A methodology to define and evaluate EU 2020 target benefits provided by smarting actions on T&D networks

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Abstract: – It is a matter of facts that, at European Union (EU) level, the attention and efforts are increasing to make the electricity system smarter and more and more efficient. To achieve these goals many EU task forces are focusing on the necessity of identifying shared indicators to evaluate the performances of proposed renewing interventions in order to point out those characterized by the more effective impact on the EU targets. The aim of the present paper is that of proposing an analytical methodology to evaluate the effectiveness of improving actions on the T&D electricity network on EU 2020 targets (energy efficiency, renewable production increasing and greenhouse gasses emission reduction) evaluating the maximum impact that the considered action is capable to produce. The work highlights the good performances of the proposed methodology providing a comparison among a limited set of interventions on a benchmark transmission network.

Keywords: – Sustainability, Key Performance Indicators, Smarting Action Assessment Policy, Sustainable Development, 20-20-20 Targets, Electricity System Improvement.

1 Introduction

The European Union (EU) climate and energy policy has established targets for year 2020 on efficiency, CO_2 reduction and increase of renewable energy deployment [1]-[4]. The energy supply system represents a powerful element that can help achieving such environmental targets. Transmission & Distribution (T&D) infrastructure efficiency can and has to be increased in order to achieve the best system performance allowed by state of the art technology. In addition, increasing T&D grids efficiency would also bring benefits at the production side, since it could allow operating generation plants at their best asset from an environmental point of view. In this context, the attention at innovation and improvement of all the processes in the energy conversion and transportation, as long as the energy usage at utility scale, have become a primary issue attracting the interest of those who want to invest in the improvement and modernization of the electricity European infrastructure.

Improving efficiency in the EU energy delivery system is a task that involves field-specialists in all the Member Countries. Many studies have been carried out by Universities and Research Centres, Electrical Companies, International Agencies for Energy Saving and International Workgroups. As a main example, a general simulation tool, called PRIMES, has been proposed in a recent past to assess the impact of EU policies in the power sector [5].

On this subject, the European Electricity Grid Initiative (EEGI) is one of the European Industrial Initiatives under the Strategic Energy Technologies Plan (SET-PLAN) that proposes a 9-year European research, development and demonstration (RD&D) programme to accelerate innovation and development of electricity networks of the future in Europe. The programme focuses on system and technology innovation, and addresses the challenge of integrating new technologies under real life working conditions [6].

The SET-PLAN supports European energy and climate policies through technology innovation. It aims at coordinating efforts at national and EU level through joint strategic planning and effective implementation mechanisms. European Industrial Initiatives are industry-driven strategic technology alliances to address key low-carbon energy technologies [7].

One of the most important aspects of this European Task Force is the definition, validation, updating and usage of Key Performance Indicators (KPIs) in order to assess and evaluate the impact of different proposed projects on both environmental and technical issues. This aspects are discussed inside the Work Package 3 (WP3) named Monitor [8].

Following the guidelines provided by the European Union, the aim of the present article is that of proposing a methodology to define and evaluate environmentally oriented KPIs that will be directly related to the 2020 EU targets [9]. The methodology is derived in order to be applied to both transmission and distribution networks. For the sake of brevity the paper will provide the results coming from simulations performed on a transmission networks in order to achieve the following goals:

1. verify that the KPI definition is well posed, i.e. it is able to identify the key point one is focusing on and represents a useful tool to produce a ranking among different interventions on the grid;
2. verify that the KPI can be either calculated (by means of a simulation in an ex-ante evaluation of the effectiveness of the proposed idea) or measured and, as a consequence, propose an efficient methodology for the evaluation of the KPI;
3. provide a tool which could be helpful in optimizing a “smarting action” on the electric network. For example, if a project is mainly focused on the installation of a device or technology, the proposed methodology will help to find out the best configuration in terms of amount, position, number and mode of operation.

To achieve all these objectives, after the definition of the proposed KPIs (Section 2), a set of possible “sample” interventions on the grid will be discussed and detailed (Section 3) with reference to the following three different action classes:

- new power and/or ICT components, in terms of replacement and additional installations;
- new network operation strategies;
- new control strategies;

Moreover, in Section 4, the methodology adopted to evaluate the KPIs will be explained in details and, in Section 5, the benchmark grids chosen for testing will be presented. Finally, Section 6 will be devoted to the presentation of the simulation results and the KPIs calculation collecting all the results of the investigation together with some conclusive remarks.

2 KPIs definition

As long as smarting actions are concerned, KPIs can be defined and evaluated in order to assess several performance aspects of the electricity grid. A first asset of KPIs can be associated to environmental and energy saving aspects (EU 2020 targets [10]), namely:

- network efficiency;
- renewable generation integration;
- greenhouse gasses (GHG) emission.

Each aspect raised in the previous list can be associated to a well-defined measurable quantity, that will allow the calculations of the correspondent KPI. As long as KPIs definition is concerned, it is possible to point out how two possible definitions are equally applicable: one is based on the incremental benefits obtained on the KPIs driving quantities with respect to their initial values, whereas the other normalizes the benefits to common base quantities related to actual network operation asset.

