnaire results indicate that the most important technical KPIs is the “energy efficiency” followed by “ramp rate”, “availability factor” “start-up time” and “share of electrical energy produced by renewable sources” or “power shifting capability”. If the researchers and MAGNITUDE partners opinion is considered as more important, the positions of “ramp rate” and “availability factor” switch and the later becomes more important.

Table 11: Five most important technical KPIs

No.	Chosen KPIs
1	Energy Efficiency
2	Ramp rate
3	Availability Factor
4	Start Up time
5	Share of electrical energy produced by renewable sources

Table 12: Five most important technical KPIs (weighted)

No.	Chosen KPIs
1	Energy Efficiency
2	Availability Factor
3	Ramp rate
4	Start Up time
5	Power Shifting Capability

3.6.2.2 Economic KPIs

In the case of economic KPIs, the most important is undoubtedly the “market price of provided energy and services”. The set of KPIs is the same for both analyses (based on weighted and unweighted votes). However, different importance level can be observed (i.e. the KPIs are ordered in a different way). The final distinguished KPIs in the economic category are: “market price of provided energy and services”, “production cost”, “energy conversion plant profitability”, “costs and revenues arising from system operation”, and “operational failure risk”.

Table 13: Five most important economic KPIs

No.	Chosen KPIs
1	Market price of provided energy and services
2	Production cost
3	Energy conversion plant profitability
4	Costs and revenues arising from system operation
5	Operational failure risk

Table 14: Five most important economic KPIs (weighted)

No.	Chosen KPIs
1	Market price of provided energy and services
2	Costs and revenues arising from system operation
3	Production cost
4	Energy conversion plant profitability
5	Operational failure risk

3.6.2.3 Environmental KPIs

The questionnaire includes only three environmental KPI candidates, therefore we have aimed at sorting them with regard to their importance. Our calculations show that the most important are "GHG emissions" followed by "fuel energy savings ratio" and "generated pollutant element". Adjusting to the weighted vote value the two last KPIs switch their positions. The final distinguished KPIs could be "GHG emission", "fuel energy savings ratio" or "Generated pollutant element".

Table 15: Ordered environmental KPIs

No.	Chosen KPIs
1	GHG emission
2	Fuel energy savings ratio
3	Generated pollutant element

Table 16: Ordered environmental KPIs (weighted)

No.	Chosen KPIs
1	GHG emission
2	Generated pollutant element
3	Fuel energy savings ratio

3.6.2.4 Social/policy KPIs

Similar to the case of environmental KPIs, we have sorted them depending on their importance. The results in both analyses are the same. The final distinguished KPIs could be "abiotic depletion potential" and "public safety and acceptability".

Table 17: Ordered social KPIs

No.	Chosen KPIs
1	Abiotic depletion potential
2	Public safety and acceptability
3	Reduction of the number of communication channels

Table 18: Ordered social KPIs (weighted)

No.	Chosen KPIs
1	Abiotic depletion potential
2	Public safety and acceptability
3	Reduction of the number of communication channels

4 Final MAGNITUDE KPIs selection

In Section 3, the statistical analysis of the questionnaires resulted with the selection of 16 KPIs in total, picked because of their statistical importance from the votes of the respondents. Those KPIs are treated as a valuable feedback and indication for the final selection of the MAGNITUDE KPIs. Particularly, all the KPIs picked from the questionnaire analysis are in the final MAGNITUDE KPIs list, with the exception of 'abiotic depletion potential' and 'public safety and acceptability' because it is not possible to calculate those KPIs within the MAGNITUDE activities and access of data. Nonetheless, Appendix 4 contains all the KPIs (and the methods to evaluate them) that are identified as highly relevant to MAGNITUDE goals, but are not accessible within MAGNITUDE.

Principally, as indicated in Section 2.1, the final selection of KPIs should be unanimously selected after:

- Internal communication within the WP in charge of the KPIs definition, namely WP6.
- The internal communication with other project WPs (namely WP3, WP4 and WP5) since the finally selected KPIs have to be approved and accepted by those WP and integrated into their internal specifications.
- The internal communication with all MAGNITUDE WP leaders to guarantee that MAGNITUDE's aims and objectives are properly addressed.

The above mentioned internal communication and brainstorming sessions with the project partners result to a selection of the most applicable KPIs from the initial literature KPIs pool (see APPENDIX 1). Project level general KPIs should capture the ultimate benefits and targets that MAGNITUDE is trying to achieve (see Table 3). KPIs across different layers and levels (as defined in Figure 2) should grasp the effectiveness of the methods and solutions suggested and examined during technical simulation, optimization of the MES , aggregation, proposed services and market mechanisms.

Taking also into account the output list of KPIs as screened from the statistical analysis, the final list of representative KPIs is constructed. The selected KPIs ought to capture and properly measure the performance of all the activities throughout MAGNITUDE and effectively quantify the impacts of proposed solutions and relevant improvements.

Eventually, the final list of KPIs is a set of 37 representative KPIs, assisting comprehensively the quantification of the performance of the project processes and activities with the benefits and targets presented in Table 3.

The KPIs are clustered according to the specific MAGNITUDE benefit they are addressing and measuring, hence 5 tables are presented below, containing the final selected KPIs.

Apart from their correspondence to the specific benefits, the KPIs are also characterised by category (technical, environmental etc.) and layer (MES internal, MES output etc.).

These correspondence tables, which are also repeated in Section 5, can help the different project partners to understand which KPIs are relevant for a specific benefit that they are trying to address through their work and equally important, which KPIs are relevant to the MAGNITUDE process that they are involved in.

For instance, partners working in modelling a particular MES configuration in WP4, might only be interested in 'MES output KPIs' and 'Project level general KPIs'. Moreover, since more than one KPI correspond to a specific benefit, the partners should decide which KPIs they will use to address the specific benefit depending on the access to data and the peculiarities of each use case and scenario.

This notably means that those final KPIs are not an exhaustive list where partners should evaluate all the 37 listed KPIs. **In contrast, this KPI list can function as a reference list for any activities throughout the MAGNITUDE project.**

Table 19: Selected KPIs for 'Increase flexibility potential from MES operation in a synergetic MES environment'

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggregation KPIs	Service and market KPIs	Project level general KPIs
Increase flexibility potential from MES operation in a synergetic MES environment	Energy efficiency	Technical		*		*	*
	Start-up time	Technical	*				
	Availability factor	Technical	*	*	*		
	Ramping capability	Technical	*	*			
	Power shifting capability	Technical	*	*			
	Flexibility factor	Technical	*	*			
	Percentage of MES units' integration	Technical			*	*	*
	Amount of flexibility	Technical		*	*	*	*
	Duration of availability of flexibility activation	Technical		*	*	*	
	Maximum number of activations per time duration	Technical	*	*	*		
	Minimum duration of recovery between two activations	Technical	*	*	*		

Table 20: Selected KPIs for 'increased sustainability and security of supply'

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggregation KPIs	Service and market KPIs	Project level general KPIs
Increased sustainability, security of supply and quality of service in electricity supply and grid operation	GHG emission	Environmental	*				*
	Energy not supplied	Technical		*		*	*
	Minimization of energy consumption	Technical		*	*	*	*
	Fuel energy savings ratio	Environmental		*			*
	Percentage utilization of electricity grid elements	Technical				*	*
	Generated pollutant element	Environmental	*				

Table 21: Selected KPIs for 'Increase of generation and utilisation of renewable energy'

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggregation KPIs	Service and market KPIs	Project level general KPIs
Increase of generation and	Share of electrical energy produced by renewables	Technical		*		*	*

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggegation KPIs	Service and market KPIs	Project level general KPIs
utilisation of renewable energy	Energy not withdrawn from renewable sources due to congestion and/or security risks	Technical		*		*	*

Table 22: Selected KPIs for 'Provision of cost effective flexibility in the electrical power system'

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggegation KPIs	Service and market KPIs	Project level general KPIs
Provision of cost-effective flexibility in the electrical power system	Energy Conversion Plant Profitability	Economic		*		*	*
	Production Cost	Economic		*		*	
	Operational failure risk	Economic		*	*	*	*
	Energy Operational Costs (fuel and electricity input costs net of profit from electricity sold back to the grid)	Economic		*		*	*
	Success factor of service delivery	Technical	*		*	*	
	Return on Investment	Economic	*			*	*

Table 23: Selected KPIs for 'Create market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (directly or through aggregators)'

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggegation KPIs	Service and market KPIs	Project level general KPIs
Create market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (directly or through aggregators)	Market price of provided energy and services	Economic				*	*
	Operational failure risk	Economic		*	*	*	*
	Net revenue of market participants	Economic			*	*	*
	Number of addressed markets	Technical		*	*	*	*
	Number of flexibility resources in the aggregator pool	Technical			*	*	*
	Time needed to simulate 24h of operation in the aggregation platform	Technical			*		
	Percentage of load demand participating in market-like schemes for demand flexibility	Technical			*	*	*
	Economic Efficiency/Social Welfare	Economic				*	*
	Limitation of loss of comfort	Technical		*	*	*	*
	Spark spread ratio	Economic	*			*	
	Computational Complexity	Technical			*	*	
	Reduction of the number of communication channels	Social				*	*

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggegation KPIs	Service and market KPIs	Project level general KPIs
	Transparency	Economic				*	*

For simplification and convenience, the table below contains only the 'project level general KPIs' (KPIs marked with * under 'Project level general KPIs in Table 19 to Table 23). Project level general KPIs, as their name indicate, reflect overall project objectives. Therefore, they can be also used for benchmarking when evaluating the integrated systems' performance of different solutions, by linking the market, system and aggregator simulations together in one simulation circle, under a uniform set of scenarios.

Table 24: Selected KPIs at project level

Benefits	Selected KPIs	Category
Increased sustainability, security of supply and quality of service in electricity supply and grid operation	GHG emission	Environmental
	Generated pollutant element	Environmental
	Energy not supplied	Technical
	Minimization of Energy Consumption	Technical
	Fuel energy savings ratio	Environmental
	Percentage Utilization of Electricity Grid Elements	Technical
Increase flexibility potential from MES operation in a synergetic MES environment	Energy Efficiency	Technical
	Percentage of MES units' integration	Technical
	Amount of flexibility	Technical

Benefits	Selected KPIs	Category
Increase of generation and utilisation of renewable energy	Share of electrical energy produced by renewables	Technical
	Energy not withdrawn from renewable sources due to congestion and/or security risks	Technical
Provision of cost-effective flexibility in the electrical power system	Energy Conversion Plant Profitability	Economic
	Operational failure risk	Economic
	Energy Operational Costs (fuel and electricity input costs net of profit from electricity sold back to the grid)	Economic
	Return on Investment	Economic
Create market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (directly or through aggregators)	Market price of provided energy and services	Economic
	Operational failure risk	Economic
	Reduction of the number of communication channels	Social
	Net revenue of market participants	Economic
	Economic Efficiency/Social Welfare	Economic
	Transparency	Economic
	Number of addressed markets	Technical
	Number of flexibility resources in the aggregator pool	Technical
	Time needed to simulate 24h of operation in the aggregation platform	Technical
	Percentage of load demand participating in market-like schemes for demand flexibility	Technical
	Limitation of loss of comfort	Technical

5 Methods to evaluate the selected KPIs

As explicitly described in Section 4, the selected KPIs are in total a reference list of 37 KPIs and are grouped with respect to the particular MAGNITUDE benefit that they are addressing. It is seen that more than one KPI can be used to measure a certain benefit. In addition, not all KPIs are relevant to each MAGNITUDE process. That is, for instance, that 'MES internal KPIs' are out of scope for partners who are working on the aggregation platform.

