OSMOSE

OPTIMAL SYSTEM-MIX OF FLEXIBILITY SOLUTIONS FOR EUROPEAN ELECTRICITY

KPIs measuring the value of flexibility

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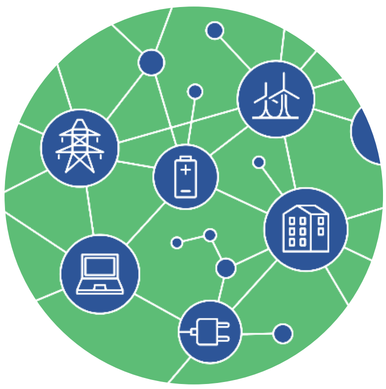

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Project Information

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1 List of acronyms and abbreviations

Acronym	Meaning
CA	Consortium Agreement
D	Deliverable
WP	Work Package
KPI	Key Performance Indicator
O&M	Operation and Management
NEC	Net Export Curve
C_m	m-firm concentration index
R_H	Hirschman-Herfindahl Index
L_I	Lerner Index
PSI	Pivotal Supply Indicator
RSI	Residual Supply Indicator
DER	Distributed Energy Resources
DR	Demand Response
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
ROCOF	Rate of Change of Frequency
LOLE	Loss of Load Expectation
LOEE	Loss of Energy Expectation
ELCC	Effective Load Carrying Capability
CC	Capacity Credit
LORP	Lack of Ramp Probability
IRRE	Insufficient Ramp Resources Expectation
EENS	Expected Energy not Served
ICT	Information and Communication Technologies
RE	Renewable Energy

2 Introduction

This report aims to propose a list of Key Performance Indicators (KPIs) that can be used to assess and compare the performance of possible electricity market designs targeting the optimal development of flexibility technologies to economically accommodate high shares of renewable energy sources (RES) in power systems.

We define four categories of indicators corresponding to the main aspects of electricity markets with high shares of RES:

- Economic indicators
- Market performance indicators
- Technical indicators
- Other indicators

The KPIs proposed in this deliverable are classified into the above categories. All possible KPIs considered by the Working Package 2 (WP2) of the OSMOSE project are listed in this document, but only some of them will be used in practice to analyse the results of the market simulations, depending on which output will be available at that time. Computing these KPIs aims at comparing different market architectures by assessing their performance regarding their economic signals, the needs for system services generated, their capabilities for solving grid management among others.

These KPIs have been proposed with a particular focus on the system services provided by the technologies implemented in WP3, WP4, WP5 and WP6.

This report is organized as follows. Section 3 gives a reminder of what the OSMOSE methodology and philosophy are, especially its will to proceed with a silo breaking and holistic approach for evaluating the value of flexibility. Section 4 discusses the KPIs relative to the economic indicators from a system perspective. This includes, for instance the social welfare and the system costs. Section 5 exposes the indicators relative to market performance, for instance, flexibility, reliability and efficiency resulting from each market design option. Section 6 presents the technical indicators. These KPIs should allow to quantify the technical performance of the power system resulting from the market design implemented. Finally, Section 7 gathers other KPIs, including environmental and implementability indicators meant to assess whether the design proposed are suitable with the existing tools and regulations.

By using the KPIs proposed, different market designs can be scored and ranked in terms of their performance related to the value added by flexibility solutions with respect to the needs for system services, grid management and wholesale markets.

3 OSMOSE Methodology

The Methodology of OSMOSE aims to tackle the need for flexibility in power systems in a comprehensive way. By using a “Silo breaking” approach, the project aims to assess the role of different sources of flexibility (for example the grid, storage, demand response, FACTS, etc) on different issues linked to power system planning and management given massive penetration of RES. As it is represented on Figure 1, this holistic methodology breaks the diversity of the issues to create one global issue of market design proposal.

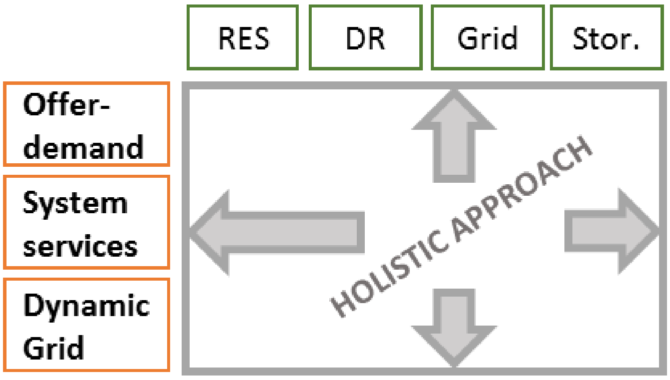

Figure 1: Holistic approach of the OSMOSE Project

4 Economic indicators

Economic indicators are needed to compare the different market designs proposed in terms of economic efficiency.