The 20-20-20 targets aim at a 20% increasing of the network efficiency, a 20% amount of renewable generation with respect to the total energy demand, and a 20% reduction of the GHG emissions. Considering these goals, the efficiency and the GHG KPIs will be defined on incremental basis, as the percentage is referred to an initial reference condition, while the renewable generation penetration KPI will be referred to a common base that is the total energy demand of the system.

2.1 Power saving KPI

From an analytical point of view, this KPI will be defined as the difference between the power losses of an electric grid before (P_{jb}) and after (P_{ja}) a generic smarting intervention divided by P_{jb}, i.e.:

$$PS_{KPI} = \frac{P_{jb} - P_{ja}}{P_{jb}} \cdot 100 \text{ [\%]}. \quad (1)$$

2.2 Share of RES KPI

The second aspect related to the sustainability of the T&D network concerns the increasing of Renewable Energy Sources (RES) into the grid. The RES hosting capacity is the maximum amount of power coming from renewable sources that the grid is capable to manage according to service quality and security criteria. According to 20-20-20 guidelines, this KPI is calculated as follows:

$$SoR_{KPI} = \frac{RES_{HCa} - RES_{HCb}}{P_L} \cdot 100 \text{ [\%]}, \quad (2)$$

being respectively: $RES_{HCb(a)}$ the RES hosting capacity before (after) the smarting intervention and P_L the network active power request.

2.3 CO_2 emission reduction KPI

Another important aspect in the environmental performance of the electricity system lays in the emission of GHG from traditional polluting power plants, commonly of thermoelectric type. This KPI is mainly related to the electricity transmission system, as long as large thermoelectric production sites are typically connected to HV transmission grids but the progressive diffusion of distribute energy resources such as small production sites or microgrids may require the application of this indicator also to distribution networks.

This KPI can then be written as:

$$GHG_{KPI} = \frac{CO_{2b} - CO_{2a}}{CO_{2b}} \cdot 100 \ [\%], \qquad (3)$$

where $CO_{2a(b)}$ is the GHG hourly emission after (before) the intervention. To quantify the $CO_{2,i}$ emission of each thermoelectric power plant it is necessary to know the actual electricity power production, P_{ci}. $CO_{2,i}$ can be written as:

$$CO_{2i} = \frac{P_{ci}\Delta t}{\eta_{el}\eta_{ti}\left(P_{ci}\right)} K_{emi} K_{oxi}. \qquad (4)$$

being $K_{em}\left[tCO_2/MWh\right]$ and K_{ox} the coefficient of emission and oxidation of the fuel and η_{eli} and η_{ti} respectively the electric and thermodynamic efficiencies of the process (it is worth noticing that the efficiency of the thermodynamic process is not constant, but depends on the electricity production of the plant P_{ci}, here this relation has been obtained by interpolation on tabled data [11]).

Typical values for the emission and the oxidation coefficients are reported in eqn (5); as can be seen, the emission coefficients depend in a stronger way on the adopted fuels than the oxidation ones [12].

$$\begin{cases} K_{emCH_4} = 0,2\left[tCO_2/MWh\right], \ K_{oxCH_4} = 0,99 \\ K_{emCoal} = 0,34\left[tCO_2/MWh\right], \ K_{oxCoal} = 0,98. \\ K_{emOil} = 0,27\left[tCO_2/MWh\right], \ K_{oxCoal} = 0,99 \end{cases} \qquad (5)$$

3. Smarting interventions on the grid

Generation, transmission, distribution and utilisation are the basic subsystems of the electric power infrastructure, presently under different multiple controls and managements. System Operators are in charge for coping with technical challenges proposed by the electric market and for managing emergency conditions. In this contest, manufactures play an important role since they design and produce power components, control systems and protection devices.

Formerly, electricity power grids could be made up of a limited variety of components; however recent advances in technology have been extending the flexibility of applications. Today utilities can take advantage of the so-called T&D state-of-the-art technologies, which represent alternative solutions to the consolidated architecture of the electricity grids [13].

Examples of possible smarting actions that are considered in this study are grouped and explicitly presented hereafter:

- the application of FACTS (Flexible AC Transmission System) devices;
- the increasing of network rated voltage;
- the control of reactive power from renewable generation.

The three considered interventions are related to three main categorizes of action namely the installation of state of the art devices, the optimization the actual operational asset of the system and the implementation of new control and management strategies for production units.

This list of actions, in combination with the previously proposed KPIs, generate a KPIs-Interventions matrix that summarizes the area of investigation of the present study and allows to evaluate the different impact of each action on every single KPI.

4. Methodology description

The proposed methodology is based on the application of the classical Optimal Power Flow (OPF) algorithm [14] for the setting of the best asset of the intervention in order to achieve the maximum impact on the considered KPI. The OPF problem is constrained by a set of equality equations describing the physical electric power flow laws and limits on electric variables. Nevertheless, in presence of an intervention that drastically changes the topology of the network (e.g. the application of FACTS devices) the classical load flow equations need to be a little revisited, as will be detailed in the following subsections.