Having that in mind, Section 5 aims to define and describe the methods that can be used to evaluate each KPI. A more detailed description of each KPI and a formula to calculate each KPI is given.

The section is divided in 5 subsections, as many as the number of benefits that have been identified and that MAGNITUDE aims to address, and a correspondence matrix is given at the beginning of each subsection, listing the relevant KPIs.

The MAGNITUDE partners will then adopt the most suitable KPIs among the 37 selected ones according to their specific objectives and activities in the project.

5.1 Benefit 1: Increase flexibility potential from MES operation in a synergetic MES environment

Table 25: KPIs related to benefit 1 'Increase flexibility potential from MES operation in a synergetic MES environment' (taken from Table 19)

KPIs	Layers				
	MES internal KPIs	MES output KPIs	MES aggregation KPIs	Service and market KPIs	Project level general KPIs
5.1.1 Energy efficiency		*		*	*
5.1.2 Start-up time	*				
5.1.3 Availability factor	*	*	*		
5.1.4 Ramping capability	*	*			
5.1.5 Power shifting capability	*	*			
5.1.6 Flexibility factor	*	*			
5.1.7 Percentage of MES units' integration			*	*	*
5.1.8 Amount of flexibility		*	*	*	*
5.1.9 Duration of availability of flexibility activation		*	*	*	
5.1.10 Maximum number of activations per time duration		*	*	*	
5.1.11 Minimum duration of recovery between two activations		*	*	*	

5.1.1 Energy Efficiency

Description

Efficiency refers to the ability of a technology to transform the primary input resource into the output resource. A technology is much more efficient with respect to another if with the same quantity of primary input energy the output energy is greater.

For different technologies, the Energy Efficiency can be described as in the following examples provided for heat:

- Energy conversion unit: The fraction of the heating value of the input fuel to the converted thermal energy.
- Heat engine: The fraction of the energy added by heat (primary energy) that is converted to network output (secondary energy).
- Thermal Energy Storage (TES): The ratio of energy available to energy charged in the storage.

Formula

In general,

$$EnergyEfficiency = \frac{OutputEnergy}{InputEnergy}$$

For different technologies, the formulas can be addressed as:

- Energy conversion unit (Boiler):

$$\eta_{th} = \frac{Q_{out}}{Q}$$

- Heat engines (Turbine):

$$\eta_{th} = \frac{W_{out}}{Q} = \frac{Q \quad - Q_{out}}{Q} = 1 - \frac{Q_{out}}{Q}$$

- Heat pump:

$$COP_{heating} = \frac{Q_H}{W}$$

$$COP_{cooling} = \frac{Q_C}{W}$$

- TES: Efficiency= energy available/energy charged in the storage

The needed inputs and key parameter in the calculation of this KPI would be: amount of input energy (e.g., in a CHP the input gas flow rate, or equivalent energy associated to the input gas), and the output power generated (that is, in the case of CHP the electrical and the thermal power generated)

Some potential values of energy efficiency are given in the following table.

Table 26: Potential efficiency values

Category	Potential efficiency values
Biomass boiler	83% Sweden, 5-20 MW_t Boiler [12]
Gas boiler	Heat Efficiency: 90-92%, 20-130 tonnes/h t [13]
Steam turbine	200 MW, Low pressure turbine: 70% Load: 40.78%, 85% Load: 40.12%, 94% Load: 41.08%
Gas Engine	43%
Heat pump	COP: Domestic HP: 1 to 6 //District Heating HP: n.a
TES	Efficiency = 50-90%
Chiller	COP: see table 1 [14]

In the literature [15], it is pointed out how natural gas or biomass integrated gasification gas turbines are the most efficient technologies in terms of exergy cost of electricity and heat.

In the literature [16] [17] [18], the exergy streams are used for cost assessment and system cost internal allocation so as to optimize the design of each component and the system as a whole while accounting for the cost of each individual piece of equipment.

5.1.2 Start-up time

Description

The start-up time is a period needed by energy conversion power station to reach desired power output from off mode. The start-up time depends strongly on the type of the power plant. For thermal power plants we can distinguish hot, warm and cold start-up times. In that case the start-up time depends on the stand-still time which is less than 12 h for hot start-up from 12 to 48 h for warm and more than 48 h for cold start-up.

Formula

The start-up time (SUP) can be calculated accordingly to the following formula:

$$|t_1 - t_2|$$

where: t_1 – time when the decision was made that generator should reach desired power output, t_2 – time when desired power output has been reached. SUP can be expressed in various units of time.

Some potential values of start-up time are given in the following table.

Table 27: Some potential values of start-up time

Category	Potential start-up time values
Biomass boiler	Fluidized bed boilers to reach stable operation ranges from 6.5 to 45 hours, while for stoker or hybrid suspension grate units the total time is 2.2 to 32 hours [19]
Gas boiler	4-6 Hours [20]
Steam turbine	To achieve full load 125 MW : 60 minutes (hot start-up)- 120 minutes (warm start-up) - 240 minutes (cold start-up) [21]
Biomass boiler + Steam turbine	Limited by the start-up time of the Biomass Boiler
Gas boiler + steam turbine	Limited by the start-up time of the Gas boiler
Gas turbine	Start-up time: 55 minutes (hot start) - 170 minutes (cold start) //shut down time: 20-25 minutes
Gas Engine	5 - 10 minutes
Electrical boiler	Quick start and easy to regulate
Battery	Continuous process
Heat pump	Domestic HP: Warm start-up time: 0 and cold start-up time: 0 //District Heating HP: Warm start-up time (hours): 0 and cold start-up time (hours): 6 [22]
TES	n.a.
Chiller	n.a.
EN	From milliseconds to minutes
DH	n.a.

5.1.3 Availability factor

Description

The evaluation of availability of a power plant is one of the most important tasks in any power station, which indicates the fraction of time that it is able to produce/consume electricity over a certain period. To analyse plant availability performance, generation unit outages should be scrutinized to identify the causes of unplanned or forced energy losses and to reduce the planned energy losses. Reducing outages increases the number of operating hours, therefore increases the plant availability factor [23]. In a similar sense, in case of a consumption component or another system component providing a certain type of response to a certain service, availability factor would indicate the fraction of time that the component is able to produce/consume electricity over a certain period.

Formula

Availability Factor of a system component can be calculated using the formula given below:

$$AvailabilityFactor = \frac{Duration \in which the component was available for operation}{Total length of the period}$$

5.1.4 Ramping Capability

Description

Ramping Capability is the rate of change in instantaneous output from system component (a power generation or demand side unit). The ramp rate is established to prevent undesirable effects due to rapid changes in loading or discharge. The ramping capability provides an estimate of how well a given component can adjust its power output to changing load requirements or market conditions. Upward and downward ramping should be assessed separately. According to NREL [24], one procedure to calculate the ramping capability of an individual component is to observe the maximum change in power output between any 2 hours over the year. For a generation plant, hours immediately before start-up and shut down should be eliminated from analysis. The observation period can be naturally shorter and consider the power output change on an hourly basis. Later the ramping capability is usually expressed in MW/min.

Formula

The Ramping Capability (Upwards) can be calculated based on the following formula (*i* is a time step in hours):

$$RC_{UP} = \min_{i=2:n}(P_{i-1} - P_i)$$

where: RC_{UP} – ramping capability upwards [MW/h], P_i – power output [MW].

The Ramping Capability (Downwards) can be calculated based on the following formula:

$$RC_{DOWN} = \max_{i=2:n}(P_{i-1} - P_i)$$

where: RC_{DOWN} – ramping capability downwards [MW/h].

Table 28: Potential ramping capability values

Category	Potential ramping capability values
Biomass boiler	20%/Hour-60%/Hour [25]
Gas boiler	10-20 MW/min [26]
Steam turbine	>1 MW : 10 % per minute
Biomass boiler + Steam turbine	Limited by the ramp rate of the Biomass Boiler
Gas boiler + steam turbine	Gas, oil 7% full load/min limited by the ramp rate of the Gas Boiler
Gas turbine	Start-up ramps that are steep in the very first megawatts: around 10 MWe/min ramps to minimum turndown level: around 4 MWe/min between minimum turndown and full capacity: up to 6 MWe/min ramps to full capacity: around 8 MWe/min
Gas Engine	250 - 300 MW/minute (50% per minute)
Battery	Continuous process

Category	Potential ramping capability values
Heat pump	Domestic HP: ramp up: 100% in 1min; ramp down: 100% in 0 // District Heating HP: 10% per 30 seconds
TES	n.a
Chiller	n.a
EN	From several kWs/kVARs to tens of MWs/MVARs, from milliseconds to minutes
DH	n.a.

5.1.5 Power Shifting Capability

Description

Power shifting capability is the relation between the change in power consumption and the duration that this shift can be maintained, before the normal operation of the system, i.e. thermal comfort, is jeopardized.

Power shifting capability is an indicator of power flexibility[4]. Power flexibility refers to the evolution of heating power during each time step of a 'flexibility control strategy', also described in the literature as 'optimal control' (OC).

To better understand what optimal control is, let's assume that we have a building configuration which includes a heat pump (HP), an additional electric heating (serving as power-to-heat conversion) and a thermal energy storage tank (TES). To investigate the flexibility towards the power grid, we would compare a reference control scenario to an OC scenario. A reference control example would be to assume that a typical controller uses the heat pump to supply heating. An OC example would be integrating a heat pump and optional electric heating with a thermal energy storage tank and aiming to optimize the total operational electricity costs. Hourly electricity prices would serve as a grid signal to optimal control and optimize flexibility towards the grid.

Formula

The power shift is defined as the difference between the heating power (or cooling power) during OC and the reference heating power during reference operation [27] [28] [29].

$$
\begin{aligned}
Powershiftingcapability(Q_\delta)[W] \\
&= HeatingpowerduringOC[W] - Heatingpowerduringreferencecontrol[W] \\
&= Q_{OC} - Q_{Ref}
\end{aligned}
$$

The duration t_δ this shift can be maintained is calculated as the duration until the thermal comfort boundaries are reached. The power shifting capability is then expressed as $(t_\delta Q_\delta)$.

[4] Energy flexibility can be calculated as the integral of power flexibility.