	Item	KPI	Description
System costs	4.1.1	Investment costs	Total capital costs of infrastructure and other equipment’s
	4.1.2	Operating costs	Fuel cost, fixed and variable O&M cost, CO_2 cost
	4.1.3	Integration costs	Balancing costs, grid related costs, profile costs
	4.1.4	Congestion management costs	Cost overruns due to network infeasibilities

	Item	KPI	Description
Social welfare	4.2.1	Producer surplus	Market price minus willingness to sell
	4.2.2	Consumer surplus	Willingness to pay minus market price
	4.2.3	Congestion rent	Net export curve
	4.2.4	Surplus of flexibility suppliers	Profits of flexibility assets. Sometimes stand-alone, but sometimes entangled in the supply side and/or in the demand side
	4.2.5	Social welfare	Sum of the previous components
RES integration	4.3.1	Revenue gap of RES	Revenue gap of RES technologies when comparing with policy goals. Both positive and negative differences shall be avoided
	4.3.2	Differences in RES-support per MWh in different countries	Global coherence assessment and efficiency.
	4.3.3	Difference between the RE target and the actual amount of market-driven RE installed capacity	Indicator of the effectiveness of market-based remuneration for RES
	4.3.4	Cost variations in comparison with conventional grid reinforcement strategies for integrating DER	System costs reductions due to the optimal development of flexibility
Others	4.4.1	Ratio of market price to marginal production cost	Marginal cost reflectivity
	4.4.2	Missing money	Difference between full costs and total revenues for every generation unit
	4.4.3	Imbalance cost ratio	Ratio of price to the sensitivity of system balancing costs with respect to changes in agent's imbalance due to regulatory framework. It

	Item	KPI	Description
			quantifies the efficiency of imbalance settlements
	4.4.4	Market and system modelling imperfection costs	Size of infeasibilities computed as the excess of capacity sold over available capacity
	4.4.5	Value of cross-border flows (€)	Level of coordination of the capacity allocation of interconnections

Table 1 : Economic KPIs

4.1 System cost

It is composed by **investment and operating costs**. Investment costs correspond to the sum of every investment made in infrastructure and installation relative to the supply chain of the power system (i.e., generation, the grid, communication infrastructure, among other). The operating costs are composed by the fuel costs, maintenance costs and CO_2 costs for example.

According to Hirth et al (2015), the **integration costs** can be decomposed into 3 categories:

- Balancing costs: the costs to balance the RE deviation from the day-schedule. It represents the forecast error costs due to the variability of the RE, i.e., the price spread between day-ahead and real-time prices.

- Grid-related costs: the marginal costs of transmission constraints and losses reflected by the locational prices.

- Profile costs: costs due to a lack of temporal coincidence of RE generation and load, i.e., when the RES produce at times of low electricity prices. The profiles costs are due to the flexibility effect and the utilization effect. The former represents the increase of the power plant constraints and cycling to follow the steep gradients of the residual load. The latter represents the decrease of the load factor which reflects an increase in cost per MWh.

Computing **congestion management costs** comprise **re-dispatch costs, counter-trading costs and any other action needed to manage network infeasibilities.** They indicate the costs of network bottlenecks and other physical constraints.

4.2 Social welfare

To compute the **social welfare** resulting from each market architecture, different components shall be calculated separately.

- Producer and consumer surplus

The producer and the consumer surplus will be computed to compare the different market architectures proposed.

The **producer's surplus** is defined as the difference between the market price and the willingness to sell of producers, while the **consumer's surplus** is the difference between the willingness to pay of consumers and the market price (the price actually paid).

- Surplus of flexibility suppliers

Moreover, one shall compute the **Surplus of the flexibility suppliers** and share earned by its market facilitator (cf. the aggregator). Calculating flexibility supplier's surplus is a way to evaluate how efficiently a market design valuates flexibility. Nevertheless, due to the diverse types of flexibility sources, new legal and accountability definitions might be necessary to allocate flexibility revenues generated by storage technologies, prosumers, among others.

- Congestion rent

When considering cross-zonal flows, imports and exports between the different market areas must be considered. The congestion rent is calculated thanks to the Net Export Curve (NEC). The NEC is represented by the net demand and the net supply (Figure 2). The grey area in Figure 2 is the congestion rent.