4.1 Modelling of FACTS devices

The second aspect related to the sustainability of the T&D network concerns the increasing of Renewable FACTS devices allow to introduce degrees of freedom in the system that can in principle be used to match the environmental and quality targets defined in the previous sections. FACTS devices are, at present, applied to increase the reliability of electric grids and reducing power delivery costs;

they improve power transmission quality and efficiency mainly by supplying reactive power to the grid [15]. Nevertheless, nowadays, it is necessary to enlarge the way of looking at FACTS devices and to study the effectiveness of their application to pursue environmental targets that are becoming more and more important. FACTS devices are commonly classified in shunt and series compensation, but it is also possible to combine the effects of these two configurations into a single unit. As proposed in [15]-[16], from a static point of view, it is possible to model the effect of the compensators as single/combined voltage or current sources (depending if one is considering a series, shunt or combined device) as depicted in Fig. 1:

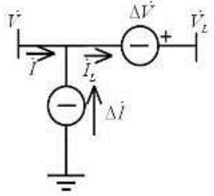

Fig. 1. General FACTS modelling.

Series, shunt and combined devices could account either for active configurations, that is with supply of active power too, or for reactive ones only delivering reactive power. In terms of degrees of freedom (DoF), one can state that [16]:

- Reactive series and reactive shunt can provide 1 DoF;
- Active series and active shunt can provide 2 DoF;
- Combined reactive can provide 3 DoF;
- Combined active can provide 4 DoF.

In this representation, the quantities $\Delta\dot{V}$ and $\Delta\dot{I}$ are the effects of the compensation, $\dot{V}$ ($\dot{I}$) is the voltage (current) at the sending node and $\dot{V}_L$ ($\dot{I}_L$) is the voltage (current) at the receiving one.

The proposed modelling takes into account the possibility of implementing FACTS devices at each end of every line of the system, as shown in Fig. 2, which represents the general model of a branch with FACTS compensator at its terminals.

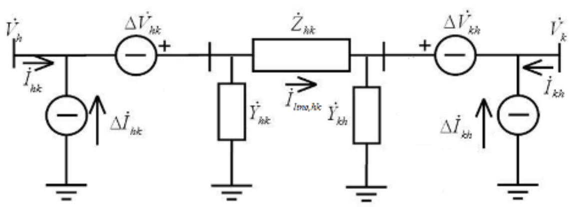

Fig. 2. Modelling of the generic "h-k" connection accounting for FACTS compensations.

On the basis of the configuration proposed above, it is now possible to draw a general formulation for the problem of investigating the FACTS impact on the KPIs defined in the previous sections.

From a mathematical point of view, the problem can be formulated as follows: find out the values of $\Delta\dot{V}_{hk}$ and $\Delta\dot{I}_{hk}$ to be inserted at each termination of each branch of the network, which maximize an objective function constrained by the load-flow equations, that is to say:

$$\min f\left(\dot{V}_h, \Delta\dot{V}_{hk}, \Delta\dot{I}_{hk}\right),\ h,k = 1..N\ , \qquad (6)$$

where f is a real function of the node voltages $\dot{V}_h$ and of the shunt and series compensations $\Delta\dot{I}_{hk}$ and $\Delta\dot{V}_{hk}$ selected in dependence of the KPI under investigation (in principle, the function f could be the KPI itself). The constraints of the problem are represented by the load-flow equations [17]:

$$\dot{S}_h = V_h \sum_{\substack{k=1,\\ k\neq h}}^{N} \dot{I}^*_{hk}\left(\dot{V}_h, \dot{V}_k, \Delta\dot{V}_{hk}, \Delta\dot{I}_{hk}, \Delta\dot{V}_{kh}, \Delta\dot{I}_{kh}\right), \qquad (7)$$

where the expression of the current $\dot{I}_h$ as a function of the variables of the problem is the following (see Fig. 2):

$$\dot{I}_{hk} = \left(\dot{V}_h + \Delta\dot{V}_{hk}\right)\left(\dot{Y}_{hk} + \frac{1}{\dot{Z}_{hk}}\right) - \frac{\dot{V}_k + \Delta\dot{V}_{kh}}{\dot{Z}_{hk}} - \Delta\dot{I}_{hk}\,. \qquad (8)$$

Inserting (8) into (7), one obtains the explicit formulation of the load flow constraints. The insertion of the FACTS devices adds (complex) degrees of freedom, thus enabling us to set up an optimization problem, which would be meaningless without those devices, as the conventional load-flow has usually only one feasible solution.

