RELEVANCE AND POTENTIAL FOR INDUSTRIAL ON-SITE ELECTRICITY GENERATION ON A EUROPEAN SCALE

Patrick Dossow, Forschungsgesellschaft für Energiewirtschaft mbH, +49 89 158121-63, pdossow@ffe.de

Serafin von Roon, Forschungsgesellschaft für Energiewirtschaft mbH, +49 89 158121-0, sroon@ffe.de

Timo Kern, Forschungsgesellschaft für Energiewirtschaft mbH, +49 89 158121-35, tkern@ffe.de

Andrej Guminski, Forschungsgesellschaft für Energiewirtschaft mbH, +49 89 158121-34, aguminski@ffe.de

Abstract

Current developments concerning Europe's electric system and its electricity markets in particular is best described as a transition from centralized to decentralized, from national to European and from static to flexible. In this regard, the high shares of renewable energies gradually increasing in Europe present a challenge for system and grid, where high shares of power reserves become inevitable in the near future [1].

A large proportion of the total electricity generated in Europe is due to industrial on-site generation by medium to large scale companies. Such industrial power plants are seldom bound to wholesale energy market conditions and therefore operate fundamentally different than plants of public supply [2]. In the context of increasing volatility of electricity generation by renewables, on-site generation might constitute a part of the solution to outbalance such fluctuations, as it incorporates a substantial proportion of conventional energy sources. For this reason, this paper regards on-site generation as a chance for development and aims on assessing possible ways to increase flexibility and grid stability on a European scale.

To fully comprehend the magnitude of industrial on-site generation on a European scale, the paper examines the status quo of on-site electricity generation in the industrial sector for 13 European countries. Distinctive features and country-specific characteristics in terms of magnitude and system structure are elaborated on a broad knowledge base. Special attention is payed to different usages of energy sources and cogenerating power plants (CHP-systems). The hourly rates of power generation of individual industrial power plants are assessed to identify characteristic modes of plant operation and relevant motives for on-site generation in industry. Such considerations give rise to benefits and drawbacks on a national scale. To examine future potentials, possible changes in the framework of flexibility options and market integration are discussed.

The study's finding show that industrial on-site generation constitutes a corner stone of the European electric system, which makes up 9 % of the total electricity generation. National differences are especially striking in terms of energy source usage, where availability and cost-effectiveness dominate the picture. As nearly 60 % of the electricity generated on-site is on average based on fossil energy sources, a transformation process of this part of the system is found to be inevitable in the future. Such a transformation process would change the typical modes of operation and motives for on-site generation.

High potential for the future of on-site generation is seen in (1) the application of industrial power plants for power control purposes, (2) the preservation of important companies in Europe, (3) the cost-efficient expansion of renewables in industries and (4) the market participation of on-site generators to sell and purchase at wholesale markets. All of these potential changes must be empowered by national or European adjustments in regulations.

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Keywords

industry; on-site generation; European electric system; status quo; national policy; electricity markets; merit order; future development; IAEE 2019

1 Introduction and objective

The generation and utilization of electricity is on the brink of a radical transformation process. Traditional means of electricity production are more and more challenged by increasing requirements concerning net stability and security of supply [3]. A major reason for the transition towards more flexible, decentralized electricity generation systems is the ever increasing share of renewable energy sources (RES) in Europe, which introduces volatility and uncertainty into the system.

The decision of the European Union to formulate a Europe-wide energy target framework implies the objective to achieve an average of 57 % of renewable energies in the power sector by 2030 [4], where each nation is free to set its own national goals for the future. France, for instance, targets a share of 40 % renewables for electricity production by 2030 [5], while the German government aims for a ratio of renewable energies in the electricity market as high as 65 % by 2030 [6]. Austria goes even further and is determined to produce 100 % of its electricity demand by renewable energies in 2030 [7].

Even though each country sets its own energy transition goals due to the uniqueness of each national power generation system, the characteristic of electrical current not being limited by national borders unites Europe in its demand for an overall adaptive power generating system including high capacities of power reserves and flexibility options [1].

In this context, the present paper investigates drawbacks and potential of a particular element of the electricity generation sector which is the on-site generation of electricity by industrial firms. On-site generation thereby means the generation of electricity (and heat if using a cogenerating system) in spacial proximity to the consumption of the same electricity, where the very purpose of the electricity production is to supply power to a company's production site. In general, the operator of the industrial power plants (IPPs) is also the operator of the production site and in most cases owns both facilities [8].

As industrial on-site generation constitutes a common and established mean of generating electricity during the last decades whenever conditions are favorable, little research has been conducted in recent years to cover the topic's usefulness and importance. Especially when broadening the perspective on a European scale, the topic appears to be underrepresented in contemporary studies. Yet, as will be shown in this paper, IPPs are operated in a fundamentally different manner than conventional plants of public supply most of the time [2]. The hypothesis is that such IPPs show little response to changes in the electricity market. If the proportion of on-site generated electricity represents a large fraction of the overall electricity production, such behavior is critical in future considerations regarding the electric grid stability. For this reason, the paper's focus lies on analyzing industrial on-site generation of electricity in Europe in great detail.

To do so, a general European overview becomes valuable due to the interconnectedness of the electric sector, where no national grid is independent from the other. To assess the structure of electric on-site generation on a national level, several individual European countries should be included in the analysis. When reducing the level of detail even further, characteristic modes of operation and typical motives for on-site generation can be identified. For such analyses, an assessment of the electricity wholesale market must be incorporated to distinguish IPPs from electricity generators of public supply.