Using the configuration described in the paragraph above (HP, electric heater and TES), power shifting capability includes thermal power shifting $Q_{\delta,th}$, and electrical thermal shifting $Q_{\delta,el}$ calculated as follows:

$Q_{\delta,th} = (Q_{OC,th} + Q_{OC,th})$-$(Q_{Ref,th} + Q_{Ref,th})$

$Q_{\delta,el} = (Q_{OC,el} + Q_{OC,el})$-$(Q_{Ref,el} + Q_{Ref,el})$

5.1.6 Flexibility Factor

Description

The flexibility factor indicates the ability to shift the energy use from high to low price periods. If the energy use is similar in low and high price periods, the factor is 0. If no energy is used in high price periods, the factor is 1. In other words, the flexibility factor varies between −1 and 1 whereas −1 correlates to a highly inflexible controlled system and 1 indicates highest desired flexibility. One of the limitations of this factor is that other grid signals or climatic conditions will lead to different values of flexibility factor [27] [29].

Formula

$$FF = \frac{\int_0^{l(lowprice)} Qdt - \int_0^{l(highprice)} Qdt}{\int_0^{l(lowprice)} Qdt + \int_0^{l(highprice)} Qdt}$$

Where Qdt is the amount of power demand [W] over low and high-price periods l. To estimate the different pricing periods, standard deviation is assumed that relates to the electricity prices of the entire 24 h control horizon. Pricing periods that exceed the normal distribution with one standard deviation of −1σ and 1σ account for either low and/or high price periods.

5.1.7 Percentage of MES units integration

This metric indicates the share of multi energy system in covering the energy needs of the considered process, consumer, group of consumers.

The value of MES unit integration ranges from 0 to 1, where 1 means that the total energy demand has been covered by the MES.

5.1.8 Amount of flexibility

Description

Flexibility is the ability to deviate from the reference electric load or generation profile during a certain interval, which is called flexibility interval. The total power shift is integrated over the flexibility interval and expressed in units of energy.

The degree of flexibility varies between load or generation categories and it should only cause minimal disruption to consumer utility. Electric space and water heating and cold appliances have thermal storage properties which allow load to be curtailed, reduced or postponed.
For loads positive flexibility is the ability to increase power consumption during the flexibility interval and negative flexibility is the ability to decrease power consumption during the flexibility interval [30].

Formula

$$Amountofflexibility[kW] = Amountof\ load/generation\ deviationfromreference\ load/generation$$

$$MaximalPositiveFlexibility[kW] = MaximalModified\ Load/generation\ [kW] - Reference\ Load/generation\ [kW]$$

$$MaximalNegativeFlexibility[kW] = MinimalModified\ Load/generation\ [kW] - Reference\ Load/generation\ [kW]$$

5.1.9 Duration of availability of flexibility activation

Description

Duration of availability of flexibility activation, or otherwise flexibility interval is the time span during which the defined flexibility is available. This interval is typically the duration of load/generation deviation until comfort is breached or the maximum time, a certain power draw can be delayed or additionally called upon at a certain moment during the day [31].

Formula

$$Durationofavailabilityofflexibilityactivation(hours) = maximumtimeacertainpowerdrawcanbedelayed \lor additionallycalleduponatacertainmomentduringtheday$$

5.1.10 Maximum number of activations per time duration

Description

It is the upper limit of occurrences of a service' activation before the consumer utility is breached, or before MES functionality is challenged. The maximum number of activations per time duration varies per MES, technology coupling, product and service. Depending on the above, there are particular Quality of Service requirements that have to be respected.

5.1.11 Minimum duration of recovery between two activations

Description

Again, depending on the type of the flexibility units participating in a specific service, there might be some Quality of Service requirements that have to be respected and taken into account for the service characteristics' formulation.

5.2 Benefit 2: Increased sustainability, security of supply and quality of service in electricity supply and grid operation

Table 29: KPIs for benefit 2 Increased sustainability, security of supply and quality of service in electricity supply and grid operation (taken from Table 20)

KPIs	Layers				
	MES internal KPIs	MES output KPIs	MES aggregation KPIs	Service and market KPIs	Project level general KPIs
5.2.1 GHG emission	*				*
5.2.2 Energy not supplied		*		*	*
5.2.3 Minimization of energy consumption		*	*	*	*
5.2.4 Fuel energy savings ratio		*			*
5.2.5 Percentage utilization of electricity grid elements				*	*
5.2.6 Generated pollutant element	*				

5.2.1 GHGs emission

Carbon dioxide (CO_2) is a gas essential for life and is also known as a greenhouse gas (GHG) — a gas that absorbs and emits thermal radiation, creating the 'greenhouse effect'. Greenhouse gases (GHGs) are so called because they contribute to the greenhouse effect. The greenhouse effect describes the natural phenomenon where certain gases in the atmosphere increase the Earth's surface temperature due to an ability to trap heat, similar to the way in which glass traps heat in a greenhouse.

There are six main GHGs covered by the Kyoto Protocol [32]:

Carbon Dioxide – CO_2: Emitted mainly from the burning of fossil fuels, carbon dioxide accounted for some 86 per cent of the UK's human-induced (anthropogenic) GHG emissions in 2003. Typically quantified in tonnes of CO_2 per year.

Nitrous Oxide – N_2O: The main anthropogenic sources of nitrous oxide emissions are agriculture, transport, industrial processes and coal combustion. Nitrous oxide accounted for approximately 6 per cent of UK GHG emissions in 2003.

Hydrofluorocarbons – HFCs, *Perfluorocarbons – PFCs* and *Sulphur Hexafluoride – SF6:* Collectively known as 'F-gases', they are emitted mainly from air conditioning and refrigeration and industrial processes. Together, F-gases accounted for around 2 per cent of the UK's anthropogenic GHG emissions in 2003.

Methane – CH_4 natural methane can be found under the sea floor and below ground. It is the main component of natural gas. Methane is accounted for 20% of total radiative forcing. Releasing 1 kg of methane into the atmosphere is equivalent to roughly 25 kg of CO_2.

Each GHG has a different capacity to cause global warming, depending on its radiative properties, its molecular weight and its lifetime in the atmosphere. The so-called global warming potential (GWP) of a gas encapsulates these factors. The GWP used for the Kyoto Protocol is defined as the warming influence over a 100-year time horizon relative to that of carbon dioxide. The GWP of methane is 21 (i.e. a 1 kg emission of methane to the atmosphere will cause an equivalent warming effect as 21 kg of carbon dioxide over 100 years). GWP of nitrous oxide is 310, for F-gases GWP can be several thousands. GWP for carbon dioxide is, by definition, 1.

GHGs can be measured by recording emissions at source by continuous emissions monitoring or by estimating the amount emitted using activity data (such as the amount of fuel used) and conversion factors (e.g. calorific values, emission factors, oxidation factors). For instance, factors can be used to calculate the amount of CO2 emitted as a result of burning a particular quantity of oil in a heating boiler.

$$TotalGHGemissions = CO2emissions + CO2equivalentemissionsofotherGHGsemitted$$

Conversion factors are published by a number of agencies and their categorization is presented in Table 30. In the UK, it is recommended that companies not already reporting for regulatory purposes use Defra's conversion protocols. These can be found on Defra's website, in the annex sections of Defra's Guidelines for Company Reporting on Greenhouse Gas Emissions. Another reference for the Member States of the European Union can be found in [33].

Table 30: Conversion factors categorized as above [34].

Category	Explanation
Fuel	For example, conversion of tonnes of oil used in boilers to tonnes of CO_2 emitted.
Combined Heat and Power	Conversion of kWh to tonnes of CO_2 emitted.
Electricity conversion factors	For example, conversion of kWh to tonnes of CO_2 emitted.
Typical process emissions	Identification of emission derived from certain processes. For example, cement production results in CO_2 emission.
Greenhouse gas conversion protocols	Conversion of individual GHGs to CO_2 equivalents
Transport: Road, Rail, Air, Road Freight and Other Freight	For example, conversion of miles travelled in medium-sized petrol car to tonnes of CO_2 emitted.

5.2.2 Energy not supplied

Description

Energy not supplied gives the estimation of the energy that has not been supplied to the connected load due to interruptions and outage events over a year.

Formula

The total Energy Not Supplied (ENS) over a year can be calculated by the following formula:

$$ENS(MWh) = \sum_{N_y} Ld_i(MW) * r_i(hours)$$

Where Ld_i is the total load disconnected due to an interruption event, r_i is the duration of the interruption event i and N_y is the total number of interruptions in a year.

5.2.3 Minimization of Energy Consumption

Description

The energy consumption minimization is a common metric used in optimization models. It can refer to the minimization of energy consumed with regard to the benchmark scenario. The energy consumption minimization can be achieved by optimizing the system configuration or/and operation, improving the performance of its components, replacing not-efficient components.

Formula

The value of this metric can be calculated by the following formula:

$$MofEC = \left(1 - \frac{E^{OS}}{E^{B}}\right) * 100\%$$

where: $MofEC$ – minimization of energy consumption [%], E^{B} – energy consumption in benchmark scenario [MWh], E^{OS} – energy consumption in the optimized system [MWh].

The MofEC metric takes percentage values ranging theoretically from -∞ to 100%. If the value is negative the system considered consumes more energy than the benchmark scenario and no minimization of energy consumption has been achieved. The energy consumption can be presented in different units as long as they are consistent in the equation. The metric can be expanded and calculated separately for fuel, thermal and electrical energy as their value strongly depends on the multi-energy system operating situation/context.

Example: It is assumed that the heating system (heat pump and electric boiler) will be equipped with thermal storage. The parameters of the new system have been optimized and operation strategy implemented. To calculate MofEC, it is mandatory to calculate the electrical energy consumption (heat demand does not change in this example) for the benchmark system and the system equipped with thermal storage. It is expected that the flexibility resulting from thermal storage will increase the use of heat pump and thereby reduce the overall electricity consumption.

5.2.4 Fuel energy savings ratio

Description

The Fuel Energy Savings Ratio (FESR) is broadly used to quantify the energy savings when multi generation is used instead of separate generation to meet the same energy demand.

The FESR indicates the primary energy saving that for example a CHP system can bring with respect to the 'separate production' of electricity and heat in reference production technologies (electricity produced by conventional power plants and heat in gas boilers). FESR is also known as primary energy saving ratio.

Formula

It is defined as:

$$FuelEnergySavingsRatio(FESR) = \frac{primaryenergysavings}{primaryenergyused \in theseparatesystem}$$

In the particular example of the CHP, then the formula would become:

$$FuelEnergySavingsRatio(FESR) = 1 - \frac{1}{\frac{n_e}{n_{er}} + \frac{n_h}{n_{hr}}}$$

Where n_e is the efficiency of a cogeneration unit for producing electricity, n_h is the efficiency of the cogeneration unit for producing useful heat, n_{er} is the efficiency reference value for the separate production of electricity and n_{hr} the efficiency reference value for the separate production of heat [35] [36] [37].

5.2.5 Percentage Utilization of Electricity Grid Elements

Description

This metric is used to determine the efficiency and utilization of the electricity grid elements.