In addition to these constraints, the formulation takes into account:

- the static current limit on every line;
- the upper and lower limits for the node voltages
- the limits on the maximum amplitude of the current and voltage compensations (related to the FACTS sizing);
- the limits on the real power produced by those devices, that is to say:

$$\begin{cases} \left|\dot{I}_{line,hk}\left(\dot{V}_h, \dot{V}_k, \Delta\dot{V}_{hk}, \Delta\dot{I}_{hk}, \Delta\dot{V}_{kh}, \Delta\dot{I}_{kh}\right)\right| \le \mathrm{I}_{\max} \\ V_{\min} \le \left|\dot{V}_h\right| \le V_{\max} \\ \left|\Delta\dot{V}_{hk}\right| \le \Delta V_{\max} \\ \left|\Delta\dot{I}_{hk}\right| \le \Delta I_{\max} \\ \mathrm{Re}\left(\Delta\dot{V}_{hk}\left[\dot{I}^*_{hk} + \Delta\dot{I}^*_{hk}\right] + \dot{V}_h \Delta\dot{I}^*_{hk}\right) \le P_{comp\max}\ . \end{cases} \qquad (9)$$

4.2 Variation of transmission voltage level

The voltage levels of distribution and transmission network have a strong and significant effect on the way of operation of the electric system itself. The increasing of the voltage level in electric systems is usually associated to a positive effects as it could reduce the losses, and the circulating currents, improving, at the same time, the voltage profile of the network busses. To assess the impact of such intervention on the different issues previously presented, an optimization multivariable approach is not necessary, as, by definition, there is only one degree of freedom (i.e. the voltage level); as a consequence, a set of different load flow problems will be solved changing the voltage base value. With reference to the transmission system, the voltage will be considered variable between 400 kV up to 800 kV [18].

4.3 Reactive power regulation of renewable generation

The recent growing in number and power of renewable generation units asks for a significant change in the way of operation of the electric system related to the stochastic behaviour of their power production. Up to now, renewable generation units have been operated in order to maximize the active power coming from RES without putting much consideration to their possible role as ancillary services suppliers. However, because of the distributed nature of these resources, they can become crucial in upgrading the quality asset of the T&D networks, since the new frontier of the inverters control will allow to fully exploit the potential of renewable generation by regulating also their reactive power injection [19]. In the present study, the effect of controlling the reactive power of renewable generation units will be analysed referring once again to the multivariable optimization problem of eqns (6)-(9), in which all the compensations $\Delta\dot{V}_{hk}$ and $\Delta\dot{I}_{hk}$ are nullified and the RES reactive powers (i.e. the imaginary parts of the LHS of eqn (7)) are optimized in a certain range defined by the device rating. As a consequence, this intervention generates a number of degrees of freedom potentially equal to the number of renewable units present in the grid.

5. Simulation and results

5.1 Test case network definition

The proposed methodology has been tested on a transmission benchmark networks. The considered transmission network is a modified CIGRE 10-bus benchmark network [20] and its structure is shown in Fig. 3. For the sake of brevity simulations on a distribution benchmark network is here omitted since results mainly recall those obtained on the transmission benchmark network. It is worth noticing that the methodology could be equally applied to a distribution network simply changing the network topology and main parameters but keeping the same formulation.

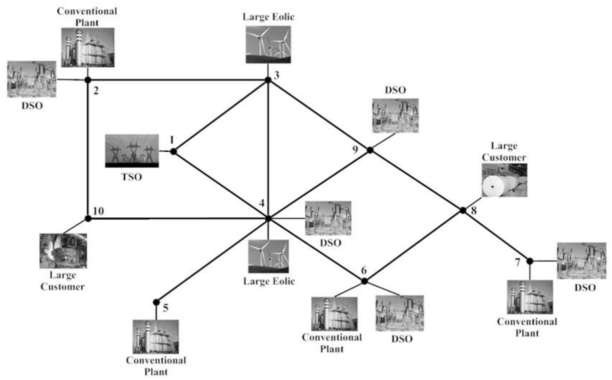

Fig. 3. Revisited CIGRE 10 node transmission test network layout and node injection characterization.

The network is operated at the rated voltage of 225 kV and its main characteristics are reported in Table 1, where X and R are respectively the reactance and the resistance of each line and I_{max} is its maximum admissible current.

Table 1: CGTN topology data

Line	X [Ω]	R [Ω]	I_{max} [A]
1-3	24.497	4.996	539
1-4	24.497	4.996	539
2-3	62.597	27.781	539
2-10	32.298	8.251	539
3-4	39.497	5.973	539
3-9	27.995	5.771	526
4-5	9.998	1.974	196
4-6	9.99	3.796	1026
4-9	96.997	24.654	539
4-10	32.997	8.251	539
6-8	31.797	9.466	539
7-8	39.497	5.973	1796
8-9	96.997	24.654	539

The grid players are: thermoelectric conventional plants, large customers connected directly to the transmission network, large wind farms, several DSOs and a neighbour TSO. Their main data are reported in Table 2 where P_{min} and P_{max} are respectively the limits of the active power capability, while P and Q are the injected active and reactive power in the reference operational scenario.

