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Developing a Method to Account for Avoided Grid Losses from Decentralized Generation: the EU Case

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Abstract

Decentralized generation is often connected to the distribution grid and consumed by end-users in geographical proximity. Compared to large centralized power plants supplying electricity that flows down the voltage chain in a top-down manner, decentralized generation can avoid grid losses and save primary energy (PE). This paper developed and demonstrated a generic method to account for avoided grid losses and PE savings from decentralized generation, using the EU as the case-region. The method can serve as an easy tool to support the discussion and decision-making process regarding a technology choice between centralized and decentralized generation. Based on this method, we estimated that for each MWh of electricity produced from decentralized generation in the EU, it saves 0.136-0.350 MWh PE under on-site generation mode and 0.103-0.286 MWh PE under off-site generation mode due to avoided grid losses.

Keywords: Grid losses; decentralized generation, primary energy

1. Introduction

Transmission and distribution (T&D) losses occur during the transfer of electricity from power plants to end-users. In 2014, global grid losses were 8.3% (or 1980 TWh) of total electricity output [1]. To cover grid losses, additional primary energy (PE) input is necessary for power generation, resulting in greater costs and CO_2 emissions [2]. The use of small-scale decentralized (or distributed) capacities for electricity generation is increasing in recent

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years. As decentralized generation often either uses renewable energy (e.g. solar) or improves the efficiency of (fossil) fuel usage (e.g. cogeneration of heat and power (CHP)), it can save PE and reduce CO_2 emissions. In addition, decentralized generation is often connected to the distribution grid and used by end-users in geographical proximity [3]. This reduces grid losses, compared to a large centralized plant supplying electricity that flows down the voltage chain in a top-down manner [2]. Due to avoided grid losses, additional PE and emissions are saved from decentralized generation. To account for the avoided losses, the reference electricity generation efficiency (i.e. efficiency of the marginal centralized power plant that is replaced by decentralized generation) used for the calculation of PE saving can be corrected. This can be ideally done through detailed bottom-up modelling of each grid node and the power flows, but such an approach is infeasible due to limited data availability (e.g. location, demand and supply of each node; length, voltage level, cross-section area, impedance of each line; size, type and loading of each transformer; power flows through each line). In absence of detailed bottom-up grid data, this paper aims to propose a generic correction method for avoided losses from decentralized generation, through establishing a top-down reference model (RM) divided by different voltage levels. To demonstrate the development of the method, the EU is used as the case-region. The developed method enables the comparison of electricity generation efficiency between centralized and decentralized technologies on a level playing field. It can also provide useful information for the power industry, policy-makers, regulators and other stakeholders to support their decision-making process.

2. Method

The development of the method consists of five main steps. First, based on literature, different grid loss components and their respective shares in total losses were characterized. Second, a reference model was built up to represent the typical top-down electricity supply from a large centralized power plant to end-users throughout the entire voltage chain of the T&D grid. The grid was divided by different voltage levels, with (marginal) grid losses occurring at each voltage level. Third, the marginal and cumulative grid losses at each voltage level were estimated for the RM, based on the output in step 1. This also served to determine avoided grid losses from decentralized generation, depending on their connection voltage levels and (on- and/or off-site) generation modes in step 4. In the last step (step 5), correction factors were developed to correct the reference efficiency of the marginal centralized plant and calculate the PE saving from decentralized generation. An application of the correction factors was demonstrated. We will elaborate how these steps were performed in chapter 3–7.

3. Characterization of grid loss component

T&D losses can be categorized into technical losses and non-technical losses. Technical losses refer to electricity dissipated into heat and noise during T&D, which mainly include line losses and transformer losses [4]. In contrast, non-technical losses consist of electricity delivered but not reflected in the sale records, such as electricity theft, non-metered supplies and metering errors [5]. Non-technical losses are relatively less significant for most countries in the EU, and they mainly occur within the distribution grid [4]. They usually ***range from 3% to less than 20%*** of total losses, based on surveys in the UK [6]. Thus, we focus here on technical losses only:

- **Line losses** contribute to ~2/3 of total technical losses in the EU [7]. Line losses mainly include joule losses due to the joule's heating effect, which inversely proportionate to the square of the grid voltage. To reduce losses from transporting electricity over long distance, electric power generated at 10-30 kV is first converted into high (or extra high) voltage levels typically ranging from 220 kV to 750 kV to feed into the transmission grid [7]. The voltage is then stepped down throughout the sub-transmission and distribution grid closer to the end-users. Power is usually supplied at less than 1 kV for most domestic and commercial customers, but 33-150 kV for major industrial customers [6]. Hence, approximately 70-75% of total grid losses in the EU are within the distribution grid [7]. The corona effect (i.e. energized conduct ionizes nearby air) also contributes to line losses. Corona losses are less significant, and can be negligible at voltage levels below 230 kV [5, 8]. For instance, only 8% of line losses within the transmission network can be attributed to corona losses in Québec [9].
- **Transformer losses** contribute to the remaining 1/3 of total technical losses in the EU [5]. Transformer efficiency (and losses) depend on the type, size and loading of the transformer. Table 1 lists the main types of transformers and their operational efficiencies at 100% and 50% rated load. Except for the generator transformer

that operates at (nearly) full load, the loading of other transformers is usually below 50%.

Table 1. Main types of transformers and their operational efficiencies at 100% and 50% rated load.

Transformer type	Definition	Rated power	Operational efficiency	
			100% load	50% load
Generator transformer	Generator transformers are connected with the generator unit of the power station to step up the voltage of electric power so as to feed it into the transmission grid at high or extra-high voltage. Its operating voltage ranges from 1-25 kV	1000 MVA	99.60%	99.75%
Interbus transformer	Interbus transformers interconnect two or more voltages within the transmission grid. With Interbus transformers, transmission voltage can be stepped down to sub-transmission voltage	400 MVA	99.60%	99.75%
Substation transformer	Substation transformers interconnect the transmission grid with the distribution grid. They are used to step down subtransmission voltage to distribution voltage	40 MVA	99.40%	99.60%
Distribution transformer	Distribution transformers are smaller transformer units used in the distribution grid, and they usually contain at least two transformation stages	1 MVA	98.60%	99.11%

Source: Adapted from Fassbinder [10] and Polish Copper Promotion Center and European Copper Institute [11]

After characterizing different grid loss components from literature, their respective shares in total grid losses were calculated (see Fig. 1). Note that if relevant parameters in literature are reported in the form of a data range (e.g. non-technical losses, distribution losses), they were treated as a mean value to perform the calculation. In absence of generic data available for the EU (e.g. non-technical losses, corona losses), relevant parameters from the UK and Québec were used, assuming that they are representative for the EU as well.

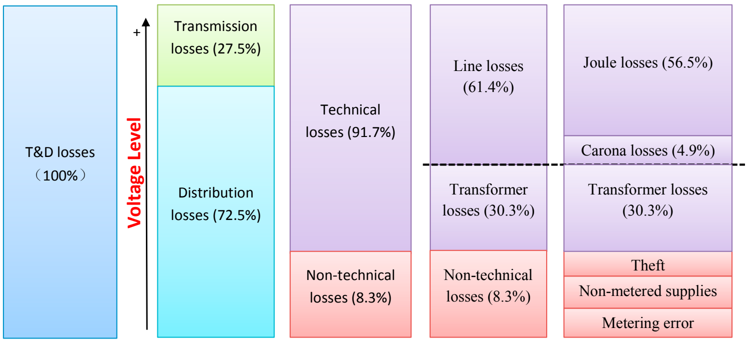

Fig. 1. Components of T&D losses and share in total losses

4. RM for top-down electricity supply from a large centralized power plant

Based on an extensive review of grid codes of each EU Member State and communication with experts[1] the detailed voltage values for the T&D grid can be divided into seven main levels. They are extra-high voltage (**EHV** (> 345 kV)), high voltage (**HV** (200-345 kV)) and upper-medium (**UMV** (100-200 kV)) voltage for the transmission grid; middle-medium voltage (**MMV** (50-100 kV)), lower-medium voltage (**LMV** (12-50 kV)), low voltage (**LV** (0.45-12 kV)) and extra-low voltage (**ELV** (<0.45 kV)) for the distribution grid. This forms the basis to develop the RM. Since the RM represents the top-down supply of electricity from a large centralized power plant, it assumes the electric power flows down the voltage chain (from highest EHV voltage level to lowest ELV level) throughout the entire T&D grid until its delivery to end-users. The RM (see Fig. 2) consists of lines at the above-mentioned voltage