Formula

For each grid component the percentage utilization can be calculated based on the following formula:

$$PUofGE = \frac{U^{Avg}}{C^{Max}}$$

Where: $PUofGE$ – percentage utilization of grid elements [%], U^{Avg} – average value of grid element utilization [corresponding unit], C^{Max} – maximal capacity of grid element [corresponding unit].

Example 1: in a given electricity network there is a DC cable. Its maximal capacity is 10 MW. The average power transferred by the cable (over the considered period) was 4 MW. Considering the above formula, the percentage utilization of this electricity grid element was 40%.

Example 2: the electricity grid utilizes a diesel generator as a backup energy source. Its nominal capacity is 4 kW. Over the considered period (year) the generator delivered 4 MWh of electrical energy. Considering the above formula, the average utilization of this grid element is 11.4% (4000 kWh/(4 kW * 8760)). Note: in this case it is the same value as for the capacity factor.

Additional reading can be found in the following references [38] [39] [40] [41] [42].

5.3 Benefit 3: Increase of generation and utilization of renewable energy

Table 31: KPIs related to benefit 3 'Increase of generation and utilization of renewable energy' (taken from Table 21)

KPIs	Layers				
	MES internal KPIs	MES output KPIs	MES aggegation KPIs	Service and market KPIs	Project level general KPIs
Share of electrical energy produced by renewables		*		*	*
Energy not withdrawn from renewable sources due to congestion and/or security risks		*		*	*

5.3.1 Share of electrical energy produced by renewables

Description

This metric is used to indicate the contribution of renewable energy sources in covering the energy demand in the considered system.

Formula

For calculating this metric the following formula can be applied:

$$SofR = \frac{\sum_{i=1}^{n} E_i^{Res}}{\sum_{i=1}^{n} E_i^{D}}$$

Where $SofR$ – share of renewables [%], E_i^{Res} – electrical energy produced by renewables [kWh], E_i^{D} – electricity demand, n – length of the considered analysis period [hours].

For consideration:

- It must be clearly stated what are the system boundaries. Energy produced by renewables but not used for covering the demand (curtailed, sold to the grid) is excluded from the calculations.
- Units in the equation are just a suggestion. Users may freely apply different time steps and units of energy as long as they are coherent.

Example: the total electricity demand in a considered system was 100 kWh. By adding a PV system with battery, the electricity acquired from the grid was reduced to 70 kWh. The national energy mix consists of 20% renewables and 80% conventional fuels. Considering the above formula, the share of electrical energy produced by renewables amounts to (30 kWh + 0.2*70 kWh)/100 kWh = 4%.

5.3.2 Energy not withdrawn from renewable sources due to congestion and/or security risks

Description

This metric is used to calculate the share of energy from renewable sources which could have been produced but had to be curtailed/rejected due to the power grid constraints.

Formula

The share of curtailed renewables generation (RES_Curtel) is calculated as follows:

$$RES_{Curtel} = \frac{\sum_{i=1}^{n} RES_{C_i}}{\sum_{i=1}^{n} RES_{T_i}}$$

where: RES_{C_i} – curtailed energy generation from renewables [MWh], RES_{T_i} – potential energy generation from renewables with no grid constraints [MWh].

The RES_Curtel metric can be expressed as a percentage of theoretical renewables generation [%], but also as a volume of energy [MWh], without reference to the theoretical generation.

Example (simplified): a 10 MW wind park and 5 MW PV installation were connected by a transmission network of 12 MW capacity to the main grid. Over the considered period (100 hours) it was observed that during 10 hours the cumulative energy generation from both sources could be equal 14 MW. Which is 2 MW above network capacity. In the remaining hours the sources operated with average power of 7 MW. Considering above the RES_Curtel index equals to:

$$RES_{Curtel} = \frac{2 * 10}{(7 * 90) + (2 * 10)} = 3.07\%$$

Additional reading can be found in reference [43].

5.4 Benefit 4: Provision of cost-effective flexibility in the electrical power system

Table 32: KPIs related to benefit 4 'Provision of cost-effective flexibility in the electrical power system' (taken from Table 22)

KPIs	Layers				
	MES internal KPIs	MES output KPIs	MES aggegation KPIs	Service and market KPIs	Project level general KPIs
5.4.1 Energy Conversion Plant Profitability		*		*	*
5.4.2 Production Cost		*		*	
5.4.3 Operational failure risk		*	*	*	*
5.4.4 Energy Operational Costs (fuel and electricity input costs net of profit from electricity sold back to the grid)		*		*	*
5.4.5 Success factor of service delivery	*		*	*	
5.4.6 Return on Investment	*			*	*

5.4.1 Energy Conversion Plant Profitability

Description

The efficient operation of an energy conversion plant shall be measured by the plant's profitability. It is calculated as the difference between the operating revenue and operating expenses. This profitability is the operating profit before payment of interest, tax, depreciation and amortization (PBITDA).

Formula

$$EnergyConversionPlantProfitability = Operatingrevenueoftheplant - Operatingexpensesoftheplant$$

Where the operating revenue of the plant consists of [44]:

a) Energy revenue - revenue earned by the sale of net electrical energy at the unit energy price [€ / MWh]
b) Capacity Revenue - revenue earned by the sale of plant capacity at the rate settled [€ /kW]

The operating expenses consist of:

a) O&M costs – total direct costs to operate and maintain the plant
b) A&G (administrative and general costs) – total indirect costs including the allocated costs from the headquarters towards O&M of the plant
c) Fuel costs-total costs associated with the fuel utilized for the operation of the plant, or more generally, the cost of purchased energy.

Operational costs can be addressed as:

$$(Costofoperation)[€] = \sum Costofturnon[€] + Costofturnoff[€] + Costofresource * operationresourcesconsumption$$

The needed inputs and key parameters in the calculation of the KPI are: cost of turn on, cost of turn off, cost of resource, operation resources consumption

Examples from MES are given below:

- In [45], the assessment indicator (objective function to minimize) is the operational costs (fuel and electricity input costs net of profit from electricity sold back to the grid) subject to given multi-energy demand constraints.
- In [16], the assessment criterion for minimization is the operational costs (net of profits from electricity sold), with the option of adding a cost to wasted heat too. That paper also gives further insights on the system operational assessment by explicitly calculating the marginal costs relevant to each operational constraint as the dual prices of the proposed linear program. Such dual prices indicate the value change in the objective function as a consequence of unitary change in one of the constraints and are given by the Lagrangian multipliers in the Karushe Kuhne Tucker first-order optimality conditions.
- In [46], there is a comprehensive economic assessment technique for CHP and DH.
- In [47], there is a planning assessment of a CHP-DH system where daily profits (difference between revenues and costs) are maximized through optimal operational control strategies.

5.4.2 Production Cost

Description

Production cost is defined as the sum of Operational & Maintenance ($O \wedge M$) costs of a plant (or a production unit) plus the fuel costs, for a given period, divided by the net generation produced over the same period.

Formula

$$productioncost[€/MWh] = \frac{O \wedge M[€] + fuelcost[€]}{netgeneration[MWh]}$$

Total O&M cost is the total non-fuel direct O&M cost. Fuel cost is the total cost associated with a load of fuel which is burnt in a given period. Net generation is the energy produced during the time period [44].

5.4.3 Operational Failure Risk

The risk index is computed according to a (operational) planning activity; the risk expresses the impact of adverse event occurrence with respect to its probability. For instance, the adverse event occurrences refer to failure of the uncertain variables taken into account in the operational model, the set of variables include: load demand, renewable production forecast (wind and photovoltaic), prices for the energy market, prices for the service market, and so on.

The risk index is computed by the probability of each adverse event time the impact of this event occurrence on the overall system. It is combined according to specific strategies within the operational model of the system.

The needed inputs and key parameters in the calculation of this KPI are: the set of adverse events, probability and impact for each event of the set.

In the literature [48], it is considered in renewable energy plants (typically wind and hydro generation) over a planning horizon T. In each decision stage, the operational plan has to verify whether the load can be supplied by renewable generation or by the main grid.

5.4.4 Energy Operational Costs (fuel and electricity input costs net of profit from electricity sold back to the grid)

Description

The purpose of this metric is to quantify the operation cost of the system.

The time resolution considered in the study is normally associated to the level of detail the multi-energy load is known with and to the relevant market price resolution; this resolution can for instance be down to 5 min (as in some electricity balancing markets) or half-hourly/hourly (particularly depending on real-time electricity pricing). Operational analysis intervals are typically in the order of a day, a week, or one to several months, depending on the purposes of the study (for instance, resource scheduling based on day-ahead market prices), the presence of short-term (intra-daily) or long-term (seasonal) storage, and the need for capturing specific seasonality effects.

Formula

The adopted metric is derived from Chicco and Mancarella [36] [45] and reads: *"The energy cost is calculated by taking into account the fuel price (FP) and two electricity prices, for the electricity bought* *from the electricity system (EB) and ES for the electricity sold to the electricity system. All prices are expressed in [€/MWh]."* Later, the operational cost (OC) can be presented in the following equation:

$$OC = FP * F + EB * W_i - ES(W_o - W_d)$$

Where: OC – operational cost [€], FP – fuel price [€/MWh], F – fuel thermal content [MWh], EB – electricity price from the electricity system [€/MWh], W_i – electricity bought from the electricity system [MWh], ES – electricity price when sold to the electricity system [€/MWh], W_o – electricity generation [MWh], W_d – electricity demand [MWh].

5.4.5 Success factor of service delivery

Description

In MAGNITUDE, a different variety of services will be proposed to provide flexibility. To better monitor the progress of the newly proposed mechanisms, it is important to measure the successful operation of the proposed schemes, which is mainly the actual outcome of a delivered service versus the contracted service that was agreed to be delivered.

Formula

$$Successfactorofservicedelivery[\%] = \frac{Servicerequestedpower[kW]}{Servicedeliveredpower[kW]} * 100$$

5.4.6 Return on investment

Description

Return on Investment (ROI) is a performance measure used to evaluate the efficiency of an investment or compare the efficiency of a number of different investments. ROI tries to directly measure the amount of return on a particular investment, relative to the investment's cost.

Formula

The Return on Investment is calculated by the following formula and the result is expressed as a percentage or a ratio:

$$ROI[\%] = \frac{Gain\ from\ Investment[€] - Cost\ of\ Investment[€]}{Cost\ of\ Investment[€]}$$

5.5 Benefit 5: Create market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (directly or through aggregation)

Table 33: KPIs related to benefit 5 'Create market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (taken from Table 23)

KPIs	Layers				
	MES internal KPIs	MES output KPIs	MES aggregation KPIs	Service and market KPIs	Project level general KPIs
5.5.1 Market price of provided energy and services				*	*
5.5.2 Operational failure risk		*	*	*	*
5.5.3 Net revenue of market participants			*	*	*
5.5.4 Number of addressed markets		*	*	*	*
5.5.5 Number of flexibility resources in the aggregator pool			*	*	*
5.5.6 Time needed to simulate 24h of operation in the aggregation platform			*		
5.5.7 Percentage of load demand participating in market-like schemes for demand flexibility			*	*	*
5.5.8 Economic Efficiency/Social Welfare				*	*
5.5.9 Limitation of loss of comfort		*	*	*	*
5.5.10 Spark spread ratio	*			*	
5.5.11 Computational Complexity			*	*	
5.5.12 Reduction of the number of communication channels				*	*
5.5.13 Transparency				*	*

5.5.1 Market price of provided energy and services

Description

In case of electricity, the market price of provided energy is the generation weighted average price of the electricity sold over a given period. The generation weighted average price is the equivalent price of all energy sold during the period.