Thus, this paper includes all of the above mentioned aspects of industrial on-site generation. On that basis, the topic's relevance and potential is examined, which enables to identify and target future challenges for the electric sector and on-site generation in particular. Under the current circumstances of climate change, not only the industrial perspective is taken, but systemic concerns to reduce emissions while maintaining cost-efficiency are also considered in the analysis.

2 Methodological procedure

In order to receive a detailed overview of both the European situation and national specifics regarding industrial on-site generation, a structured methodology is employed. In general, the analysis level of detail begins on a large European scale and successively reduces its granularity down to the smallest level of individual producers. For reasons of clarity, the methodology is divided into four steps: (1) The gathering of statistical data regarding industrial on-site generation in 13 European countries to provide an European overview; (2) The country-specific evaluation of characteristics in on-site generation and analysis of differences between the countries; (3) The identification of individual IPPs for several countries and their mode of operation in regard to electricity wholesale market prices; (4) The assessment of future potentials of industrial on-site generating plants in the context of expected developments and national objectives. Figure 1 simplifies the procedure while summarizing the desired outcome of each step.

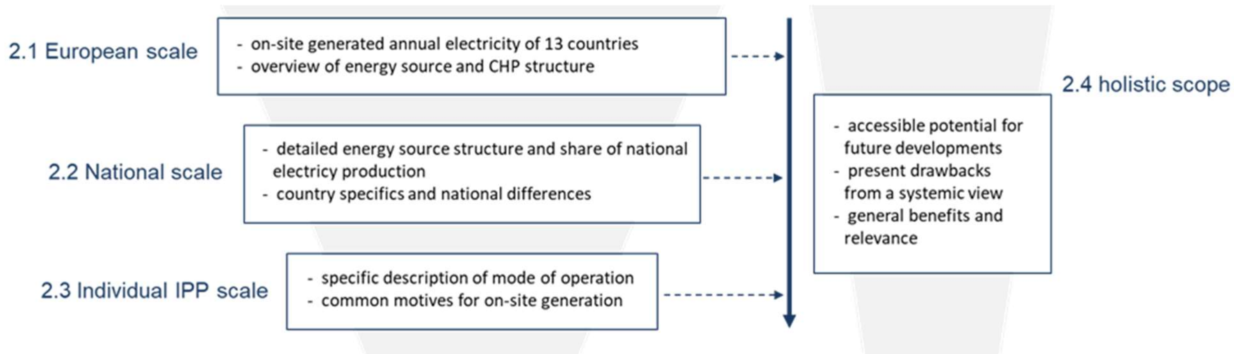

Figure 1: Methodology to assess European on-site generation: Step 1-3 represent a top-down approach, whereas step 4 follows a holistic structure thereby utilizing the findings of the previous three steps.

2.1 European data processing

To cover a large share of Europe’s electric sector, the Eurostat database provided by the statistical office of the European Union constitutes a fitting source of information [9]. The database allows for a distinction between the annual amount of electricity produced by generators of public supply and annual amount of electricity produced by industrial on-site generators on a national scale. In addition, the electricity production can be partitioned by the source of energy used for generation and by the share of electricity produced through CHP-systems. For each country included in the database, the nationwide electricity consumption as well as industry specific data is available. Thus, the Eurostat database represents a sufficient mean to analyze the overall situation of industrial on-site generation in Europe.

In the framework of the eXtremOS project, the following 13 countries are assessed to limit the research work while covering the most important central European nations:

- Germany
- France
- United Kingdom
- Italy
- Sweden
- Denmark
- Czech Republic
- Slovakia
- Hungary

- Netherlands
- Poland
- Slovenia
- Belgium

No data regarding industrial on-site generation for Norway and Switzerland, which are also included in the eXtremOS scope, has been obtained, which is why these countries are not examined. The most recent complete set of data available when conducting the analysis is from 2017, so that this is the year the study is based on.

The Eurostat data is aggregated and brought in an appropriate format to assess the status quo. The resulting tables can also be used to investigate national characteristics, as explained in the following section. To evaluate the general situation of European on-site generation in a structured manner, the 35 basic energy sources covered by Eurostat are assorted to 7 main energy sources. The allocation is based on the commonly used standard international energy product classification (SIEC) [10], which the following slight adjustments:

- SIEC 0 (coal) is divided into two main energy sources: (1) Recovered gases, gas works gas and coke oven gas, which will be called *furnace gases* for simplification; (2) All coal products and by products of the coal mining called *coal*
- SIEC 2 (oil shale/ oil stands) and SIEC 4 (oil) are combined and called *oil*
- SIEC 3 (natural gas) remains unchanged and is called *natural gas*
- SIEC 5 remains unchanged and is called *biofuels/renewables*
- SIEC 6 remains unchanged and is called *waste*
- All remaining sub-groups are aggregated to the main energy source called *unknown/ others*

An additional distinction is made between all kinds of *fossil energy sources*, which are coal, oil, natural gas and unknown/ others, and such energy sources which either are defined as renewable or must be disposed from an industrial perspective if not used for electricity generation purposes. This second group comprises furnace gases, biofuels/renewables and waste and is henceforth called *must-run energy sources*. This distinction becomes useful as IPPs operated with one of the must-run energy sources are considered to exploit the full potential of their energy source. Furnace gases and waste must be disposed without an energetic benefit if not used for energy generation. Since biofuels are considered renewable, their usage is also beneficial. On the contrary, IPPs operated with fossil energy sources do not entail this benefit. In fact, this type of industrial on-site generation represents the conventional production of electricity by fossil fuels and will be examined in section 3 in more detail.