[1] This research is a follow-up study inspired by the European Commission DG Energy project "Review of the Reference Values for HighEfficiency Cogeneration". The communication is based expert consultation in the project.

levels and transformers that interconnect these voltage lines. Based on the definition provided in table 1, different types of transformers (generator, interbus, substation and distribution transformers) are set up in the model. Grid losses occur at each voltage line and each transformer that electric power passes through. The cumulative grid losses from the centralized power plants to end-users depend on the voltage level at which electric power is supplied to end-users. The lower the voltage level of an end-user grid connection, the greater amount of upstream lines and transformers the electric power has to pass through and thus the more cumulative grid losses.

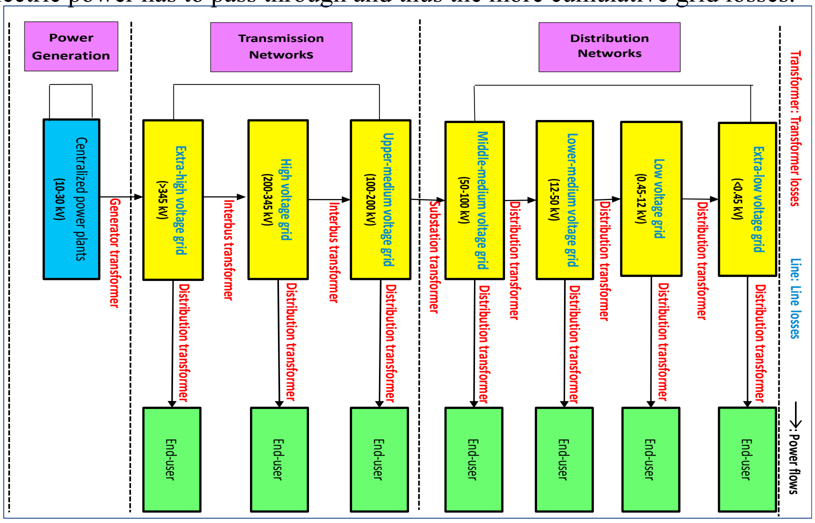

Fig. 2. RM for top-down electricity supply from large centralized power plants

5. Estimating marginal and cumulative losses at each voltage level for the RM

For convenience, we consider the line at the voltage level connected to end-users as the marginal line. In addition, we also distinguish the marginal and last transformer. The marginal transformer refers here to the bordering transformer, next to the marginal line. Electric power has to pass through it before entering the marginal line. For instance, the marginal transformer for EHV grid connection is the generator transformer, while for LV and ELV grid connection it is the distribution transformer. Besides the marginal transformer, electric power has to pass through the last transformer, usually a distribution transformer that interconnects the marginal line with end-users.

Following the RM, the cumulative grid losses for end-users connected at each voltage level can be determined once the marginal total losses are determined. The marginal total losses include marginal line losses, marginal transformer losses and marginal non-technical losses. Therefore, the cumulative losses for each connection voltage level is the sum of the marginal total losses, the last transformer losses and the total upstream losses under the same connection voltage. Estimation of marginal and last transformer losses can be assisted by the efficiency value for each type of transformer (see Table 1). To reflect operation situation in reality, the full-load efficiency was assumed for the generator transformer, while for other types of transformer the half-load efficiency was considered. We further made two assumptions: First, that corona losses only occur at EHV and HV, and non-technical losses only occur at ELV, which closely reflects the reality; Second, that the share of different grid loss components calculated in figure 1 (used as constraint conditions) corresponds to the maximum cumulative grid losses of the RM, i.e. cumulative electric power losses throughout the entire T&D grid (from highest voltage to lowest voltage) that represent the maximum total grid losses that could possibly occur. These enabled the calculation of the marginal losses for different loss components (corona losses, joule losses, transformer losses and non-technical losses) under the reference situation that electricity is supplied by a centralized plant connected at EHV. The calculated marginal and cumulative losses for each voltage level of the RM are presented in Table 2.