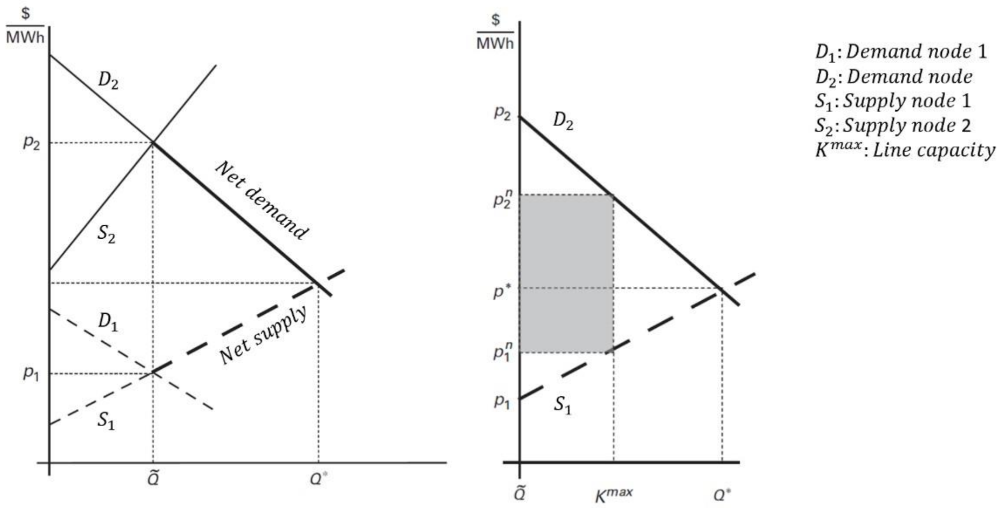

Figure 2: Net export curve and congestion costs (Cretì and Fontini, 2019)

4.3 RES integration

The **Revenue gap of RES technologies** when comparing with policy goals is meant to measure the difference of revenues coming from the RES technologies between what the policy target is and what the actual revenue is. Both positive and negative differences should be avoided.

One may look at the **Difference in RES-support per MWh in different countries** to check the global coherence and assess the feasibility and the efficiency of the market designs considered.

One shall compute the **Difference between the targeted RES capacity to be installed and the amount of market-driven RES capacity.** This gives a good indicator of the effectiveness of the remuneration processes as this difference can be interpreted as follow (Olmos et al., 2016).

- A positive difference means that the targeted level of RES generation capacity has not been reached. The remuneration processes are then not effective and does not pay RES generation enough to attract a large enough amount of it, or the risk associated with revenues is too high for the remuneration level established.
- A negative difference should emphasise that the remuneration scheme is inefficient. The application of this scheme has led to a larger amount of subsidies paid than needed.

Both positive and negative differences must be avoided.

One shall compute the **cost variation due to the integration of Distributed Generation**. Comparing the costs variations from current grid reinforcement methods will allow choosing the design option that takes the more benefits out of DER[1].

4.4 Other indicators

The **Ratio of market price to marginal production cost** will allow us to evaluate the marginal cost reflectivity of the market design. This ratio should be as close to one as possible.

The **Missing Money** indicator will be computed as the revenue gap of every generation technology due to the considered market design. The value of this indicator should be minimized by each design.

The **imbalance cost ratio** will be computed as the ratio of the unit price paid for imbalances to the sensitivity of the system balancing costs. The difference in price paid by an agent should reflect the sensitivity of system balancing costs with respect to an increase in the imbalance by the agent (Olmos et al., 2016). This will be a measure of the efficiency of imbalance settlement designs.

The **market and system modelling imperfection costs** can be measured by the size of infeasibilities, which should be computed as the excess of capacity sold over available capacity. The sold capacity in long term auctions should never exceed the available capacity (Olmos et al., 2016).

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[1] In the case RES are composed mainly for DER.

The **value of cross-border flows** can be measured within each market model as the sum of the flow through each border, hour per hour. The higher the flow is (in aggregate terms), the more interconnection capacity is used.

5 Market performance indicators

These indicators are needed to assess the overall performance of each market architecture regarding competition, liquidity, risk management, revenue distribution, even with massive shares of RES.

	Item	KPI	Description
Market concentration	5.1.1	m-firm concentration index (C_m)	Aggregated market share of the m largest companies
	5.1.2	Hirshman-Herfindahl Index (R_H)	Sum of the squares of each participant's market share
	5.1.3	Lerner Index (L_I)	Measure market imperfection as overpricing with respect to a perfect market
	5.1.4	Pivotal Supplier Indicator (PSI)	Binary indicator measuring whenever a generation company is pivotal in the market
	5.1.5	Residual Supply Index (RSI)	Ratio of total capacity of all company's competitors to total demand
Market complexity	5.2.1	Number of market segments[2]	Each market segment will be considered separately These indicators are meant to assess the diversity of the products sold on the market.
	5.2.2	Number of products[3] traded for each market segment	

[2] A segment is a category of products traded. For example: capacity, energy, flexibility, availability, etc.
[3] A product is a good or a service exchanged on a market with well-defined specifications (cf. for energy we can have 1h and/or 15min firm energy blocks or products traded of the same underlying).

	Item	KPI	Description
	5.2.3	Number of different lead times for each kind of product	
	5.2.4	Number of different contract durations for trading products	
	5.2.5	Occurrence of negative prices	Symbolizing possible market failures
Market liquidity	5.3.1	Volume traded for each market segment (e.g., capacity, energy, reserves) within each market zone	Liquidity goes by a sufficient volume of trades
	5.3.2	Bid-ask price spread	Difference between the highest price proposed by a buyer and the lowest price that a seller is willing to accept for a given product
	5.3.3	Volume of bids and flexible energy or capacity exchanged in the relevant market from the demand side (MW or MWh)	Demand participation
Market volatility	5.4.1	Risk for investors in generation/demand response	Calculated as a value at risk
	5.4.2	Price convergence	Average price differentials between adjacent zones or nodes

Table 2 : Market performance KPIs

5.1 Market concentration

The **Concentration index C_m** is computed as the aggregated share of the m largest companies in the market. It is interesting to know the number of firms representing e.g. 95% of the market share: $C_m = \sum_{f=1}^{m} \alpha_f$

Where α_f represents company f 's market share.