Table 2: Generation characteristics

	Node	P_{min} [MW]	P_{max} [MW]	P [MW]	Q [MVAr]
Conv. Gen.	2	300	1000	300	101.38
	5	170	600	170	22.73
	6	280	900	280	110.6
	7	110	400	110	126.93
Large RES	3	0	400	300	0.00
	4	0	200	124	0.00
Large Customers	8	0	-1000	-100	-50.00
	10	0	-90	-90	-45.00
DSO	2	-450	405	-200	-120.00
	4	-450	405	-65	-40.50
	6	-450	405	-80	-30.00
	7	-450	405	-200	-50.00
	9	-450	405	-230	-80.00
TSO	1	-	-	-294.5	159.5

5.2 Power saving KPI results

The function to be minimized in this section is represented by the system total Joule losses. They can be expressed as a function of the electric variables of the system, including those introduced by the intervention. The objective function for the Power Saving KPI can be written as:

$$f = \sum_{h=1}^{n}\sum_{k=h}^{n} R_{hk} \cdot \left| \dot{I}_{hk}\left(\dot{V}_h, \dot{V}_k, \Delta\dot{V}_{hk}, \Delta\dot{I}_{hk}, \Delta\dot{V}_{kh}, \Delta\dot{I}_{kh}\right)\right|^2, \quad (10)$$

where n is the total number of the grid busses and R_{hk} and I_{hk} are respectively the per unit resistance and current of the generic *h*-*k* network branch.

5.2.1 Application of FACTS devices for network losses reduction

The application of FACTS devices to CGTN network has been performed with respect to both active and reactive ideal UPFC (combined FACTS with respectively 4 and 3 degrees of freedom). The investigation has explored the whole set of possible locations for the component, namely 26, in order to evaluate the effects on the Power Saving KPI in the best possible location. The values of ΔI_{max} and ΔV_{max} appearing in eqn (9) have been set to 20 % of the network p.u. base values, i.e. 45 kV and 108 A while $P_{compmax}$ is 4 MW (0 MW for the case reactive device). Table 3 summarizes the results in terms of optimal location, losses and operating conditions of the compensator considering both its active and reactive version.

Table 3: Reactive combined FACTS results.

	Reactive	Active
Optimum location	3-2	3-2
Losses before [MW]	24.52	24.52
Losses After [MW]	23.44	23.39
$\lvert\Delta\dot{v}\rvert$ [p.u.]	0.064	0.064
$\lvert\Delta\dot{v}\rvert$ [kV]	14.4	14.3
$\angle\Delta\dot{v}$ [°]	151.7	151.5
$\lvert\Delta\dot{i}\rvert$ [p.u.]	0.42	0.42
$\lvert\Delta\dot{i}\rvert$ [A]	107.8	107.8
$\angle\Delta\dot{i}$ [°]	-92.4	-97.5
P_{comp} [MW]	0.00	-3.99
Q_{comp} [MVAR]	44,89	44.45

It is worth noticing that in both cases the best location is the same, with the FACTS device located at bus three on the interconnection 3-2. The application of active compensation gives a very reduced improvement of the system efficiency in spite of the necessity of storing a relevant amount of power. In both cases, the absolute losses reduction is equal to almost 1 MW. From the obtained results, it is possible to calculate the Power Saving KPI as detailed in Table 4.

Table 4: Power Saving KPI for FACTS application

	Power Saving KPI
Active Combined FACTS	$\frac{24.52MW - 23.39MW}{24.52MW} \cdot 100 \cong 4,6\%$
Reactive Combined FACTS	$\frac{24.52MW - 23.44MW}{24.52MW} \cdot 100 \cong 4.4\%$

The results obtained by the Power Saving KPI evaluation confirms the almost identical impact of the intervention on system efficiency, giving an indication on the possibility of applying a reactive combined compensation in spite of an active one.

5.2.2 Increasing transmission rated voltage for network losses reduction

The analysis of the variation of the transmission voltage for the benchmark network CGTN has been performed considering the variation of the total losses of the system as a function of the transmission voltage. The starting point is, of course, 225 kV which represents the rated transmission voltage of the benchmark network. Because of the relevant number of busses and branches, it is impossible to obtain an explicit analytical expression connecting the system losses to the transmission voltage. For this reason, the problem has been solved implementing a numerical algorithm, considering a voltage range between 225 kV and 800 kV, sufficiently wide in order to highlight relevant behaviors of the quantities under investigation. Fig. 4 depicts the variation of the total losses of the system in accordance to the adopted transmission voltage. The minimum value of the system losses, equal to 7.08 MW, occurs at 575 kV. Nevertheless, examining the figure, it is apparent that the system losses and lower than 8 MW for a significantly wide range of rated voltages, from 450 kV to 750 kV. Increasing the transmission voltage over 800 kV will reduce the effectiveness of the intervention and continuing to increase could also lead the system to a situation even worse than the original one

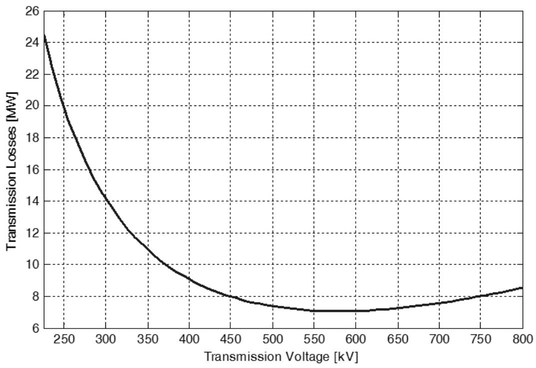

Fig. 4. Total losses of the system as a function of the transmission rated voltage.