Table 2. Marginal and cumulative grid losses for different voltage levels.

Voltage level		Transmission Networks			Distribution Networks			
		EHV	HV	UMV	MMV	LMV	LV	ELV
		>345 kV	200-345 kV	100-200 kV	50-100 KV	12-50 kV	0.45-12 kV	<0.45 kV
Marginal line losses	Corona losses	0.005	0.002	0.000	0.000	0.000	0.000	0.000
	Joule losses	0.006	0.009	0.010	0.012	0.013	0.015	0.020
Marginal transformer losses		0.004	0.002	0.002	0.004	0.008	0.008	0.008
Marginal non-technical losses		0.000	0.000	0.000	0.000	0.000	0.000	0.012
Marginal total losses (excluding last transformer)		0.015	0.013	0.012	0.015	0.021	0.024	0.040
Last transformer losses (to end-user)		0.009	0.009	0.009	0.008	0.008	0.008	0.008
Cumulative losses		0.024	0.037	0.049	0.064	0.086	0.109	0.149

6. Determining avoided grid losses from decentralized generation

In comparison with the top-down supply of electricity from a large centralized power plant connected at EHV, other (centralized or decentralized) power plants (or power generations) connected at lower voltage levels can save grid losses because of shorter T&D pathways. Since decentralized generation is mostly connected with the distribution grid, the connection voltage level of a power plant can be used to distinguish centralized power plants (i.e. connected to EHV, HV, or UMV) and distributed generation (i.e. connected to MMV, LMV, LV or ELV). To account for the avoided grid losses for power generation at different voltage levels, we differentiate whether the generation is used on-site or off-site. For electricity used on-site, the connection voltage of the power generation is the same as the connection voltage of the end-user. Therefore, the cumulative losses for a given voltage level that would have been incurred from the centralized power plant connected at EHV are entirely avoided due to the omission of T&D. For electricity used off-site, the avoided losses in reference to a large centralized plant connected at EHV are more uncertain. This is because off-site power from a power generation connected at a given voltage level can flow either down or up the voltage chain to end-users at other connection voltage levels. However, here we assume off-site electricity supplied from centralized plants always flows down the voltage chain in a top-down manner (to end-users connected at lowest ELV voltage level). Note that since the reference case is a centralized plant connected at EHV, its avoided losses under off-site generation mode is by definition zero. Considering the geographical proximity of decentralized generation to its end-users, we also reasonably assumed that off-site electricity from decentralized generation connected at a given voltage level can be fully absorbed by end-users connected at the same voltage level or the adjacent higher or lower voltage level with equal probability[2]. For instance, if the decentralized generation is connected at LMV, its off-site electricity generation can supply to end-users at LMV, MMV and LV with respective 1/3 chance. Therefore, for decentralized generation connected at the same voltage level, its avoided grid losses under off-site generation mode is lower than under on-site generation mode due to induced additional marginal losses. Table 3 presents the avoided losses for on/off -site electricity generation of centralized and decentralized generations connected at different voltage levels. Note that if a combination of on-site and off-site is supplied by a generation connected at a given voltage level, the avoided losses are the weighted average of avoided losses for on-site generation and avoided losses for off-site generation, depending on the specific share of on-site and off-site generation within absolute generation.

Table 3. Avoided cumulative grid losses for on/off site electricity production (in reference to a centralized plant connected at EHV)

Plant type	Connection voltage level	Avoided cumulative losses (On-site)	Avoided cumulative losses (Off-site)
Centralized generation	EHV (>345 kV)	0.024	0
	HV (200-345 kV)	0.037	0.013
	HMV (100-200 kV)	0.049	0.027
Decentralized generation	MMV (50-100 kV)	0.064	0.049
	LMV (12-50 kV)	0.086	0.068
	LV (0.45-12 kV)	0.109	0.085
	ELV (<0.45 kV)	0.149	0.125

[2]Note that this only applies to the situation that the penetration of decentralized generation is low.