The **Hirshman-Herfindahl Index R_H** is another concentration-based index. It is computed as the sum of the squares of each participant market share. It includes more information on the distribution of company size than the previous indicator: $R_H = \sum_f \alpha_f^2$

The **Lerner Index** measures market imperfection as overpricing with respect to a perfect market. It is a measure of the impact of market power abuse on prices.

$$L_I = \frac{p_{real\ market} - p_{perfect\ market}}{p_{real\ market}}$$

The **Pivotal Supplier Indicator PSI** is a binary indicator measuring whether a generation company *f* is pivotal in the market. A company is regarded as pivotal if all other producers are unable to cover market demand. It is needed to supply demand.

The **Residual Supply Index RSI** is defined as the ratio between the total capacity of all a company's competitors to total demand.

$$RSI_f = \frac{Company\ f's\ residual\ supply}{Total\ demand} = \frac{Total\ supply\ capacity - Company\ f's\ supply\ capacity}{Total\ demand}$$

If RSI > 1, then the plant f is not pivotal and conversely, if RSI < 1, then plant f is pivotal. The smaller the RSI is, the higher is the power market of plant f.

5.2 Market complexity

The **Number of market segments**, the **Number of products traded for each market segment**, **Number of different lead times for each kind of product,** the **Number of different contract durations** for trading products are indicators meant to assess the diversity of products traded in the market. A certain diversity is needed to assure that total demand and supply of different services are balanced, and enough hedging alternatives exists, but simple market architectures should be preferred. Provided such diversity exists, then the lower these indicators are, the better.

The **Occurrence of negative prices** can be computed as the number of hours with negative prices over a given period. Negative prices are the evidence of an inefficient market reaction to a given perturbation or the lack of completeness of the market itself[4].

5.3 Market liquidity

[4] Perturbation such as subsidies or the lack of completeness such as for risk hedging or for pricing non-convexities might be at the origin of negative prices.

We will compare the **Volume traded for each market segment** (e.g., capacity, energy, reserves) within each market zone for each market design considered. Larger volumes reflects higher market liquidity.

The **Bid-ask price spread** is computed as the difference between the highest price proposed by a buyer and the lowest price that a seller is willing to accept. "This indicator may be seen as a direct measure of market liquidity since it shows the extent of transaction costs resulting from an instantaneous change in a market participant's contractual position." (ACER, 2014)

Market liquidity can also be measured in terms of **Volume of bids and flexible energy or capacity exchanged in the relevant marke**t. It shows the impact of market design for demand participation in flexibility supply. The higher the level of market liquidity is, the better is the market design proposed.

5.4 Market volatility

The **Risk for investors in the generation and in demand response**, calculated as the value at risk, will be an indicator of the price volatility.

An indicator for **Price convergence** can be the time during which prices of different zones are equal (or that their differences are lower than a certain amount). We can also compute the **average price differential for every time step of two adjacent zones or nodes**. The lower the average difference (or the bigger the time during which prices are equal), the better the market behaves.

6 Technical indicators

These KPIs are meant to compare the different market design options from a technical point of view. The efficiency, the reliability and flexibility of electricity markets are deeply changed by the introduction of Renewable Energy Sources (RES). One should then compare the different scenarios and options on a technical basis.

	Item	KPI	Description
Resource diversification	6.1.1	Market shares of RES (%)	Shares of energy produced by RES on total supply
	6.1.2	Total traded volume of RES over a given period (MWh)	RES penetration into the market

	Item	KPI	Description
	6.1.3	Installed capacity of RES and share of RES at the distribution level (DER)	
	6.1.4	Market share of Distributed Energy Resources (DER) (%)	It captures trend towards decentralisation on the supply side. It may point to possible grid management challenges at medium and low voltage networks.
	6.1.5	Curtailment of DER (MWh and %)	Optimisation of the system with respect to the decentralisation of supply
	6.1.6	Amount of load capacity participating in Demand Response (DR) programs	Estimation of the participation of DR in the market
Reliability	6.2.1	System Average Interruption Duration Index (SAIDI)	Average duration of involuntary interruptions for customers served during a specified time period
	6.2.2	System Average Interruption Frequency Index (SAIFI)	Average number of interruptions a consumer will know in the time period considered
	6.2.3	Voltage quality variations	The voltage quality measure is based on the voltage profile measured at some neuralgic nodes
	6.2.4	Rate of Change of Frequency (RoCoF)	The second derivative of the phase of the frequency signal. It is a proxy of the inertia of the system
	6.2.5	Loss of Load Expectation (LOLE)	Expected number of hours in a year that the system generation cannot meet the system load
	6.2.6	Loss of energy expectation (LOEE)	The expected energy volume not supplied in a year due to inadequate capacity
	6.2.7	Effective Load Carrying Capability (ELCC)	Capacity value of the generation systems
	6.2.8	Capacity Credit (CC)	