2.2 Country-specific investigation

The previously described process of collecting and processing basic data can be used to subsequently describe the 13 countries in detail. To do so, the same aggregated form of main energy sources is used for each national on-site generation in industry. In addition, the countries' share of CHP-systems used for on-site generation of electricity is calculated. For a first overview concerning country specifics, the share of on-site generation of the total electricity generation as well as of the total electricity consumption and the industrial electricity consumption are considered important. To focus on the comparison between countries, such shares are portrayed in diagrams so that differences visibly stand out.

The second step on the national level aims on analyzing the countries individually. To reduce the complexity and extent of this paper, a selection of countries is discussed in greater detail here. The chosen countries display a cross section of the European electric sector, where highly relevant as well as unusual cases regarding the previously mentioned aspects are included. These countries are:

- Germany
- Netherlands
- Poland

- United Kingdom
- Denmark

This selection of countries, which are assessed individually, is thereafter compared with one another. The main objective of this section is to establish a bigger picture of the European structure of industrial on-site generation and its heterogeneous nature based on pertinent facts. Conclusions regarding the nation's industrial orientation can be drawn, which enables to evaluate the national relevance of industrial on-site generation of electricity.

2.3 Assessing individual IPP characteristics

The third methodological step comprises the identification and investigation of specific IPPs. Such IPPs are essential to fully comprehend the unique character of industrial on-site generation, as typical modes of operation and motives for on-site generation can be explained. It is therefore no sufficient to simply obtain a list of European IPPs, but the actual power generation of each plant is additionally required to acquire a full picture. The European network of transmission system operators for electricity (ENTSO-E) provides electricity production data on an hourly base for most European power plants of at least 100MW rated capacity shared by transmission system operators (TSOs), power exchangers and qualified third parties, which can be employed for this purpose [11].

The ENTSO-E data does not comprise any information regarding the type of power plant. Thus, the raw data is not of any particular value, since all types of power plants are included and IPPs are not distinguished. It is therefore crucial to further process the electricity production data in order to identify relevant IPPs. This process of identification is presented in a simplified manner in figure 2. A first narrowing is achieved by matching the ENTSO-E production data with the country-specific day ahead market prices for each hour of the year. When calculating the correlation coefficient between both data curves, IPPs should generally yield a low coefficient, as they are assumed to be operated with little or no regard to market prices. Taking the generally high annual number of hours under full load into account, the selection can be reduced even further. In combination with a division into groups of similar main energy sources, characteristic modes of operation can be identified, which vary from the average power generation. A second selection with a reduced amount of power plant data is produced, which represents the list of potential IPPs. These steps are conducted by an algorithm combining data in the FfE-internal database. For each of the listed IPPs, a manual research is conducted to verify its legitimacy.

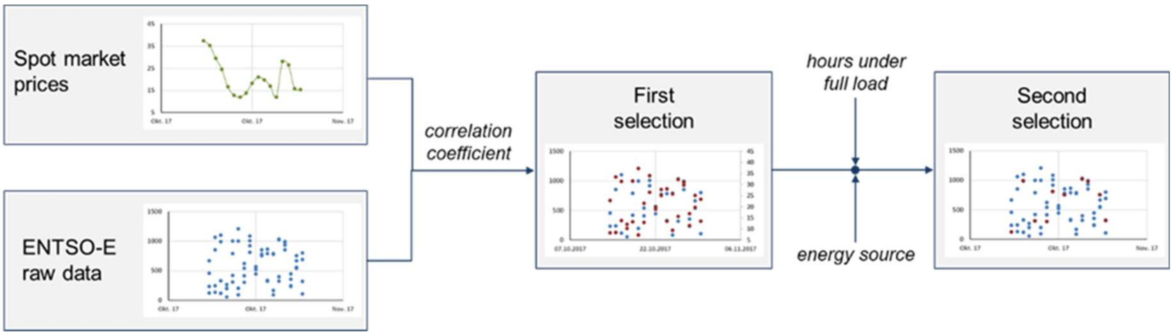

Figure 2: Process of identifying relevant IPPs, where for each country various data sources are matched to detect characteristic modes of operation.

Due to data constrains such as a limited availability of spot market prices for European countries, the final list of IPPs only comprises countries where at least 5 % of the annual industrial on-site generation is covered by electricity produced by identified IPPs. These countries, from which some of the IPPs are discussed in detail, are:

- Germany
- France
- Belgium
- United Kingdom

The analysis of the individual IPPs focusses on the mode of operation in comparison with market prices and generators of public supply. Distinctive features should be revealed to comprehend main drives for on-site generation, which in turn may evoke suggestions for potential drawbacks of such operational modes. Similarities and differences should be determined between different systems and countries. This deepest level of assessment therefore builds the foundation to evaluate the concept of on-site generation on a European as well as on a national scale.

2.4 Analysis of potential and drawbacks

The fourth step of the employed methodology connects all previous steps to formulate well-founded statements concerning the benefits, drawbacks and potential of industrial on-site generation of electricity in the present-day context. In contrast to the previously described top-down procedure, a holistic view now enables a line of argumentation to extrapolate from IPP-specific to country-specific to European statements. Figure 3 displays this approach, which is described in the following paragraphs.