The KPI value for the intervention under investigation is calculated on a loss value of 8 MW in order to allow a flexibility range of the new transmission voltage of approximately 300 kV (Table 5).

Table 5: Power saving KPI evaluation for the increasing of system rated voltage

.	**Power Saving KPI**
Increase of Transmission Voltage	$\frac{24.52MW - 8.00MW}{24.52MW} \cdot 100 = 67.37\%$

5.2.3 Reactive power control of renewable generation units for network losses reduction

CGTN network is characterized by the presence of two renewable generation units located at bus 3 and 4, i.e. two large wind power plants. The reference operation scenario is obtained imposing the present usual praxis for renewable generations [19], that is: maximum active power deliverable from the power plant and no reactive power injection. The aim of the present study that of analyzing the effect led from the introduction of a novel operation criterion for the renewable generation allowing the generation/consumption of reactive power from the energy converter (more and more requested by several TSOs and DSOs). This action can be implemented in the optimization problem simply by relaxing the constraint of no reactive power exchange at the point of common coupling of each renewable generation unit. Such reactive power can be now chosen in a range determined by the inverter capability curve and the maximum allowable power factor (here set to 0.9 lagging or leading). With the aforementioned constraints, the optimization algorithm asks the wind generator at bus 3 to produce 145 MVAr and the one to bus 4 to inject 60 MVAr with an active power production of 300 MW and 124 MW, respectively. The result obtained from the regulation of the renewable reactive power generation are reported in Table 6:

Table 6: Reactive power control results.

Losses before [MW]	**Losses after [MW]**	**Q_3 [MVAR]**	**Q_4 [MVAR]**
24.52	23.89	145.0	19.5

From the results obtained by the optimization analysis, it is possible to calculate the Power Saving KPI for this third intervention. Results are reported in Table 7.

Table 7: Power saving KPI evaluation for the renewable reactive power control

.	**Power Saving KPI**
Renewable Reactive Power Control	$\frac{24.52MW - 23.89MW}{24.52MW} \cdot 100 = 2.57\%$

5.3 Reduction of the CO2 emissions KPI results

In order to better emphasize the effects of the proposed actions on GHG emission reduction by conventional generation units, it is necessary to introduce some minor variations to the operation scenario of CGTN test-network. These modifications are introduced in order to avoid a distorting effect caused by several conventional units already producing at their minimal technical power. The quantities that change with respect to the original operational condition are reported in Table 8:

Table 8: Changes to the original asset of CGTN

	Bus	**P [MW]**	**Q [MVAR]**
Large Customer	8	-300	-150
	10	-180	-135
DSO	2	-600	-360
	4	-195	-121
	6	-240	-90
	7	-200	-50
	9	-230	-80

Moreover, one has to specify the kind of plant associated with the four conventional units present in CGTN; in our case, we are supposing that:

- A steam production unit supplied by oil is placed at bus two,
- A coal supplied steam generation unit injects power at bus 5
- Bus 6 presents a gas turbine generator
- Bus 7 is equipped with a combined cycle production unit.

The objective function to be minimized in the present section is the sum of the traditional power plants CO_2 emissions, defined as:

$$f = \sum_{h=1}^{N} CO_{2h} = \sum_{h=1}^{N} \frac{P_{\text{conv,h}}}{\eta_{el,h} \cdot \eta_h} k_{Oss,h} \cdot k_{Em,h} \,. \qquad (11)$$

Starting from the modified reference scenario described here above, the total CO_2 hourly emission is of 1,031 tCO_2/h. The rated emission calculated in accordance to eqn (13) is equal to 1,915 tCO_2/h. These values are obtained with reference to the specific rated values for the different conventional power plants detailed in section 0.

5.3.1 Application of FACTS devices for CO2 emission reduction

Table 9 reports the results obtained for the CO_2 KPI thanks to the adoption of the combined active/reactive FACTS devices:

Table 9: Optimization results for the application of reactive combined FACTS

	Reactive	**Active**
Location	10 - 2	10 - 2
CO_2 emission before [tCO_2/h]	1,031	1,031
CO_2 emission after [tCO_2/h]	873	870
$\lvert\Delta\dot{v}\rvert$ [p.u.]	0.134	0.133
$\lvert\Delta\dot{v}\rvert$ [kV]	30.2	29.9
$\angle\Delta\dot{v}$ [°]	-108.0	-107.1
$\lvert\Delta\dot{i}\rvert$ [p.u.]	0.42	0.42
$\lvert\Delta\dot{i}\rvert$ [A]	107.8	107.8
$\angle\Delta\dot{i}$ [°]	-82.4	-76.6
P_{comp} [MW]	0.00	4.00
Q_{comp} [MVAR]	49.36	47.51

In both cases, the location that allows the highest reduction of the GHG emissions is at bus 10 on line 10-2. The results highlight that the two different typologies of FACTS devices produce substantially the same effect, with a reduction of the CO_2 emission of almost 160 tCO_2/h. Once again, the application of active FACTS devices introduce a very limited improvement with respect to the reactive ones. According to the obtained results, it is possible to assess the CO_2 emission KPI in reason of 15.7% for both active and reactive compensation as reported in Table 10.