The market price of provided services (such as capacity services), either related to availability of flexibility or capacity could be calculated in a similar fashion. In the case of an electricity capacity service for example, the market price of provided service is the capacity weighted average price of electricity capacity sold over a given period.

Formula

For energy:

Assuming that for a period i, the amount G_i (in MWh) of energy was sold for price P_i (in €/MWh) and for a period j, the amount G_j was sold for price P_j then the generation weighted average price is [44]:

$$generationweightedaverageprice = \frac{(G_i * P_i) + (G_j * P_j)}{totalgeneration}$$

For a capacity service:

Assuming that for a period i, the amount G_i (in MW) of capacity was sold for price P_i (in €/MW) and for a period j, the amount G_j was sold for price P_j then the capacity weighted average price is:

$$capacityweightedaverageprice = \frac{(C_i * P_i) + (C_j * P_j)}{totalcapacity}$$

5.5.2 Operational Failure Risk

The KPI is defined in 5.4.3.

5.5.3 Net revenue of market participants

Description

A net revenue is an indicator used the economic performance of the system from the perspective of market participants. The market participant is defined as a decision maker/economic agent in the model. From the MAGNITUDE perspective by market participants we can understand the system/service owners/operators, entities directly influenced by the system operation or service provided, owners of the infrastructure or other parties affected by the system or service under consideration.

Formula

Net revenue can be calculated by applying the following formula:

$$NR = GR - SC$$

Where: NR – net revenue [€], GR – gross revenue [€], SC – service/system directly related costs [€].

The gross revenue is the “raw” income from providing services. It can be identified with the price paid by the buyers of the services. The service/system related costs are associated with distributing, marketing and selling the product or service.

5.5.4 Number of addressed markets

This KPI describes the ability of a flexible unit or an aggregated pool to participate in various markets for electric energy, capacity or ancillary services. In MAGNITUDE this KPI describes a requirement for the Aggregation Platform. The participation on different markets depends on several factors, like amount of flexibility, ramping behaviour, precision of control of generation, formal prequalification granted by the market operator, market specifications, implementation of communication APIs, etc.

In case of expected price differences or deviations, the market participant can offer products for the following trading period to the markets with highest revenue expectations. A higher number of addressed markets reduces the dependency on market price fluctuations and is a fundament for more stable revenue streams and a more resilient business model.

5.5.5 Number of flexibility resources in the aggregator's pool

A number of technologies can provide flexibility, including centralised or de-centralised generation, demand side participation, energy storage, big industrial sites or other sectors such as DH. Their flexibility potential can be exploited via aggregation and its function of pooling de-centralised generation and/or consumption to provide energy and services to actors within the system. The aggregator could afterwards gather, manage and utilize that potential to participate in the market.

The flexibility potential (aggregated energy in kilowatt-hours) of similar resources and technologies is dependent on the number of the resources that an aggregator manages in his pool.

In an aggregated pool a higher number of flexibility resources provide a more reliable service because of statistical reduction of relative output fluctuations and the possibility to plan internal backup. On the other hand, the computational effort may increase fast with increasing count of pooled units. Pools dedicated to ancillary service provision usually contain 5 – 50 flexible units, while pools providing less critical flexibility services may contain several 100s or even 1000s of units (e.g. if a supplier pools private customer's heat pumps and uses their flexibility to reduce consumption during high-price hours).

5.5.6 Time needed to optimize a schedule for 24h of operation

This KPI describes the computation time of an algorithm or system required to fulfil an optimization task and calculate optimized trading schedules for the next trading period.

Given to the trend on many markets, that the timespans between gate closure and delivery time are reduced towards 30 min or less and product durations for ancillary services are shortened as well, a quick overview for a market participant and fast and powerful short-term optimization algorithms gain importance in portfolio management and energy trading. Additionally, intraday trading gets more important due to increasing amount of fluctuating renewable generation. As a consequence, the requirements for bidding systems and aggregation platforms are raised and more powerful algorithms must be implemented.

5.5.7 Percentage of load demand participating in market-like schemes for demand flexibility

Description

The objective of this metric is to calculate the share of electrical or heat load which can participate in the demand side management strategies. For the purpose of calculation, a time frame has to be specified. For example, the flexible load on an hourly, daily, weekly, and so on, basis. For example, realization of some energy demanding processes can be postponed by only one hour ; whereas other processes can be realized in a couple of days.

Formula

The percentage of load demand participating in demand flexibility options can be calculated based on the following formula:

$$SofLinDF = \frac{\sum_{i=1}^{n} E_i^F}{\sum_{i=1}^{n} E_i^D}$$

Where: SofLinDF – share of load in demand flexibility [%], E_i^F – flexible load [kWh], E_i^D – energy demand [kWh].

Example: the manufacturing facility on a weekly basis has an electricity demand of 200 MWh, from which 10 MWh can be considered as flexible load. Considering the above formula, the value of SofLinDF metric is 0.5%.

Additional reading can be found in the references [49] [50].

5.5.8 Economic Efficiency/Social Welfare

In classic cost-benefit economics, economic efficiency is measured through social welfare or surplus, the sum of economic surpluses across all market parties.

5.5.9 Limitation of loss of thermal comfort

Description

Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation” [51]. The specification of air temperature, radiant temperature, humidity, air speed, metabolic rate and clothing insulation is often considered to be sufficient to estimate the average degree of satisfaction with given environmental conditions.

European Standard EN 15251 specifies diverse criteria for the indoor environment [52]. Several classes of requirements are specified, as summarized in Table 34 [53] [52]:

Table 34: Applicability of categories used in EN 15251

Category	Applicability
I	High level of expectation, recommended for spaces occupied by very sensitive persons
II	Normal level of expectation, to be used for new buildings
III	Moderate level of expectation, acceptable for existing buildings
IV	Only acceptable for limited time

Based on the selected criteria (comfort category) a corresponding temperature interval is established regarding different categories.
According the European Standard EN 15251, recommended values for the acceptable range of the indoor temperature for heating and cooling are presented in Table 35 considering metabolic rate [W/m^2] and clothing insulation [m^{2}K/W]:

Table 35: Temperature ranges for hourly calculation of cooling and heating energy in three categories of indoor environment used in EN 15251

Type of building or space	Category	Temperature range for heating, [C] Clothing ~ 1,0 clo	Temperature range for cooling, [C] Clothing ~ 0,5 clo
Residential buildings, living spaces (bedrooms, living rooms etc.) Sedentary activity ~1,2 met	I	21.0-25.0	23.5-25.5
	II	20.0-25.0	23.0-26.0
	III	18.0-25.0	22.0-27.0
Residential buildings, other spaces (kitchens, storages etc.) Standing-walking activity ~1,5 met	I	18.0-25.0	
	II	16.0-25.0	
	III	14.0-25.0	
Offices and spaces with similar activity (single offices, open plan offices, conference rooms, auditorium, cafeteria, restaurants, class rooms, Sedentary activity ~1,2 met	I	21.0-23.0	23.5-25.5
	II	20.0-24.0	23.0-26.0
	III	19.0-25.0	22.0-27.0
Kindergarten Standing-walking activity ~1,4 met	I	19.0-21.0	22.5-24.5
	II	17.5-22.5	21.5-25.5
	III	16.5-23.5	21.0-26.0
Department store Standing-walking activity ~1,6 met	I	17.5-20.5	22.0-24.0
	II	16.0-22.0	21.0-25.0
	III	15.0-23.0	20.0-26.0

Below, two relevant temperature–based indicators are considered, depending on the input data that is available for the calculations.

5.5.9.1 Temperature-based indicator 1: Thermal discomfort indicator [C]

Formula

Thermal discomfort indicator $Th_{discomf}$ **[°C]:** is calculated as the quantity in degrees that exceeds the comfort temperature range during the occupied hours of the building depending on the type of the building and category as defined in EN 15251 and Table 34 and Table 35.

For not occupied hours:

$$Th_{discomf} = 0$$

For occupied hours:

$$Th_{discomf} = \begin{cases} 0, \Theta_{o,limit,lower} < \Theta_o < \Theta_{o,limit,upper} \\ \Theta o - \Theta_{o,limit} \Theta o < \Theta_{o,limit,lower} \vee \Theta_{o,limit,upper} < \Theta o \end{cases}$$

5.5.9.2 Temperature-based indicator 2: Uncomfortable hours [h]

Formula

Uncomfortable hours $Time_{discomf}$ **[%]:** The limitation of loss of thermal comfort can be calculated by the limitation of number of occupied hours with uncomfortable thermal environment.

It is the percentage of hours outside of comfortable range according to EN 15251 with category III. It corresponds to a moderate level of expectation, meaning that the non-complying hours are likely uncomfortable.

Alternatively, an index can be defined expressing the composition of thermal discomfort indicator $Th_{discomf}$ with the time the discomfort took place:

$Discomfort = Th_{discomf} * Time_{discomf}$

5.5.10 Spark spread ratio

Description

The spark spread is a common metric for estimating the profitability of natural gas-fired electric generators. The spark spread is the difference between the price received by a generator for electricity produced and the cost of the natural gas needed to produce that electricity. It is typically calculated using daily spot prices for natural gas and power at various regional trading points.

Formula

Spark spreads are calculated using the following equation:

$$Sparkspread[€/MWh] = Powerprice[€/MWh] - naturalgasprice[€/mmBtu] * heatrate[mmBtu/MWh]$$

A key component of the spark spread equation is the heat rate, or measure of efficiency, of a generating unit. Those marketing the output of a unit will use the unit's tested heat rate to assess its profitability. Market participants and observers rely on a generic benchmark to assess overall market conditions.

In the literature [54] a benchmark heat rate of 7,000 Btu/kWh is found to be used and represents a new and efficient natural gas combined-cycle generator. One kWh has a heat content of 3,412 Btu. A generator that uses 7,000 Btu to produce one kWh has a conversion efficiency slightly below 50% [5]. Less efficient units have higher heat rates, and therefore require more natural gas to produce a kWh of electricity. A combined-cycle unit, which combines a combustion turbine with a steam turbine, is more efficient than a steam turbine alone [55].

5.5.11 Computational Complexity

Description

Computational complexity is a computer science concept that focuses on the amount of computing resources needed for particular kinds of tasks, such as clearing algorithms.

In MAGNITUDE, we consider the total computational time for a given number of computational resources as the metric to measure the complexity of the problem.

Formula

Time complexity is commonly estimated by counting the number of elementary operations performed by the algorithm, supposing that each elementary operation takes a fixed amount of time to perform. Thus, the amount of time taken, and the number of elementary operations performed by the algorithm are taken to differ by at most a constant factor.