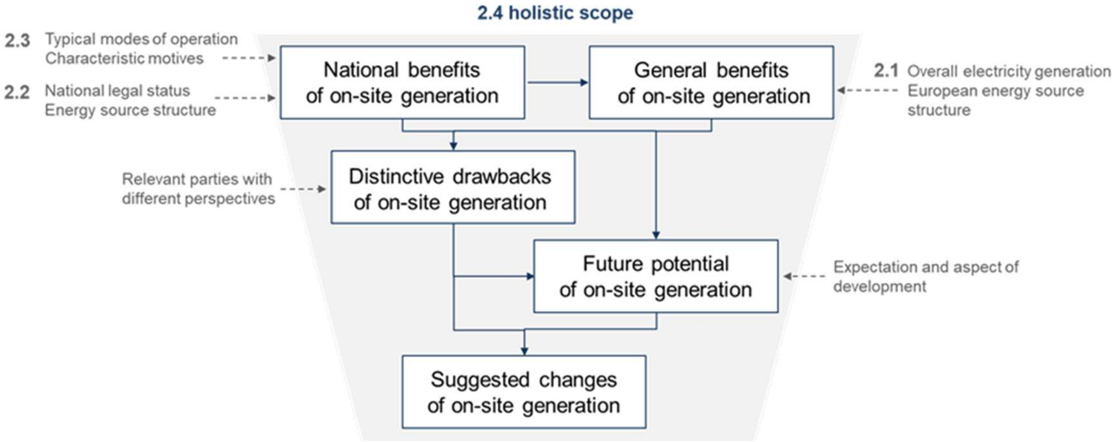

Figure 3: Process of analyzing benefits, drawback and potential of industrial on-site generation.

First, information regarding branch- and system-specific modes of operation and characteristic motives for electrical on-site generation drawn from the individual IPP assessment is combined with country-specific information such the commonly utilized energy sources. This yields the national benefits of on-site generation, which can be aggregated to Europe-wide statements of relevant benefits for industrial on-site generation as it is today.

The holistic approach allows for different perspectives when examining the effect of electric on-site generation. Major implications induced by industrial on-site generation on several different parties are presented. Relevant parties in this context are:

- Industrial companies owning/ operating an IPP
- Electricity generators of public supply
- Participants of the electricity wholesale market
- All end consumers of electricity
- The electric system (including transmission and distribution grid)

The identified implications are subsequently utilized to reveal existing drawbacks, which can be discussed in terms of severity. The anticipated development of the industrial sector, the overall electricity generation structure and the European electric market should be taken into consideration. The impact of on-site generation and its drawbacks on these developments are discussed in a qualitative manner. To reduce complexity, no scenario framework should be included, but the general trend of development is taken as a sufficient basis for augmentation.

Based on the general developments in electricity generation and their impact on relevant parties (as described above), substantiated predictions regarding a potential change in scope and fields of application of industrial on-site generation are articulated. This part is crucial, as the very purpose of the previous in-depth investigation of industrial on-site generation is to identify and highlight potential weak spots and possibility for improvement in the existing system.

The aspect of the potential to use market mechanisms to maximize cost effectiveness through an integrated electrical system including IPPs receives particular attention, as it follows specific market analyses, which have been conducted for Germany in [2]. It is explained in-depth in section 3.4.

All identified potentials are discussed with regard to their significance on a national and European scale. As aspects of future potential might be contradicting or even incompatible, this step aims on clarifying which potential is easily realized and where difficulties might occur in the future. Conflicts of objectives as well as connected difficulties which bear the danger of causing serious restriction in the future are identified.

For both serious drawbacks and achievable improvement potentials, possible changes regarding the status quo of industrial on-site generation are suggested. The most likely developments are employed to provide a summary of potentially necessary adjustments in the structure and utilization of industrial on-site generation, which aim on supporting on-site generation to adapt proactively before climate protection goals or similar tipping points force a radical shift.

3 Results and interpretation

The findings regarding a comprehensive analysis of the European on-site generation of electricity in industry are presented for 2017. By gradually increasing the level of detail this section aims on underlining the relevance of on-site generation on a European scale. The importance of this topic is further emphasized when discussing major drawbacks, future potentials and suggested changes. The methodological structure explained in the preceding section is employed here to follow a consistent thread.

3.1 European status quo

As described in section 2.1, the 13 relevant European countries are first aggregated to present a basic overview of the status quo of industrial on-site generation in Europe. As a result, figure 4 shows the sum of electricity generated by all IPPs of the 13 countries in relation to the sum of electricity by generators of public supply. The net electricity production of 212 TWh in 2017 by industrial on-site generators represents 9 % of the overall electricity production which was 2,459 TWh in 2017. Thus, a substantial proportion of the electricity produced in the 13 countries is generated by IPPs for the very purpose of self-consumption.

When examining only the industrial sector, the share of on-site generation accounts for 36 % of the consumed electricity in this sector. This share stress the relevance of industrial on-site generation all over Europe. For instance, a slight decrease in the amount of on-site generated electricity would result in a substantial rise in electricity demand thereby increasing the load of the electric grid. Hence, every consideration regarding the electricity supply and demand of the industrial sector should take on-site generation into the equation.