Table 10: CO2 emission KPI evaluation

.	**CO_2 Emission KPI - Incremental**
Active Combined FACTS	$\frac{1031\, tCO_2/h - 870\, tCO_2/h}{1031\, tCO_2/h} \cdot 100 = 15.6\%$
Reactive Combined FACTS	$\frac{1031\, tCO_2/h - 870\, tCO_2/h}{1031\, tCO_2/h} \cdot 100 = 15.6\%$

5.3.2 Increasing of distribution voltage level for CO_2 emission reduction

With specific reference to the CO_2 KPI, the effect of the increasing of transmission voltage on the total hourly emissions of the grid is depicted in Fig. 5.

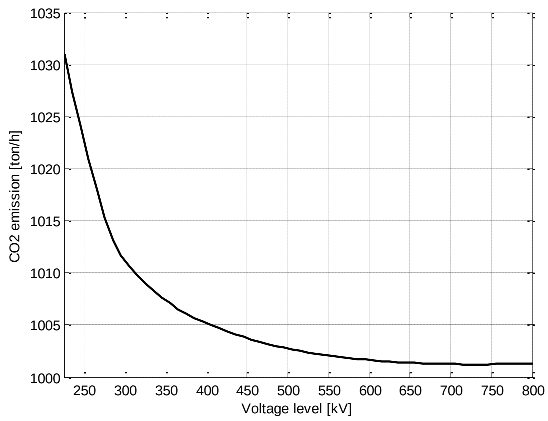

Fig. 5. Variation of CO_2 emission in accordance with rated voltage increasing.

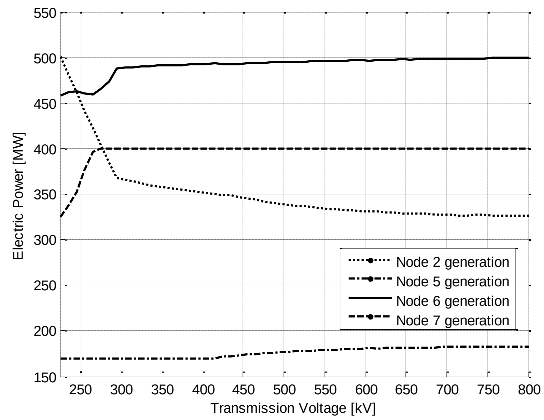

Fig. 6. Power plant dispatch as a function of voltage increasing

As can be seen examining the graph, the quantity of hourly polluting emissions exhibits a decreasing trend whose limit is 1001 ton/h. Fig. 6 shows how the more polluting central, i.e. the one placed at bus two, slowly tends to reduce its production in favour of the combined cycle unit (bus 7) and turbo-gas generators (bus 6). The effect of increasing the transmission voltage can be evaluated by the KPI defined in the previous section of the paper. Numerical results are reported in Table 11.

Table 11: CO_2 emission KPI evaluation

	CO_2 Emission KPI
Increase of Transmission Voltage	$\frac{1031\, tCO_2/h - 1001\, tCO_2/h}{1031\, tCO_2/h} \cdot 100 = 2.90\%$

5.3.3 Renewable reactive power control for CO_2 emission reduction

Table 12 reports the results obtained with the implementation of a reactive control strategy of the renewable generation within the limits described in the previous section:

Table 12: Renewable reactive power control effects on greenhouse gasses emission.

CO_2 emission before [tCO_2/h]	1,031
CO_2 emission after [tCO_2/h]	948
Q_3 [MVAR]	-60.0
Q_4 [MVAR]	145.3

The reactive power from renewable generation units allows to optimize the asset of the polluting generation in order to reduce the amount of the GHG emissions of almost 8%; so the relative KPIs can be calculated as detailed in Table 13.

Table 13: CO2 emission KPI evaluation

	CO_2 Emission KPI
Renewable Reactive Power Control	$\frac{1031\, tCO_2/h - 948\, tCO_2/h}{1031\, tCO_2/h} \cdot 100 = 8.1\%$

5.4 Share of RES KPI results

The objective of the present KPI, as detailed in the previous chapters, is that of increasing the renewable hosting capacity (HC) of the system. For this particular study case, the function to be minimized can be expressed as:

$$f = \sum_{k=1}^{N} P_{r,k}\,, \tag{12}$$

where $P_{r,k}$ is the renewable generation of the *k-th* node. The study case of the CGTN presents a renewable generation of 424 MW despite an installed capacity of 600 MW. The test case scenario does not allow the increasing of renewable generation without creating problems of overloading and inadmissible voltage profiles; so the original RES HC is equal to 424 MW.