Since an algorithm's running time may vary for different inputs of the same size, one commonly considers the worst-case time complexity, which is the maximum amount of time required for inputs of a given size. Time complexity is generally expressed as a function of the size of the input. Since this function is generally difficult to compute exactly, and the running time for small inputs is usually not consequential, one commonly focuses on the behaviour of the complexity when the input size increases — that is, the asymptotic behaviour of the complexity. Therefore, the time complexity is commonly expressed using big *O* notation, typically:

$$O(n), O(n \cdot logn), O(n^a), O(2^n)$$

---

[5] The U.S. Energy Information Administration gives a general explanation for how to translate a heat rate value into a power plant's efficiency value. To express the efficiency of a generator or power plant as a percentage, you can divide the equivalent Btu content of a kWh of electricity (3,412 Btu) by the heat rate. For example, if the heat rate is 10,500 Btu, the efficiency is 32.5% (since 3,412 Btu / 10,500 Btu = 32.5%)

etc., where n is the input size in units of bits needed to represent the input [56].

5.5.12 Reduction of the number of communication channels

Description

To evaluate the entire multi energy systems including the single (or coupling) technology as well as aggregation of technologies, and to explore the new business opportunities, one should understand the complexity of interaction between stakeholders.

Stakeholders can be any individuals, a group or an organization that may affect, be affected by, or perceive itself to be affected by a decision, activity or outcome from the project. E.g., in the daily electricity supply business and ancillary service provision, there is an increasing number of required data exchange between different parties (supplier, trader, market operator, balance responsible party, TSO, etc.), which lead to increasing complexity and effort in communication. For the sake of increased resilience, reduced costs and data security, the number of communication channels should be optimized by means of appropriate design of market organisation and data handling systems.

Formula

The total number of potential communication channels is given by the following formula where n represents the number of stakeholders:

$$numberofpotentialcommunicationchannels = \frac{n(n-1)}{2}$$

5.5.13 Transparency

Market transparency is defined as the ability of market participants to observe information about the trading process. Information can be related to current or past prices, quotes, offers, volumes and the identities and motivations of market participants.

This is a qualitative KPI which can be measured as: High (H)/ Medium (M)/ Low (L).

6 Conclusions

MAGNITUDE aims at developing business and market mechanisms, as well as coordination tools to provide flexibility to the European electricity system, by enhancing the synergies between electricity, heating/cooling and gas systems. The overall goal is to support the cost-effective integration of renewable energy sources in the power system and to enhance the security of supply.

This report summarizes the process of selecting the most important key performance indicators (KPI), which can be used to evaluate the realization of simulated flexibility options. The selection of KPIs is based on a hybrid approach consisting of literature review, questionnaire analysis and expert knowledge of partners involved in the project execution.

Considering the scope of the project and nature of multi-energy systems (MES), the KPIs are classified into four categories: technical, economic, environmental and social/policy. They are also divided into five layers in order to enable the assessment across system levels: multi-energy system internal KPIs, which measure mostly the flexibility options of individual components forming a MES; MES output KPIs, which measure the flexibility options offered by MES; MES aggregation KPIs, which measure the performance of the aggregation platform; services and market KPIs, which measure the performance of MES or aggregation of MESs which provides a service inside given market structures; and project level general KPIs, which measure the performance of services with regard to the MAGNITUDE project targets.

Based on the performed analysis, 37 KPIs have been selected, each of them corresponding to a particular benefit and also to a certain process inside MAGNITUDE. As explained in Sections 4 and 5, these KPIs are not meant to be calculated as an exhaustive list to quantify MAGNITUDE performance. In contrast, project partners are encouraged to decide which KPIs from Section 5 are relevant with respect to the benefit that they are trying to address and the specific process that they are involved in MAGNITUDE.

Table 36: Summarizing table with the Selected KPIs per category and layer

Category	Layer				
	MES Internal	MES output	MES aggregation	Services and Markets	Project level general
Technical	• Availability factor • Start-up time • Ramping Capability • Power Shifting Capability • Flexibility Factor • Success factor of service delivery	• Energy Efficiency • Power Shifting Capability • Minimization of Energy Consumption • Flexibility Factor • Amount of flexibility • Duration of availability of flexibility activation	• Percentage of MES unit integration • Minimization of Energy Consumption • Amount of flexibility • Duration of availability of flexibility activation • Success factor of service delivery • Computational Complexity	• Energy Efficiency • Minimization of Energy Consumption • Percentage Utilization of Electricity Grid Elements • Percentage of MES unit integration • Amount of flexibility • Duration of availability of flexible activation	• Energy Efficiency • Minimization of Energy Consumption • Percentage Utilization of Electricity Grid Elements • Percentage of MES unit integration • Amount of flexibility • Duration of availability of

Category	Layer				
	MES Internal	MES output	MES aggregation	Services and Markets	Project level general
		• Share of electrical energy produced by renewables • Energy not withdrawn from renewable sources due to congestion and/or security risks • Limitation of loss of comfort • Energy not supplied • Number of addressed markets • Maximum number of activations per time duration • Minimum duration of recovery between two activations	• Number of addressed markets • Number of flexibility resources in the aggregator pool • Time needed to simulate 24h of operation in the aggregation platform • Percentage of load demand participating in market-like schemes for demand flexibility • Limitation of loss of comfort • Maximum number of activations per time duration • Minimum duration of recovery between two activations	• Share of electrical energy produced by renewables • Energy not withdrawn from renewable sources due to congestion and/or security risks • Success factor of service delivery • Computational Complexity • Number of addressed markets • Number of flexibility resources in the aggregator pool • Time needed to simulate 24h of operation in the aggregation platform • Percentage of load demand participating in market-like schemes for demand flexibility • Limitation of loss of comfort • Energy not supplied • Maximum number of activations per time duration • Minimum duration of recovery between two activations	flexible activation • Share of electrical energy produced by renewables • Energy not withdrawn from renewable sources due to congestion and/or security risks • Number of addressed markets • Number of flexibility resources in the aggregator pool • Time needed to simulate 24h of operation in the aggregation platform • Percentage of load demand participating in market-like schemes for demand flexibility • Limitation of loss of comfort • Energy not supplied • Success factor of service delivery

Category	Layer				
	MES Internal	MES output	MES aggregation	Services and Markets	Project level general
Economic	• Spark Spred Ratio • Return on Investment	• Production Cost • Energy Conversion Plant profitability • Operational failure risk • Energy operational Cost • Economic Efficiency	• Operational failure risk	• Market price of provided energy and services • Production Cost • Energy Conversion Plant profitability • Operational failure risk • Operational Cost • Net Revenue of Market Participants • Economic Efficiency • Transparency • Spark Spred Ratio • Return on Investment	• Market price of provided energy and services • Energy Conversion Plant profitability • Operational failure risk • Energy operational Cost • Net Revenue of Market Participants • Economic Efficiency • Transparency • Return on Investment
Environmental	• Generated pollutant element • GHG emission	• Fuel energy savings ratio			• GHG emission • Generated pollutant element • Fuel energy savings ratio
Social/policy				• Reduction of the number of communication channels	• Reduction of the number of communication channels

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APPENDIX 1 - Full KPIs list from the literature (prior to the final selection)

Table 37: Full KPIs list (includes all the relevant KPIs that have been identified in the literature)

Number	KPIs
1	Start Up time
2	Energy Efficiency
3	Availability Factor
4	Running Plant Factor
5	Operating cycle
6	Unit capability factor
7	Power Capacity Reserve margin
8	Load Factor
9	Ramp rate
10	Frequency Excursions
11	Voltage Excursions
12	Energy not supplied
13	System Minutes Lost
14	Flexibility factor (FF)
15	Power Shifting capability
16	Percentage of MES units integration, revenues for the aggregator
17	Electrical network stability
18	Percentage of load demand participating in market-like schemes for demand flexibility
19	Share of electrical energy produced by renewable sources
20	Duration and frequency of interruptions per customer
21	Energy not withdrawn from renewable sources due to congestion and/or security risk
22	Energy Conversion Plant profitability
23	Production cost
24	Return on investment
25	Market price of provided energy and services
26	Utility Asset Costs
27	Costs and revenues arising from system operation
28	Operational failure risk
29	Economic efficiency/ Social Welfare
30	Economic efficiency/ Price of Anarchy
31	Transparency
32	Revenue for the network operator from the service
33	Maximization of social welfare
34	Fuel energy savings ratio
35	GHG emission
36	Generated pollutant element
37	Public safety and acceptability
38	Reduction of the number of communication channels
39	Abiotic depletion potential
40	Energy operational costs (fuel and electricity input costs net of profit from electricity sold back to the grid)
41	Incremental heat rate indicators

Number	KPIs
42	Storage efficiency
43	Hosting capacity for MES in the electrical system
44	Minimum time needed to get the specified power
45	Revenues for the aggregator
46	Success factor of service delivery
47	Duration of successful service delivery
48	Relation between power demand and market price for electricity
49	Percentage utilisation (i.e. average loading) of electricity grid elements
50	Additional high-value product to be traded
51	Spark-spread ratio
52	Modifications of electricity consumption patterns after new pricing schemes
53	Minimization of Energy consumption
54	Satisfaction of grid users with the ‘grid’ services they receive
55	Optimised use of capital and assets
56	Ratio of reliably available generation capacity to peak demand
58	Limitation of loss of comfort
59	Electricity import capacity
60	Amount of flexibility
61	Wear and tear of equipment
62	Ability of storage to follow a scheduled profile
63	Duration of availability of flexibility activation
64	Maximum duration of activations
65	Maximum number of activations
66	Net revenue of market participants
67	Computational complexity
69	Number of addressed markets
70	Number of flexibility resources in the aggregator pool
71	Time needed to simulate 24h in the aggregation platform

Table 38: KPIs identified in the literature to measure 'Increased Sustainability and Security of Supply'

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggregation KPIs	Service and market KPIs	Project level general KPIs
Increased Sustainability , Security of Supply and Quality of Service in Electricity Supply and Grid Operation	GHG emission	Environmental					*
	Generated pollutant element	Environmental					*
	Minimization of Energy Consumption	Technical		*	*	*	
	Public Safety and Acceptability	Social				*	*
	Duration and Frequency of interruptions per customer	Technical		*		*	*
	Satisfaction of grid users with the grid services they receive	Technical			*	*	*
	System Minutes Lost	Technical		*			*
	Electrical Network Stability	Technical		*		*	*
	Energy not supplied	Technical		*		*	*
	Ratio of reliable available generation capacity to peak demand	Technical				*	*
	Power capability reserve margin	Technical		*		*	

	Load factor	Technical	*	*		*	
	Frequency Excursions	Technical				*	*
	Voltage Excursions	Technical				*	*
	Costs and revenues arising from system operation	Economic				*	*
	Optimised use of capital and assets	Technical		*		*	*
	Percentage Utilization of Electricity Grid Elements	Technical				*	*
	Wear and tear of equipment	Technical		*		*	