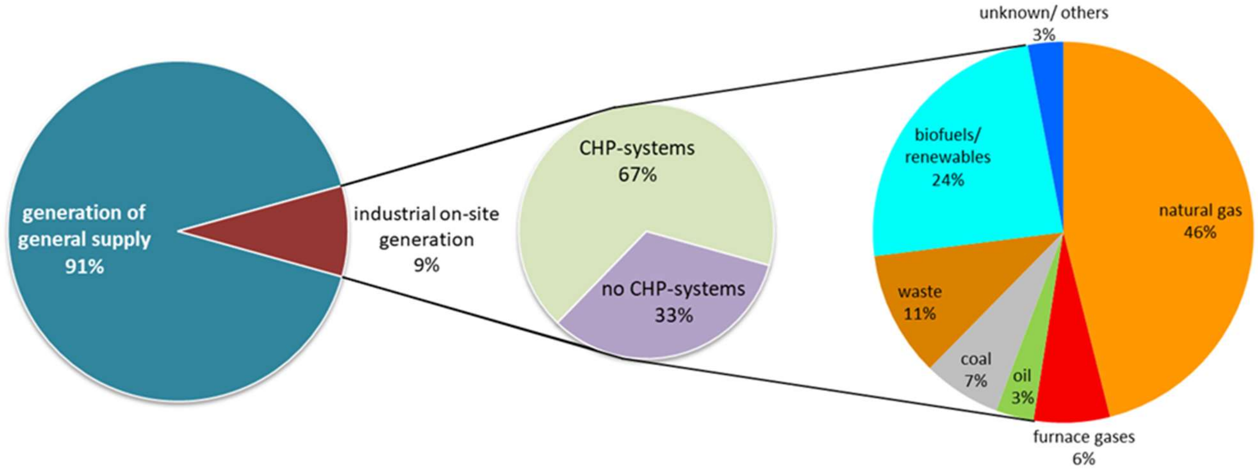

Figure 4: European share of industrial on-site generation of total electricity production (left), share of CHP-systems of on-site generated electricity (middle), and share of main energy sources of on-site generate electricity (right) for 2017.

The relevance of industrial on-site generation becomes even more clear when examining the structure of generating plants. As displayed in figure 4, more than two thirds of the generated electricity of IPPs is due to CHP-systems. In contracts, for the generation of public supply only one fifth of the generated electricity comes from a CHP-system. It is therefore logical to reason that operator of IPPs favor CHP-systems because of their high efficiencies whenever the co-generated heat can be utilized in a practical way. For the remaining third of on-site generated electricity there must be other motives to operate an IPP. The great difference in CHP usage between IPPs and generator of public supply highlights the importance of analyzing on-site generation in detail, as such contrasts imply a substantially different production structure between the two parts of the electric sector.

The right part of figure 4 assists to obtain an overview of the utilized main energy sources for industrial on-site generation. It is evident that natural gas accounts for the larges share, where nearly half of the produced electricity (precisely 98 TWh) is based on this energy source. Other fossil sources such as coal (14 TWh) and oil (7 TWh) are far less common. In total, 125 TWh or 59 % of on-site generation are considered to be generated by fossil energy sources of which 80 % are employed in CHP-systems. In contrast, 41 % i.e. 87 TWh of on-site generated electricity are based on must-run energy sources, where only 48 % are used for the co-generation of heat. The mayor share of this group is allocated to biofuels/ renewables, which represent 24 % or 51 TWh. Waste (22 TWh) and furnace gases (14 TWh) are used to a lesser extent.

When comparing this composition of energy sources with the energy source mixture of generators of public supply summed up for the 13 countries, several distinctions become apparent. First, the average share of fossil energy sources is way smaller for generators of public supply than for on-site generator. Only 27 % of the electricity generated for public supply are based on fossil energy sources (as defined in section 2.1). Thus, on-site generation relies much more on fossil fuels than does the generation for public supply due to the high share of renewable energies for public supply accounting for 44 % of the generated electricity. Second, out of the group of fossil energy sources, natural gas is less dominant as for the on-site generation accounting for only 12 % of the generated electricity, which is less than the usage of coal (14 %). The high percentage of natural gas presented in figure 4 therefore implies a unique feature of industrial on-site generation, which deviates from the situation for public supply. Thirds, the share of must-run energy sources employed for generation of public supply (44 %) is slightly higher than for on-site generation. The share is only marginally increased as another large proportion, which is the group of nuclear fuels (29 %), is not considered a renewable source of energy. Yet, out of the group of must-run sources, biofuels/renewables make up 99 %, which highlights the widespread usage of renewables for public supply of electricity nowadays. The contrast to on-site generation becomes ever more evident in that regard. It is thus clear that industrial on-site generation in Europe is to an uncommonly high percentage based on fossil energy sources, which provides a great contrast with generator of public supply. To investigate this differences in energy source structure further, a national scope becomes advantageous.

3.2 National characteristics

To begin with, the examination of industrial on-site generation on a national level is conducted to display general differences between the European countries in terms of magnitude of on-site generation in industry, energy sources and CHP usage. Concerning the magnitude of on-site generation regarding the 13 different countries, on the left of figure 5 the share of national on-site generation of the overall on-site generation is portrayed. On the left, the national on-site generation is related to the total electricity generation of each country. In Germany and the United Kingdom, the most on-site generation is conducted in absolute numbers. The Netherlands, France and Italy also generated a substantial sum of electricity through IPPs. The annual industrial on-site generation of the other countries is of lesser importance. Concerning the share of on-site generation, Germany, Italy, Belgium, Poland, Czech Republic, Denmark and Slovakia represent countries of average proportional on-site generation. In France, Sweden, Hungary and Slovenia industrial on-site generation plays a minor role. A high share of IPPs is evident in the United Kingdom and the Netherlands.