	Item	KPI	Description
	6.2.9	Lack of Ramp Probability (LORP)	Adequacy of the available capacity for ramping
	6.2.10	Insufficient Ramp Resources Expectation (IRRE)	Expected number of times in a given period that a system will not be able to meet changes in net load
	6.2.11	Expected Energy Not Served (EENS)	Amount of energy demand expected not to be met by generation in a given year (MWh)
Efficiency	6.3.1	Peak load reduction (MW)	Obtained from comparing peak loads obtained by implementing different market architectures
	6.3.2	Rate of reduction of energy losses (MWh)	
	6.3.3	RES curtailment (MWh)	Duration and volume of curtailments shall be compared from one market design to another
	6.3.4	Load curtailment (MWh)	
	6.3.5	Saturation index	Indicator of the global saturation of the transmission network
	6.3.6	Congestion index	Level of congestion on a given system compared to an ideal situation (i.e., nodal pricing)
Flexibility	6.4.1	Flexible generation capacity (MW)	Capacity of installed/available flexibility sources by category
	6.4.2	Grid transportation capacity	MW transportable from a point A to B

Table 3 : Technical KPIs

6.1 Resources diversification

The market shares of RES, Total traded volume of RES over a given period (MWh), Installed **capacity of Distributed Energy Resources (DER)**, are three indicators meant to measure the RES penetration into the market (with respect to total supply).

Measuring the **Total traded volume of RES over a given period** is a way to measure their market participation. An active market is likely to be an attractive market.

The total shares of RES for the entire grid should be obtained, and then their voltage level on the grid should be identified by assessing the **market shares of Distributed Energy**

Resources (DER) (%). At least two types of RES should be differentiated, bulk RES connected to a voltage level higher than 132 kV, and distributed RES feeding the network at voltage level lower than 132kV. If possible, behind-the-meter (prosumer) generation of RES should also be accounted.

The **Curtailment of DER** (MWh and %) shall be computed to assess to what extent the grid is well optimized for distributed energy resources. The more MWh from DER are curtailed, the less adapted the system is to accommodate decentralized produced energy.

In order to take Demand Response (DR) into account and see what its effects are on flexibility, one shall compute the **Amount of load capacity participating in DR programs**. As it is defined by Birch et al (2014), this KPI shall capture the amount of flexibility provided by Demand Response necessary to accommodate a pre-set level of DG without harming any threshold values of grid stability. The KPI differentiates between positive (DR+) and negative (DR-) Demand Response capability activated to address imbalances. In this respect DR+ is defined as the reduced power consumption due to the ability to switch off (completely or partly) flexible loads, whereas DR- is defined as the increased power consumption due to the ability to switch on (completely or partly) flexible loads for a certain time frame in order to reach the required level of load in the grid. Thus, asymmetrical amounts are possible.

6.2 Reliability

Computing the Improvement of the **System Average Interruption Duration Index** (SAIDI/ASIDI) is a way to access the reliability of the system against outages. We compute this index as the average duration of involuntary interruptions for customers served during a specified time period (Warren and Saint, 2005). It can be computed by the following equation:

$$SAIDI = \frac{Sum\ of\ all\ customers - minutes\ of\ all\ interruptions}{number\ of\ customers\ served} \quad (1)$$

The improvement of the **System Average Interruption Frequency Index** (SAIFI) will be computed as well. It describes the average number of times that a customer’s power is interrupted during a specified time period. Sustained interruptions and momentary interruptions shall be distinguished. This is the average number of interruptions a consumer will know in the time period considered (Warren and Saint, 2005). It can be computed with the following equations:

$$SAIFI_{sustained} = \frac{number\ of\ customers\ affected\ by\ sustained\ interruptions}{average\ number\ of\ customers\ served} \quad (2)$$

$$SAIFI_{momentary} = \frac{number\ of\ customers\ affected\ by\ momentary\ interruptions}{average\ number\ of\ customers\ served} \quad (3)$$

As explained by Birch et al (2014), "**Voltage quality** refers to the attribute of voltage level not to under or overrun certain threshold values". This KPI measures the voltage quality based on the voltage profile (line voltage) measured at various key neuralgic (or potentially problematic) nodes of the grid. The implementation of ICT and the associated enhanced monitoring capabilities will lead to improved line voltage profiles. In order to receive a full picture of the voltage quality, the voltage profile is monitored through two values that are directly retrieved from power stability instrumentation or calculation: V_{MAX} and $V_{95\%}$. V_{MAX} is the maximum reached line voltage during the defined monitoring period and $V_{95\%}$ the value for which 95% of all voltage line measurements fall below. The objective is that due to control measures the V_{MAX} and $V_{95\%}$ will decrease and the difference between $V_{95\%}$ and V_{MAX} will diminish (Birch, 2014). We will then compare the quality of the voltage with the one in the current situation and see its **variations** at least for a particularly challenging point.