7. Applying reference efficiency correction factors for avoided grid losses

Corresponding to avoided on/off -site grid losses, correction factors were developed for on/off -site electricity production at different connection voltage levels (see table 4). Correction factors equal to 1 minus avoided losses. They can be used to correct the reference electricity generation efficiency of the marginal centralized power plant (connected at EHV) that is replaced by decentralized generation, enabling the calculation of the additional PE saving from decentralized generation. For decentralized generation used for both on-site and off-site generation, the correction factor is the weighted average of correction factor for on-site generation and correction factor for off-site generation, depending on the specific share of on-site and off-site generation in absolute generation. The corrected reference efficiency can be calculated through multiplying the reference efficiency of the marginal centralized plant by the correction factor.

Table 4. Reference efficiency correction factors for on/off -site electricity production

Plant type	Connection voltage level	Correction factor (On-site)	Correction factor (Off-site)
Centralized generation	EHV (>345 kV)	0.976	1.000
	HV (200-345 kV)	0.963	0.987
	HMV (100-200 kV)	0.951	0.973
Decentralized generation	MMV (50-100 kV)	0.936	0.951
	LMV (12-50 kV)	0.914	0.932
	LV (0.45-12 kV)	0.891	0.915
	ELV (<0.45 kV)	0.851	0.875

An example is given to demonstrate the use of reference efficiency correction factor to account for avoided grid losses and primary saving from decentralized generation: a 50 KWe CHP unit generates 350 MWh electricity annually at 1 kV, of which 80% is used on-site and 20% is fed into the grid. The reference electricity generation efficiency of the marginal centralized plant connected at EHV that is replaced by the CHP is 50%. The reference heat efficiency of a boiler is 90%. The rated electricity generation efficiency and heat generation efficiency of the CHP unit are 35.5% and 45.5%, respectively.

Corrected reference electricity generation efficiency: η_e = 50%* (80%*0.851+20%*0.875) = 42.8%
Total PE saving = (350/42.8% + (350/35.5%*45.5%/90%)) –350/(35.5% + 45.5%) = 884.1 (MWh)
Of which PE saving resulting from avoided grid losses = 350/42.8% - 350/50% = 117.8 (MWh)

8. Conclusion and discussion

In this paper we developed and demonstrated a generic method to account for avoided grid losses and PE savings from decentralized generation, using the EU as the case-region. Despite limited data availability and a few assumptions, this method attempts to capture the major characteristics of the EU T&D grid to the possible largest extent. Reference efficiency correction factors derived from this method enable the accounting of avoided grid losses from decentralized generation connected at different voltage levels, in reference to a large centralized plant connected at EHV for off-site generation. Based on the correction factors (see table 4) and assuming a reference efficiency of 50%, for each MWh of electricity produced from decentralized generation, it saves 0.136-0.350 MWh PE under the on-site generation mode and 0.103-0.286 MWh PE under the off-site generation mode. The lower and higher ends of the ranges correspond to generation connection voltage level at MMV and ELV, respectively. They can serve as an easy tool to support the discussion and decision-making process regarding a technology choice between centralized and decentralized generation.

Not limited to the EU, the demonstrated method based on the establishment of a top-down RM also applies to other regions. However, different RMs and associated reference efficiency correction factors should be developed to reflect the grid configurations and main voltage levels of the applied regions. For instance, the lay-out of the grid is not always based on the 7 main voltage levels as identified for the EU case. Different numbers of main grid voltage levels can result in different correction factors. In addition, in this research avoided grid losses and correction factors for decentralized generation connected at different voltage levels were determined in reference to a centralized plant connected at EHV. The reference case needs to change into a centralized plant connected at lower voltage level when the share of EHV in the grid is less significant for a certain region. This could result in lower avoided losses and higher correction factors.

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