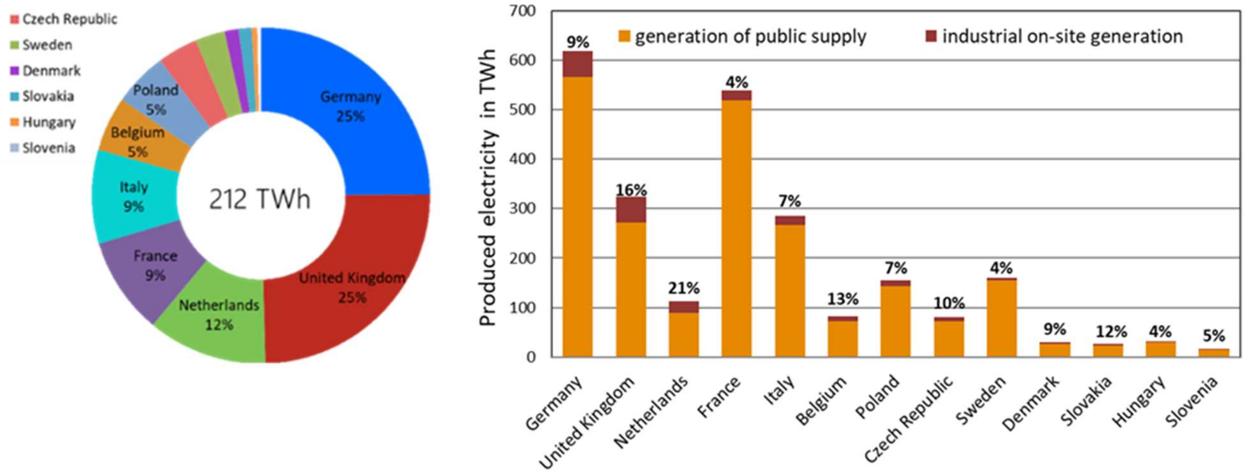

Figure 5: National share of overall industrial on-site generation of electricity (left), and share of industrial on-site generation of electricity of total electricity generation per country (right) for 2017.

Not only the share of industrial on-site generation of the total national electricity generation but also the share of overall electricity consumption and of electricity consumption in the industrial sector should be taken into account to evaluate the national relevance of on-site generation. Concerning these two aspects, figure 6 displays the results. It is evident that again the United Kingdom and the Netherlands represent the two countries with the highest share of on-site generation of total national consumption as well as of industrial electricity consumption. More than half of the electricity consumed by industry in the United Kingdom is generated by IPPs. For the Netherlands, the share is even more than two thirds. Countries such as Germany, Belgium, Czech Republic and Denmark also obtain a substantial share of electricity from IPPs when considering the industrial sector only.

These investigations display a conclusive picture, which is that on average industrialized countries with generally high demand of electricity more often use industrial on-site generation to ensure the supply of electricity than those countries with smaller industrial sectors. Yet, as the exception of France or Sweden shows, not all industrialized countries utilize on-site generation to a similar extent. Apparently the structure of the industrial sector represents a decisive factor in this regard.

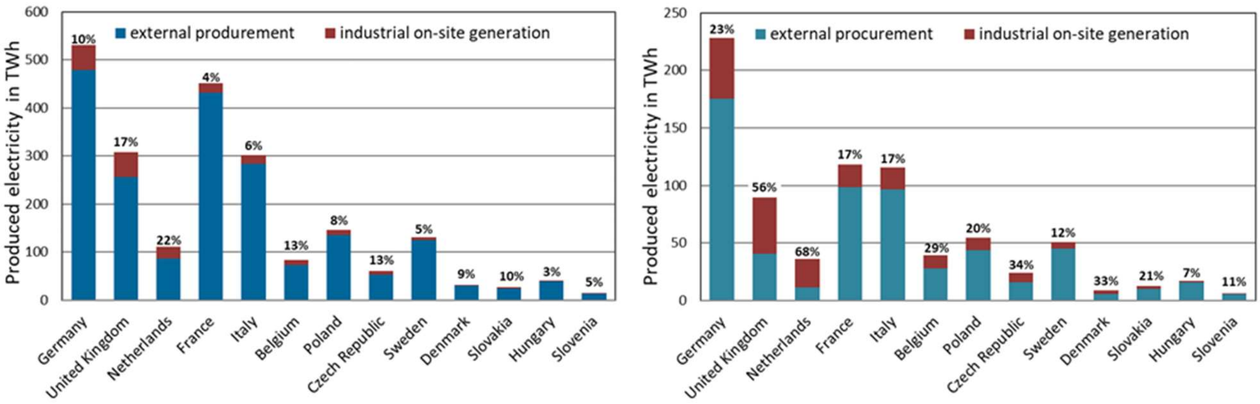

Figure 6: Share of industrial on-site generation of total national consumption of electricity (left), and of electricity consumption by the industrial sector only (right) for 2017.

When analyzing the structure of each nation's on-site generation of electricity, figure 7 becomes valuable. Several country-specific characteristics in terms of energy source mix and co-generation of heat are identified:

- In Germany, an unusually high share of furnace gases (16 %) and coal (13 %) is presented, whereas biofuels/ renewables (8 %) are below average. At the same time, an average share of CHP-systems exists.
- In the United Kingdom, the highest usage of biofuels/ renewables (48 %) exists. The share of natural gas (37 %) usage and other fossils (3 %) is relatively low as is the proportion of CHP-systems.
- The Netherlands utilize a large share of natural gas (66 %) compared to other countries. Apart from that, shares of energy sources are roughly average. CHP-systems are often used, especially for gas-fired IPPs.
- France uses a considerable share of biofuels/ renewables (33 %), but a low share of CHP-systems.
- In Italy, the largest share of natural gas (79 %) and a high share of CHP-systems is identified. Apart from a high share of furnace gases (12 %), must-run energy sources are below average.
- The energy source structure and CHP-usage of Belgium correspond to the average of all countries.
- In Poland, a prominently high share of CHP-systems is used even though the share of natural gas (33 %) is relatively small. The share of coal (24 %) and oil (13 %) is considerably higher than average.
- Other eastern European countries such as Czech Republic, Slovakia, Hungary and Slovenia also utilize relatively small shares of natural gas (max. 32 %), but larger shares of coal (12-30 %) for on-site generation. Shares of waste and biofuels/ renewables vary from average to above average.
- Sweden and Denmark combine low shares of natural gas (17 % and 20 %) with uncommonly high shares of waste for Denmark (52 %) and biofuels/ renewables for Sweden (36 %).