Another indicator that may be computed to measure the reliability of the market is the **Rate of Change of Frequency** (ROCOF). This is a key indicator of the network stability and of the balance between supply and demand (Roscoe et al., 2017). It is computed as the second derivative of the phase of the electric signal. Thus, it is a proxy of system inertia. Let θ be the phase of the signal. The Rate of Change of Frequency is then defined as follows:

$$ROCOF(t) = \frac{1}{2\pi}\frac{d^2\theta}{dt^2}(t) \quad (4)$$

The **Loss of Load Expectation (LOLE)** will be computed as the expected number of hours in a year than the system generation cannot meet the system load.

The Loss of Expected Energy (LOEE) will be computed as the expected energy volume not supplied in a year due to inadequate capacity, and it provides information about the magnitude of the forced outage (Alferidi, 2018). These two quantities shall be computed by the following equations:

$$LOLE = \sum_{k=1}^{n} p_k.t_k = \sum_{k=1}^{n} P_k.(t_k - t_{k-1}) \quad (5)$$

$$LOEE = \sum_{k=1}^{n} P_k.E_k \quad (6)$$

All the variables used in the previous formulas are defined in the following table.

Variables	Description
n	Number of capacity outages states
p_k	Probability of the capacity outage O_k
P_k	Cumulative outage probability for capacity state O_k

t_k	The time for which load loss will occur due to O_k
E_k	Energy not supplied

Table 4 : description of the variables used in the equations (5) and (6)

The **Expected Load Carrying Capability** (ELCC) and **Capacity Credit** (CC) evaluate the capacity value of the generation systems (Alferidi, 2018).

The **Lack of ramp probability** (LORP) shall be calculated in different ways, with respect to the time scale of the assessment. Thatte et al. (2016) define different types of LORP. The system-wide $LORP_s$ provides an assessment of the adequacy of the available system ramping capability from dispatched generators to meet both expected changes as well as uncertainty in forecasted net load.

It is defined for the ramp up and the ramp down cases as follow:

$$LORP_s^{up,\tau}(t) = \mathbb{P}(\sum_{i\in I}\{P_i^g(t) + \min(\tau R_i, P_i^{max} - P_i(t))\} < \widetilde{P_s^l}(t+\tau)) \tag{7}$$

$$LORP_s^{dn,\tau}(t) = \mathbb{P}(\sum_{i\in I}\{P_i^g(t) - \min(\tau R_i, P_i(t) - P_i^{max})\} > \widetilde{P_s^l}(t+\tau)) \tag{8}$$

One shall also define the zonal $LORP_z$, in which inter-zonal flows are considered.

$$LORP_z^{up}(t) = \mathbb{P}\left(\sum_{i\in I^z} P_i^g(t) + RC_z(y) < \widetilde{P_z^l}(t+\tau)\right) \tag{9}$$

The zonal LORP for down ramp can be similarly defined.

All the parameters and variables used in the previous formulas are defined in the following table.

Variables	**Description**
$P_i^g(t)$	Dispatch output of generator i at time t
R_i	One interval (5 min) ramp rate of generator i. (MW)
P_i^{max}	Maximum output of generator i (MW)
$P_i(t)$	Output of generator i at time t (MW)

$\widetilde{P_s^l}(t+\tau)$	System wide net load for the interval τ time steps in the future. It is assumed to be a Gaussian random variable with known mean and standard deviation (Thatte and Xie, 2016).
$RC_z(t)$	Ramp capability (5min) for zone z at time t. (MW)
$\widetilde{P_z^l}(t+\tau)$	Net load of zone z for the interval τ time steps.
I (I_z)	Set of generators (set of generators in zone z)

Table 5 : description of variables used in the equations (7), (8) and (9)

The **Insufficient ramp resources expectation** (IRRE) is the expected number of times for a given period that a system will not be able to meet changes in net load. It can be computed as the cumulative probability that the flexibility will not be enough to overcome the ramps. It offers a high level insight into the flexibility of a system (E. Lannoye et al., 2012). The computation of this indicator will be calculated by following the algorithm proposed by Eamonn et al. (2012).