5.4.1 Application of FACTS devices for share of RES increasing

Table 14 reports the results obtained by the application of active and reactive combined compensations on CGTN:

Table 14: Reactive combined FACTS results on the Share of RES KPI

	Reactive	**Active**
Optimum location	1-4	1-4
RES HC before [MW]	424	424
RES HC After [MW]	465	523
$\lvert\Delta\dot{v}\rvert$ [p.u.]	0.14	0.13
$\lvert\Delta\dot{v}\rvert$ [kV]	3.0	3.00
$\angle\Delta\dot{v}$ [°]	57.6	57.0
$\lvert\Delta\dot{i}\rvert$ [p.u.]	0.42	0.42
$\lvert\Delta\dot{i}\rvert$ [A]	107.8	107.8
$\angle\Delta\dot{i}$ [°]	-122.5	-115.8
P_{comp} [MW]	0.00	4.00
Q_{comp} [MVAR]	58.74	59.93

By the application of a reactive compensation, one obtains an increasing of 41 MW of the RES HC of the system, while, with the application of active FACTS devices, the RES hosting capacity increases of 99 MW. The KPI evaluation is reported in Table 15**Errore. L'origine riferimento non è stata trovata.**.

Table 15: Share of RES KPI evaluation

	Share of RES KPI
Active Combined FACTS	$\frac{523MW - 424MW}{775MW} \cdot 100 = 12,76\%$
Reactive Combined FACTS	$\frac{465MW - 424MW}{775MW} \cdot 100 = 5,29\%$

5.4.2 Increasing of distribution voltage level for share of RES increasing

The simulations performed in this section take into account the increasing of the distribution voltage up to 800 kV. The application of the proposed methodology produced an optimum value of rated transmission value of 450 kV. With this value the transmission system is capable of receiving all the renewable generation giving a RES hosting capacity of 600 MW. The corresponding KPI evaluation is reported in Table 16:

Table 16: Share of RES KPI evaluation

.	Share of RES KPI
Increase of Distribution Voltage	$\frac{600MW - 424MW}{775MW} \cdot 100 = 22.71\%$

5.4.3 Reactive power control of renewable generation for share of RES increasing

The results derived from the implementation of the RES reactive power control are detailed in Table 17:

Table 17: RES reactive power control effects on the increasing of the RES hosting capacity

RES HC before [MW]	424
RES HC after [MW]	444.5
Q_3 [MVAR]	155 (cap.)
Q_4 [MVAR]	60 (cap.)

The reactive power produced from the renewable generation helps to locally satisfy the reactive request of loads; thanks to this, lines are less loaded and the amount of renewable generation can slightly increase up to 444.5 MW. The corresponding KPI evaluation is detailed in Table 18.

Table 18: Share of RES KPI evaluation

.	Share of RES KPI
RES Reactive Power Control	$\frac{444.5MW - 424MW}{775MW} \cdot 100 = 2.65\%$

5.5 Overall comparison of achieved results

In order to summarize the results obtained in the previous sections, it could be useful to analyze the entries of Table 19, which reports KPIs values calculated in correspondence of each of the proposed actions on CGTN.

Table 19: Result summary for KPIs evaluation

		Power Saving KPI	GHG Emission KPI	SoR KPI
Installation of FACTS Devices	**Active**	4.60%	15.60%	12.76%
	Reactive	4.40%	15.60%	5.29%
Increasing of Transmission voltage		67.37%	2.90%	22.71%
RES Reactive Power Supply		2.57%	8.10%	2.65%

More in details, if one wants to improve the energy efficiency of a Transmission Network, it is apparent that the most effective intervention, among those considered, is the increasing of the transmission voltage level. As far as the reduction of GHG is concerned, the installation of (reactive) FACTS devices appears as the most suitable smarting action among the considered ones. Increasing the transmission voltage level provides also the most relevant effect in order to increase the system HC of RES. Despite the specific conclusions of the proposed interventions it is important to notice the good applicability of the methodology and KPIs definition which helps in the identification of the action with the most relevant potential effect on the considered issues.

Having in mind the main aims of the paper, this analysis pointed out that:

- KPIs definition is well posed in all the cases, since it has helped to identify the key point one is focusing on and to produce a ranking among different interventions on the grid;
- It has been possible to perform an ex-ante evaluation of the KPIs (by means of simulations);
- A useful methodology has been defined to optimize the “smarting action” on the electricity network (e.g. the best location of FACTS devices, the optimum value of rated voltage and the best reactive power injection from RES).

6. Conclusions

This paper performed an overall study for the definition and application of Key Performance Indicators (KPIs) suitable for the quantification of environmental benefits provided by smarting actions for the improvement of the electricity EU transmission and distribution networks. KPIs are also thought as a decision support tool for the ranking of different proposals in order to assign financing and economical support to those projects that have the more effective impact on 2020 EU environmental targets. The present article details a comprehensive definition of a methodology for the quantification of the KPIs in accordance to the actions taken into account. The proposed methodology is based on the application of Optimal Power Flow algorithms which represents a powerful and flexible tool for the evaluation of several situations and targets. Simulations performed on a Cigré benchmark network highlighted the validity of the proposed KPIs definition in order to point out the effectiveness of the interventions in the specific study case. Future development will account for the extension of the KPIs definition to different goals, related to power quality or security of energy supply, in order to extend the field of evaluation of smarting actions and improving projects beyond EU 2020 targets.

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