Table 39: KPIs identified in the literature to measure 'Increase flexibility potential from MES operation in a synergetic MES environment'

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggregation KPIs	Service and market KPIs	Project level general KPIs
Increase flexibility potential from MES operation in a synergetic MES environment	Start-up time	Technical	*				
	Availability factor	Technical	*				
	Running Plant Factor	Technical	*				
	Unit Capability Factor	Technical	*				
	Operating Cycle	Technical	*				

	Ramping Capability	Technical	*				
	Energy Efficiency	Technical		*		*	*
	Flexibility Factor	Technical	*	*			
	Power Shifting Capability	Technical	*	*			
	Incremental Heat Rate Indicators	Technical		*			
	Storage Efficiency	Technical	*	*			
	Percentage of MES units integration	Technical			*	*	*
	Electricity import Capacity	Technical				*	*
	Amount of flexibility	Technical		*	*	*	*
	Ability of storage to follow a scheduled profile	Technical		*		*	
	Duration of availability of flexibility activation	Technical		*	*	*	
	Maximum duration of activation of flexible demand	Technical		*	*	*	
	Maximum number of activations of flexible demand	Technical		*	*	*	
	Hosting Capacity for MES in the electrical system	Technical				*	*
	Fuel energy savings ratio	Environmental		*			*

Table 40: KPIs identified in the literature to measure 'Increase of generation and utilisation of renewable energy'

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggregation KPIs	Service and market KPIs	Project level general KPIs
Increase of generation and utilisation of renewable energy	Share of electrical energy produced by renewables	Technical		*		*	*
	Energy not withdrawn from renewable sources due to congestion and/or security risks	Technical		*		*	*

Table 41: KPIs identified in the literature to measure 'Provision of cost effective MES flexibility in the electrical power system'

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggregation KPIs	Service and market KPIs	Project level general KPIs
Provision of cost-effective MES flexibility in the electrical power system	Energy Conversion Plant Profitability	Economic		*		*	*
	Production Cost	Economic		*		*	
	Energy Operational Costs (fuel and electricity input costs net of profit from electricity sold back to the grid)	Economic		*		*	*
	Operational failure risk	Economic		*		*	*
	Success factor of service delivery	Technical			*	*	

	Duration of successful service delivery	Technical			*	*	
	Analysis of costs and revenues from the service (with and without network constraints)	Economic				*	*
	Return on Investment	Economic				*	*
	Minimum time needed to get specified power	Technical		*	*	*	
	Utility Asset costs	Economic		*		*	*
	Additional High value product to be traded	Economic				*	

Table 42: KPIs identified in the literature to measure 'Create market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (directly or through aggregation)'

Benefit	KPIs	Category	Layers				
			MES internal KPIs	MES output KPIs	MES aggregation KPIs	Service and market KPIs	Project level general KPIs
Create market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (directly or through aggregation)	Operational failure risk	Economic		*		*	*
	Market price of provided energy and services	Economic				*	*
	Net revenue of market participants	Economic				*	*
	Economic Efficiency/Social Welfare	Economic		*		*	*

	Maximization of Social Welfare	Economic		*		*	*
	Transparency	Economic				*	*
	Revenues for the aggregator	Economic			*	*	*
	Relation between power demand and market price for electricity	Economic			*	*	
	Spark spread ratio	Economic				*	
	Modification of electricity consumption patterns after new pricing schemes	Technical				*	*
	Computational Complexity	Technical			*	*	
	Reduction of the number of communication channels	Social			*	*	*
	Economic Efficiency/ Price of Anarchy	Economic				*	*
	Number of addressed markets	Technical			*	*	*
	Number of flexibility resources in the aggregator pool	Technical			*	*	*
	Time needed to simulate 24h of operation in the aggregation platform	Technical			*	*	*
	Percentage of load demand participating in market-like schemes for demand flexibility	Technical			*	*	*
	Limitation of loss of comfort	Technical		*	*	*	*
	Abiotic depletion potential	Social				*	*

APPENDIX 2 - Questionnaire

D6.2 – MAGNITUDE Questionnaire: Key Performance Indicators (KPI)

Objective of this survey

This survey aims at identifying the important KPIs that can be used to evaluate and assess the performance of the combined system modules for the evaluation of the entire systems under study and monitor the MAGNITUDE improvements.

The identified KPIs should be able to specifically illustrate performance of services and markets with respect to MAGNITUDE general project targets, performance of different control strategies to deliver a similar service, performance of different MES with respect to technologies and configurations.

The overall system performance is assessed by linking the market, system and aggregator simulations together in one simulation circle to investigate the combined performance based on the specified KPIs.

KPIs will be used to assess the performance of the combined system modules for evaluation of the entire systems under study and monitor the MAGNITUDE improvements. KPIs reflect assessment across system levels (system to market) and are separated in the following layers:

- MES internal KPIs: KPIs expressing the ability to deliver flexibility through the components forming a MES
- MES output KPIs: KPIs measuring performance of a MES offering a flexibility option within a specific configuration and control function – technical use cases
- Services and markets KPIs: KPIs measuring performance of a MES providing a service inside a market structure
- Project level general KPIs: KPIs measuring performance of different services with respect to project targets

Instruction

Potential KPIs have been collected from the literature and the different work packages of MAGNITUDE, which are divided into 4 categories. Please choose the most important ones to your opinion and also give a score for each selected one.

KPIs are calculated and considered throughout and coherently throughout the MAGNITUDE processes: starting from the selection of technologies and the relevant coupling to the MAGNITUDE progress towards its objectives.

MES internal KPIs – pls select Max. 5

MES output KPIs– pls select Max. 5

Services and Market KPIs – pls select Max. 5

Project level general KPIs– pls select Max. 5

1 Your organization

☐ Case study plants

☐ Grid companies

☐ Electricity retailers

☐ TSO

☐ Electricity customers

☐ Consulting companies

☐ Municipal governments

☐ MAGNITUDE partners

☐ Others, Pls specify ______________________

Your role

☐ Managers

☐ Engineers/technicians

☐ Consultants

☐ Government Staffs

☐ Researchers

☐ Others, Pls specify ______________________

MES internal KPIs (select Max. 5)

No.	KPI	Category	Level	Level of importance							
				0	1	2	3	4	5	6	7
1	Start Up time	Technical	System								
The period of time a unit is heated to the normal operating temperature											
2	Energy Efficiency	Technical	System								
The ratio of the useful energy output to the total energy input											
3	Availability Factor	Technical	System								
The fraction of time that it is able to produce electricity and heat over a certain period.											
4	Running Plant Factor	Technical	System								
The running plant factor of a generation unit is the ratio of the actual energy output of a generation unit over a period of time to its potential output if it had operated at full nameplate capacity during the period in which it has been operated.											
5	Operating cycle	Technical	System								
The duration of the operating cycle, i.e. the time between two refuelling/overhaul outages											
6	Unit capability factor	Technical	System								

The percentage of maximum energy generation that a plant is capable of supplying to the electrical grid, limited only by factors within the control of plant management.											
7	Power Capacity Reserve margin	Technical	System								
Power capacity reserve margin aims to describe the ability of the power system to cover peak load. TSOs use it as the main indicator to assess the security of power supplies											
8	Load Factor	Technical	System								
Load Factor is an indicator of how steady an electrical load is over time											
9	Ramping Capability	Technical	Service								
The ability of modulate the rate of change in instantaneous output from a power plant.											
10	Frequency Excursions	Technical	Service								
Frequency variation is the deviation of frequency beyond a certain range from the nominal supply frequency.											
11	Voltage Excursions	Technical	Service								
Voltage variation is the deviation of voltage in a certain range.											
12	System Minutes Lost	Technical	Service								
This index measures the severity of each system disturbance relative to the size of the system, in terms of duration of total system wide blackout.											
13	Flexibility factor (FF)	Technical	System								
An energy flexibility indicator that relates to the dimension of electricity costs during operation											
14	Power Shifting capability	Technical	System								
Energy flexibility is introduced as the integral of power flexibility, which refers to the evolution of heating power during each time step of optimal control. An indicator of power flexibility is the power shifting capability											

MES output KPIs (select Max. 5)

No.	KPI	Category	Level	Level of importance							
				0	1	2	3	4	5	6	7
1	Energy operational costs (fuel and electricity input costs net of profit from electricity sold back to the grid)	Economic	System								
2	Incremental heat rate indicators	Economic	System								

They discount the quota of fuel input used to produce electricity to take into account the simultaneous production of other energy vectors)											
3	Power Shifting capability	Technical	System								
Energy flexibility is introduced as the integral of power flexibility, which refers to the evolution of heating power during each time step of optimal control. An indicator of power flexibility is the power shifting capability											
4	Storage efficiency	Technical	System								
The ratio between discharging and charging events over the entire 24 h control horizon is defined as storage efficiency or shifting efficiency. The storage efficiency indicates the effective use of the stored heat that compensates HP heating power during optimal control.											
5	Hosting capacity for MES in the electrical system	Technical	System								
6	Minimum time needed to get the specified power	Technical	System								
7	Fuel energy savings ratio	Environmental	System								
Fuel energy saving ratio means, to meet the same energy supply, the ratio of energy saving that CCHP systems relative to separate production systems											
8	GHG emission	Environmental	System								
Carbon Dioxide, Methane, Nitrous Oxide, Hydrofluorocarbons – HFCs, Perfluorocarbons – PFCs and Sulphur Hexafluoride – SF6											
9	Generated pollutant element	Environmental	System								
it is computed as the quantity of (main) pollutant elements produced by the different technologies (according to their effective usage) and the dispatch of the technology is decided according to the minimal amount of the generated pollution											
10	Energy Conversion Plant profitability	Economic	System								
Operating profit before payment of interest, tax, depreciation and amortization (if any) which is also designated as profit before interest, tax, depreciation and amortization											
11	Production cost	Economic	System								
An effective measure of the variable and controllable costs of the O&M of units											
12	Return on investment	Economic	System								
The profit or earnings after tax plus interest paid for a given period divided by the average outstanding investment over the same period (%).											