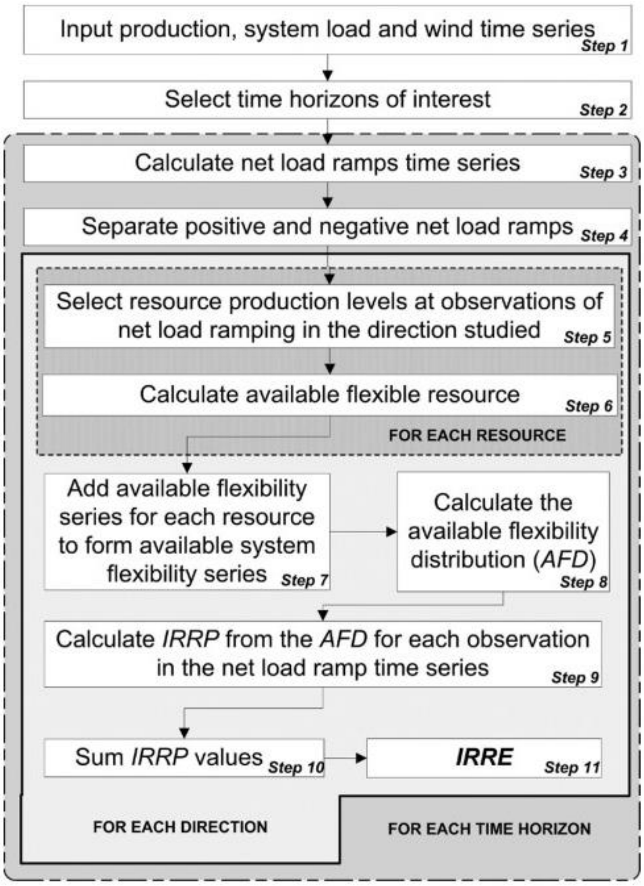

Figure 3: Algorithm computing the IRRE (Eamonn Lannoye et al., 2012)

After computing the *net load ramps* ($NLR_{t,i,\pm}$) for each observation *t*, and the *available flexibility distribution* for time interval *i* in both direction ($AFD_{i,\pm}$), it should be possible to compute for each observation *t*, for each horizon, *i*, the insufficient ramping resource probability ($IRRP_{t,i,\pm}$):

$$IRRP_{t,i,\pm} = AFD_{i,\pm}(NLR_{t,i,\pm} - 1) \tag{10}$$

And finally, the insufficient ramping resource expectation in each direction for a time interval *i*:

$$IRRE_{i,\pm} = \sum_{t \in T_\pm} IRRP_{t,i,\pm} \tag{11}$$

6.3 Efficiency

The **Peak load reduction** shall be measured with respect to the considered market design and compared to the value obtained by following a benchmark market design.

Rate of reduction of energy losses shall also be measured and compared with the values obtained between alternative designs.

RES curtailment shall be measured to compare the different market design outcomes. The average volume (in MWh), and the duration (in hours) of RES curtailment may increase due to a lack of efficiency of the network representation. The lower this KPI is, the more efficient the design option will be (Olmos et al., 2016).

Load curtailment may occur because of insufficient generation capacity, insufficient import capacity and/or insufficient ramping capability. The average volume (in MWh), the duration (in hours) of load curtailment may increase due to a lack of efficiency of the network representation. The lower the level of this indicator, the more efficient the design results (Olmos et al., 2016).

The **Saturation index** provides a measure of the exploitation/usage degree of the transmission network. This is an indicator of the global saturation of the network. If the value exceeds 1, there is a global saturation. The index is lower than 1 if there is no global saturation, but this does not mean that there are not any saturated lines (Aguado et al., 2017). It is computed by the following equation (see Table 6 for the variables):

$$i_s = \frac{\sum_{(s,r,k)\in\Omega_L} \left| p_{srk}^{c_{max}} \right|}{\sum_{(s,r,k)\in\Omega_L} p_{srk}^{max} . w_{srk}} \tag{12}$$

The **Congestion index** measures the level of congestion on a given system compared to an ideal one based on nodal prices. If the value is large it means that the nodal prices largely deviate from the average zonal price. This KPI provides a quantitative approach of the behaviour of the system concerning market operations (Aguado et al., 2017) and points to possible losses on economic performance from socializing congestion costs. It is computed by the following equation:

$$i_c = \frac{\sum_{s\in\Omega_N}\left|\bar{\lambda_s} - \bar{\lambda}\right|}{N.\bar{\lambda}} \tag{13}$$

Where:

$$\bar{\lambda_s} = \sum_{c\in\Omega_c} \lambda_s^c.W^c \tag{14}$$

$$\bar{\lambda} = \frac{1}{N}\sum_{s\in\Omega_N} \bar{\lambda_s} \tag{15}$$

All the variables used in these formulas are defined in the following table

Variables	Description
Ω_L	Set of all transmission lines, prospective and existing
Ω_N	Set of all network buses
Ω_C	Set if all scenarios
$p_{srk}^{c_{max}}$	Power injection in line k of corridor (s,r) in the scenario c_{max} with the highest demand
p_{srk}^{max}	Capacity of line k in corridor (s,r)
w_{srk}	Binary variable that is equal to 1 if line k from corridor (s,r) is functional, 0 otherwise
λ_s^c	Nodal price for bus s in the scenario c
W^c	Weight of the scenario c
$\bar{\lambda_s}$	Average nodal price for bus s
$\bar{\lambda}$	Average nodal price of the system (for all the buses)

Table 6 : Description of the variables used in the equations (12), (13), (14) and (15).

The simultaneous use of the last two indexes provides a global representation of the system status (Aguado et al., 2017).