From this characteristics, a general idea of the primary national drives for on-site generation can be drawn. A major cause of the differences in energy source mix is definitely due to the resources available in each country. While Poland, Czech Republic and also Germany use their coal resources, the Netherlands harvest their natural gas resources and Scandinavian countries such as Denmark and Sweden employ wood waste on a larger scale. Other residuals remaining after industrial production can also be considered a national resource to be used for on-site generation. In the case of Germany or Italy, furnace gases constitute such a resource implying a large usage in steel industry. For the United Kingdom or France, biofuels and renewables exist on a large scale and are therefore employed in IPPs above average.

The cheaper and easily accessible such energy sources are, the more industrial on-site generated electricity is produced in a country. Thus, even though France represents a highly industrialized country consuming substantial amounts of electricity, its share of on-site generation in industry is relatively low, as nuclear energy, which is a major energy source for public supply, cannot be applied for IPPs in a easy and cost-efficient manner. When analyzing the shares of CHP-systems, it becomes evident that some energy sources are most efficient in CHP-systems, whereas others are not applicable. Hence, the relatively low share of CHP-systems in the United Kingdom is mainly due to the high share of biofuels/ renewables, whereas Poland relies much less on such volatile energy sources for on-site generation therefore utilizing CHP-systems to a way larger extent.

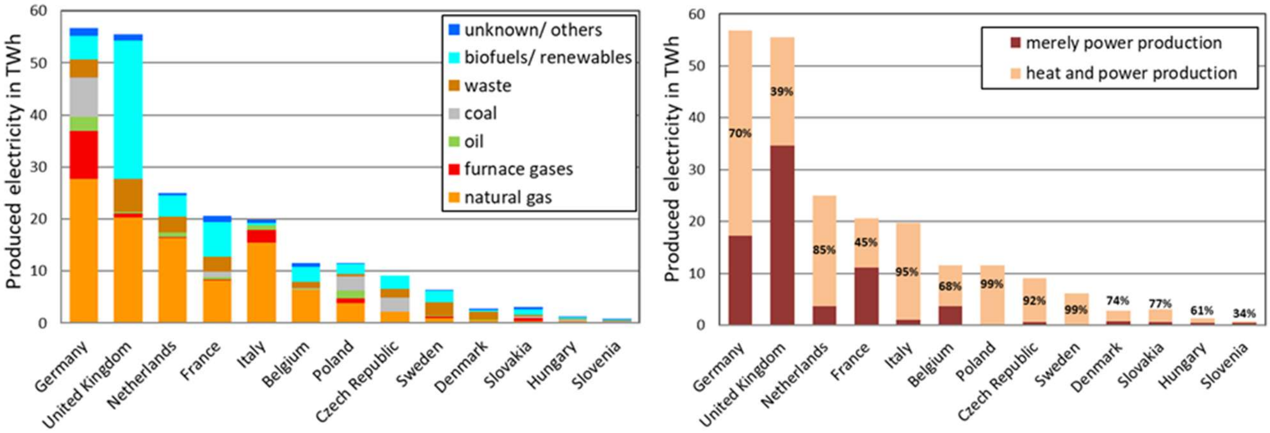

Figure 7: Structure of national industrial on-site generation of electricity regarding main energy sources (left) and CHP-systems (right) for 2017.

To assess this correlation between CHP-usage and must-run energy sources in greater detail, figure 8 displays 5 of the 13 countries and their share of CHP-systems and must-run energy sources of the national industrial on-site generation of electricity. Such analysis can be applied to all 13 countries. In this paper, a concise overview of possible national characteristics is provided by these 5 specific cases. In general, it can be seen that the more electricity is generated through CHP-systems, the less must-run energy sources are included in the national energy source mix. Germany and the United Kingdom, which produce roughly the same amount of on-site generated electricity, differ largely when comparing these two aspects. It is apparent that Germany's energy source structure is well suited for CHP-usage, whereas in the United Kingdom, such systems are less common. Yet, as nearly two third of the on-site generated electricity is due to must-run energy sources, it is still beneficial for the United Kingdom to apply IPPs on a large scale.

As for the case of Poland compared to the Netherlands, where the must-runs share is approximately the same, CHP-systems are still more common in some countries than in others. If a country's policy generally includes CHP-systems on a large scale, this country can operate IPPs based on fossil energy sources more efficiently, which is why in such countries industrial on-site generation commonly plays a significant role. Denmark represents a particular case in this regard, as a high share of CHP-systems is combined with a high share of must-runs. Here, the must-run energy sources are evidently applicable in CHP-systems suggesting a high share of biomass and storable waste products.