13	Market price of provided energy and services	Economic	Market								
Market price of provided energy and services (€/MW·h) is the generation weighted average price of the electricity sold over a given period.											
14	Utility Asset Costs	Economic	System								
The cost of the assets required to do the utility's main job of generating, transmitting, and/or delivering power.											
15	Costs and revenues arising from system operation	Economic	System Service Market								
The time resolution considered in the study is normally associated to the level of detail the multi-energy load is known with and to the relevant market price resolution; this resolution can for instance be down to 5 min (as in some electricity balancing markets) or half-hourly/hourly (particularly depending on real-time electricity pricing). Operational analysis intervals are typically in the order of a day, a week, or one to several months, depending on the purposes of the study (for instance, resource scheduling based on day-ahead market prices), the presence of short-term (intra-daily) or long-term (seasonal) storage, and the need for capturing specific seasonality effects											
16	Operational failure risk	Technical/economic	Service/system								
The risk index is computed according to a (operational) planning activity; the risk expresses the impact of adverse event occurrence with respect to its probability. For instance, the adverse event occurrences refer to failure of the uncertain variables taken into account in the operational model, the set of variables include: load demand, renewable production forecast (wind and photovoltaic), prices for the energy market, prices for the service market, and so on.											
17	Economic efficiency/ Social Welfare	Economic	Market								
In classic cost-benefit economics, economic efficiency is measured through social welfare or surplus, the sum of economic surpluses across all market parties											
18	Economic efficiency/ Price of Anarchy	Economic	Market								
The ratio between the optimal centralized optimum and the worst-case equilibrium (resulting from decentralized market design) is a concept in economics and game theory that measures how the efficiency of a system degrades due to selfish behaviour of its agents.											
19	Transparency	Economic	Market								
Market transparency is defined as the ability of market participants to observe information about the trading process. Information can be related to current or past prices, quotes, offers, volume and the identities and motivations of market participants.											

Services and Markets KPIs (select Max. 5)

No.	KPI	Category	Level	Level of importance							
				0	1	2	3	4	5	6	7
1	Revenues for the network operator from the service (operational costs with and without the network constraints),	Economic	System								
2	Percentage of MES units integration, revenues for the aggregator	Technical	System								
3	Success factor of service delivery	Technical	System								
4	Duration of service delivery	Technical	System								
5	Electrical network stability	Technical	System								
6	Number of addressed markets (min 4)	Technical	Market								
7	Max. number of resources in the pool (min 50)	Technical	Market								
8	Hardware requirements of Aggregation platform (max RAM, HDD, CPU)	Technical	Market								
9	Time needed to simulate 24h of operation (ex 0.5h)	Technical	Market								
10	Time needed for bid generation (max 30 min)	Technical	Market								
11	Optimality of generated bid (>95% of optimal solution)	Technical	Market								
12	Average error on price forecasts (metrics not defined yet) (<10% (depending on market))	Technical	Market								
13	Number of “unmanaged devices” in sub-pool(min 50)	Technical	Market								
14	Time to calculate required backup (of a pool) for 24h (max 5.min)	Technical	Market								
15	Maximization of social welfare	Economic	Market								

No.	KPI	Category	Level	Level of importance							
				0	1	2	3	4	5	6	7
16	Relation between power demand and market price for electricity	Economic	Market								
17	Percentage utilisation (i.e. average loading) of electricity grid elements	Technical	Service								
18	Additional high-value product to be traded	Technical	Service								
19	"Classical" spark-spread ratio	Economic	system								
(Between the market price of electricity and the variable cost of electricity production based on the market price of fuel). For instance, the spark spread is the theoretical gross margin of a gas-fired power plant from selling a unit of electricity, having bought the fuel required to produce this unit of electricity. All other costs (operation and maintenance, capital and other financial costs) must be covered from the spark spread.											
20	Percentage of load demand participating in market-like schemes for demand flexibility	Technical	Service								
21	Modifications of electricity consumption patterns after new pricing schemes	Technical	Market								

Project level general KPIs (select Max. 5)

No.	KPI	Category	Level	Level of importance							
				0	1	2	3	4	5	6	7
1	Primary energy efficiency	Technical	Service/Market								
2	Minimization of energy consumption	Technical	Service/Market								
3	Overall welfare increase, i.e. always running the cheapest generators to supply the actual demand	Technical	Service/Market								
4	Share of electrical energy produced by renewable sources	Technical	Service								

5	Satisfaction of grid users with the 'grid' services they receive	social	Service								
6	Energy not supplied	Technical	Service								
7	Optimised use of capital and assets	Technical	Service								
8	Ratio of reliably available generation capacity to peak demand	Technical	Service								
9	Duration and frequency of interruptions per customer	Technical	Service								
10	Energy not withdrawn from renewable sources due to congestion and/or security risks	Technical	Service								
11	Efficiency targets	Technical	Service								
12	Fuel energy savings ratio (Primary Energy Saving)	Environmental	System								
Fuel energy saving ratio means, to meet the same energy supply, the ratio of energy saving that CCHP systems relative to separate production systems											
13	GHG emission	Environmental	System								
Carbon Dioxide, Methane, Nitrous Oxide, Hydrofluorocarbons – HFCs, Perfluorocarbons – PFCs and Sulphur Hexafluoride – SF6											

APPENDIX 3 - KPI encoding for the questionnaire analysis

Table 43: KPIS numbers –reference for scatterplot

Number	KPIs
1	Start Up time
2	Energy Efficiency
3	Availability Factor
4	Running Plant Factor
5	Operating cycle
6	Unit capability factor
7	Power Capacity Reserve margin
8	Load Factor
9	Ramp rate
10	Frequency Excursions
11	Voltage Excursions
12	Energy not supplied
13	System Minutes Lost
14	Flexibility factor (FF)
15	Power Shifting capability
16	Percentage of MES units integration, revenues for the aggregator
17	Electrical network stability
18	Percentage of load demand participating in market-like schemes for demand flexibility
19	Share of electrical energy produced by renewable sources
20	Duration and frequency of interruptions per customer
21	Energy not withdrawn from renewable sources due to congestion and/or security risk
22	Energy conversion plant profitability
23	Production cost
24	Return on investment
25	Market price of provided energy and services
26	Utility Asset Costs
27	Costs and revenues arising from system operation
28	Operational failure risk
29	Economic efficiency/ Social Welfare
30	Economic efficiency/ Price of Anarchy
31	Transparency
32	Revenue for the network operator from the service
33	Maximization of social welfare
34	Fuel energy savings ratio
35	GHG emissions
36	Generated pollutant element
37	Public safety and acceptability
38	Reduction of the number of communication channels
39	Abiotic depletion potential

APPENDIX 4 - KPIs relevant for MAGNITUDE analysis but not accessible in the scope of MAGNITUDE

This section contains all the KPIs (and the methods to evaluate them) that are identified as highly relevant to MAGNITUDE goals, but are not accessible within MAGNITUDE. The following KPIs are not included in the final list of KPIs, although they are quite relevant to the MAGNITUDE scope, either because it is very challenging to acquire the particular input data from the industrial partners and their case studies, or because input data is inaccessible to MAGNITUDE partners.

Table 44: KPIs selected but not included in the final list

Benefit	KPI	Category	Layer
Increased Sustainability, Security of Supply and Quality of Service in Electricity Supply and Grid Operation	Public Safety and Acceptability	Social	Services and Markets Project level general
	Satisfaction of grid users with the grid services they receive (SAIFI and SAIDI)	Technical	MES aggregation Services and Markets Project level general
	Wear and Tear of Equipment	Technical	MES Internal KPI
Create market mechanisms and business opportunities to mobilize flexibility and participation in a synergetic MES environment (directly or through aggregators)	Abiotic Depletion Potential	Social	MES output Services and Markets Project level general

Public Safety and Acceptability

Safety

To understand how a given investigated improvement option has improved or worsened the ability of utility workers to perform their jobs and how this option has impacted the convenience, comfort, and electricity bills for consumers.

To assess this KPI, the following elements should be considered:

- Record observations and reactions to MES from utility workers (e.g., planners, designers, operators, and maintenance crews), consumers, regulatory commissioners, and other stakeholders.

- Develop a structured approach to solicit, collect, analyse and disseminate these observations. Examples of structured approaches include surveys and interviews.

Acceptability

On the other hand, public acceptability is key to the implementation of any energy technology. For example, main issues affecting the implementation of wind power are related to land requirement, visual intrusion and noise. For large hydro-power plants, lack of public acceptance is mainly associated with transformation of land and relocation of population. Main social concerns for biomass are related to competition for agricultural land, water and food production.

This is a qualitative KPI which can be measured as: High (H)/ Medium (M)/ Low (L).

Satisfaction of grid users with the 'grid' services they receive

Description

Customer satisfaction for the quality and the reliability of the service they receive is basically dependant on the frequency and the duration of power outages. The number of interruptions experienced by the customers and the average length of the interruptions are indicators of the reliability and availability of the electricity grid.

Formula

The relevant metrics are:

System Average Interruption Duration Index:

$$SAIDI(minutes) = \frac{\sum of\ allcustomersinterruptiondurations}{totalnumberofcustomersserved}$$

System Average Interruption Frequency Index:

$$SAIFI(interruptionspercustomer) = \frac{totalnumberofcustomerinterruptions}{totalnumberofcustomersserved}$$

Wear and tear of equipment

When fossil-fuelled generators cycle on and off or ramp down to minimum generation, the thermal cycling of the components can lead to fatigue, creep and fatigue-creep interaction which results in increased maintenance and repair [57] [58] [59].

It is known that one of the most common failure modes for mechanical equipment is wear failure. Failure caused by wear takes up more than 70–80% of all usual failure modes of mechanical components [60]. Moreover, loss caused by abrasive wear takes up 50% of all wear loss in the whole industrial field [61]. Usually lubricants are put in tribo-pairs to reduce the friction and wear of mechanical equipment, and good condition of lubricants is essential to normal running of machines.

Increased cycling, deeper load following, and rapid ramping may result in wear and tear impacts on equipment, e.g. fossil-fuelled generators, that lead to increased capital and maintenance costs, increased equivalent forced outage rates, and degraded performance over time [62].

This "wear and tear" cost depends on plant design, operation, maintenance, and repair history. Determining the wear and tear cost therefore requires significant investigation and analysis. This type of analysis is typically commissioned by the plant owner to better understand implications of operations of a specific plant, and these results are proprietary information for the plant owner [62].

Wear and tear of equipment can be measured by estimating the maintenance cost and renewal activity with econometric approach [63]. The econometric approach proceeds by estimating a variable cost function that relates total variable costs to output variables, prices of variable inputs (labour, energy, and so on) and levels of fixed inputs (route-km, number of switches and crossings, and so on); see, for example, Caves et al. [64].

Incorporating these full wear and tear costs in utility operational decisions may affect how utilities choose to operate these plants. These wear and tear costs may also have implications in the compensation required for certain types of operation [65]. Cycling and ramping of fossil-fuelled generators also affect emissions and may result in higher emissions rates than steady-state operation.

Abiotic depletion potential (ADP)

Description

In order to measure the depletion of fossil fuel reserves (such as oil, gas, coal and uranium), which has also a direct social impact, ADP is the relevant KPI. Abiotic resources are natural resources which are regarded as non-living. These resources are based on ultimate reserves. ADP is the characterization factor and it is derived from each extraction of elements and fossil fuels and is a relative measure with the depletion of the reference element.

Formula

The ADP can be calculated using the following equation [66] [67]:

$$ADP_i = \frac{\frac{DR_i}{{R_i}^2}}{\frac{DR_{ref}}{{R_{ref}}^2}}$$

Where for a resource i:

R_i: ultimate reserve of resource i [kg]

DR_i: extraction rate of resource i [kg/year]

R_{ref}: ultimate reserve of the reference resource, antimony [kg]

DR_{ref}: extraction rate of reference resource, antimony [kg/year]