6.4 Flexibility

The **Flexible generation capacity** and the **Grid transportation capacity** available resulting from different market designs should be compared.

7 Other indicators

Other indicators that did not fit into the three previous main categories are presented and explained here. The following KPIs are meant to assess the implementability and the efficiency of the design options considered but also analyse them in terms of environmental efficiency.

	Item	KPI	Description
Implementability	7.1.1	Coherence with existing regulation and legislation	Some rules should be respected to assure the implementability of the market design
	7.1.2	Simplicity and transparency	Improve implementability
	7.1.3	Computation time	Compute the time required to simulate the market design as an indicator of its simplicity and its implementability
	7.1.4	Feasible/optimal solution possible	Does an optimal solution exist? Can it be found?
	7.1.5	Compatibility with existing regulation in Europe	Shall some regulations be extended/evolved?
	7.1.6	Number and relevance of changes to be made to existing regulation to adapt it to the considered scheme	
Environmental	7.2.1	CO_2 emissions (ton)	Computing the emissions of these greenhouse gas will be an indicator of the environmental impact of the market design option considered
	7.2.2	NO_x emissions (ton)	
	7.2.3	N_2O emissions (ton)	
	7.2.4	CFC emissions (ton)	

	Item	KPI	Description
	7.2.5	CO_2 equivalent emission (ton)	A single CO_2 equivalent indicator is computed by aggregating the most relevant greenhouse emissions into a single indicator by following the CO_2 equivalency method
	7.2.6	SO_2 emissions (ton)	Not a greenhouse gas, but a component of acid rains and atmosphere particulates
Efficiency	7.3.1	Infeasibilities resulting from the ex-post simulation of system operations	Aggregated line overflows resulting from the market trades
	7.3.2	Clear rules and behaviour	All the rules and laws implemented should be easily understood by every market agent
	7.3.3	Central platform for the publication of information with easy access	Create a Central platform for the publication of information to assure transparency
	7.3.4	Access to aggregated data	
	7.3.5	Access to results	
	7.3.6	Access to bids	

Table 7 : Other KPIs

7.1 Implementability

In a more qualitative way, one shall assess the **coherence of a model with the following existing regulation and legislation** (Nordström et al., 2014):

- Target model in the short-term
- Security of Supply Directive
- State Aid Control Regulation

The **simplicity and the transparency** of the market architectures (segments, products, type of auctions, etc) shall also be assured by market designers to allow a successful implementation and a certain appeal to investors. The simplicity and the feasibility of the implementation may be proxied by the **computation time** required to attain the equilibrium. Whether the **feasible/optimal solution of these problems** can be found is also an indicator of the feasibility of the implementation.

The last two indicators are meant to compare the scheme used in the models and the existing regulations. The degree of compatibility with the existing laws and regulations should be considered for evaluating the implementability of the architecture proposed. One shall also try to emphasise the relevant changes in the existing regulations to adapt them to the proposed scheme.

7.2 Environment

To compare the environmental impact of the different market design options (including the current one), the choice has been made to focus on greenhouse gases emissions. Total **CO_2, N_2O, NO_x and CFC emissions** will be computed for each design options. First, these greenhouse gases will be computed separately, and then they will be aggregated into a **CO_2 equivalent emission** composite indicator. To do so, one shall consider the different global warming potential of each gas. The **emissions of SO_2** will also be computed, even if this gas is not considered a greenhouse gas, it is known to be responsible for acid rains and poor air quality. The market design option with the lowest gas emission will be considered as the most environmentally friendly.

7.3 Efficiency

Infeasibilities resulting from ex-post simulation of system operation for market results: If possible, a simulation of the real operation of the system when implementing a market design could be run. Any infeasibility resulting from this simulation would represent an “imperfection cost”. Thus, when infeasibilities exist, the lower this KPI is, the better. This should be measured as the aggregate size of overflows in the lines of the system for the operation resulting from the market (Nordström et al., 2014).

Market agents need **clear rules** to guide their behaviour and to know what other actors can legally do. One shall create this qualitative indicator to describe the rules implemented and ensure that they are easily understandable for every market agent.

Regarding the transparency exigence, one should be aware of the importance of giving access to information. A **Central platform for the publication of information** will be a help to access it. This access is divided into three main categories (Nordström et al., 2014):

- Access to aggregated data
- Access to results
- Access to bids

8 Conclusion

In this report, we propose a list of quantitative and qualitative key performance indicators (KPIs) that will allow comparing different market design alternatives. The goal of this comparison is to rank different market designs regarding their performance for providing flexibility needs given a massive integration of RES.

For each aspect of markets, KPIs have been proposed in the previous tables. A definition and explanations are then given in text below to bring a clear understanding of the calculation and the use of each indicator.

The process has been to identify a list of several indicators that would allow comparing different market designs. The research for these indicators has been lead through the study of previous works that had been done on the subject (particulary, Olmos et al. (2016) and Nordström et al. (2014)), as well as through an in dept reflection on flexibility assessment.

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