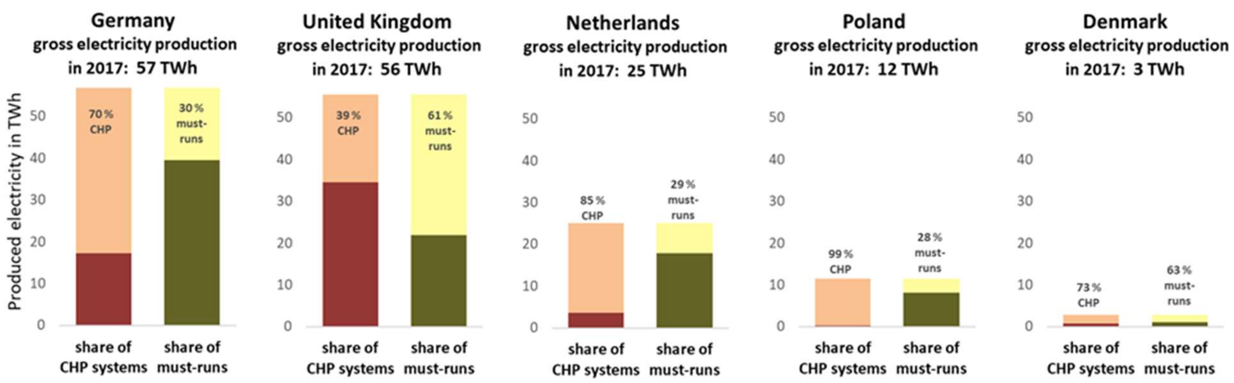

Figure 8: Share of CHP-systems and must-run energy sources of the national gross on-site generation of electricity for five relevant countries for 2017.

It is evident from the previous paragraphs that the average energy sources usage does not necessarily represent each national energy source mix for on-site generation in industry. The diversity of Europe's industrial sectors and each country's economic policy for industrial on-site production of electricity are key reasons for this finding. Even though national policies are not discussed in this paper, it is important to acknowledge their major importance in this regard. The evaluated differences in energy sources used in IPPs may suggest some of the most important motives for industrial on-site generation. Yet, in order to avoid speculation and base reasoning on facts and figures instead, modes of operation of real IPPs complement the conclusive analysis.

3.3 Typical modes of operation and motives for on-site generation

To discuss typical modes of operation of IPPs, some power generation curves of real IPPs are identified by the method explained in section 2.3. The difficulty of the identification process, as described in section 2.3, is to ensure that all power plant generation curves the algorithm considers to be of industrial origin are in fact IPP curves with utmost certainty. Even though no mistakes regarding the algorithm's output have been detected so far, there is no 100 % certainty that some generators of public supply might by chance be falsely included into the selection of IPPs. For this reason, each identified IPP is manually reviewed. As the ENTSO-E data is slightly different for each country, national labels of potential IPPs of some countries are unsuitable to conduct a manual review. Thus, no IPPs of such countries are included into the final list.

Since the process of manually reviewing IPP data is time-consuming, the process is limited to the 6 most relevant countries in terms of on-site generation, which make up 85 % of the total industrial on-site generation. As a result, 30 IPPs with a nominal power greater 100 MW of four different countries (Germany, United Kingdom, France and Belgium) are identified. For the Netherlands and Italy, no IPPs could be identified with certainty, as the data's label is unusable for a manual review. The 30 identified IPPs account for 28.6 TWh of on-site generated electricity in industry in 2017, which is 13 % of the total industrial on-site generation of all 13 countries. The data therefore provides a substantial but not a holistic overview of different modes of operations for industrial on-site generation.

For comparison reasons, four characteristic modes of operation are presented here, which cover most of the characteristics observed in on-site generation. Out of this discussion combined which the previously analyzed energy source structure, the most common motives for on-site generation are concluded. Figure 9 shows the chosen curves of on-site generation for an exemplary timespan of two weeks for the following four IPPs:

IPP NAME	LOCATION	INDUSTRY BRANCH	INSTALLED POWER	HEAT GENERATION	ENERGY SOURCE
INEOS CHP [12]	Grangemouth, United Kingdom	Oil refining	145 MW	257 MW	Natural gas
DK 6 UNIT 2 [13]	Dunkirk, France	Steel production	230 MW	-	Furnace gases (natural gas)
BASF SÜD [14]	Ludwigshafen, Germany	Chemicals	360 MW	408 MW	Natural gas
VW HKW WEST [15]	Wolfsburg, Germany	Automotive	260 MW	140 MW	Coal, waste

Starting with the INEOS CHP plant, which is displayed on the top left of figure 9, a constant electricity generation with two sharp changes in the magnitude of power at an interval of approximately 6 days is apparent. The generated power is at all times well below nominal power. When interpreting the power generation curve, the first and most striking observation is that the constant rate of power production is counterintuitive when taking the national spot market prices into consideration. The highly volatile rate of change in market prices appears to have no effect on the plant's power production. It is concluded that industrial on-site generation seldom orients its electricity production towards market prices, as the electricity is consumed on-site in any case. Market incentives to not play a role in such regards. Only if the IPP would be selling additional electricity in the market, a higher change rate of power production may become evident.

In the present case, it is reasonable to assume that the IPP's operation is heat-driven, so that all necessary heat consumed by the oil refinery is produced by the IPP at any time. The simultaneously generated electricity is also fully consumed by the production side. As for the period of reduced power generation, it is most likely that the production process, which the INEOS CHP is powering, is reduced due to production shortage or maintenance work. The swift reaction of the IPP's power output is possible, as the plant is operated with natural gas, which allows for fast adjustments.

Since the IPP is operated in part load during the two weeks, the full capacities of both production and electricity generation are not exploited in this period. The demanded heat, which determines the IPP's load, is less than half of the possible heat production. This part load operation is observed for many IPPs. It appears that IPPs are often dimensioned larger than necessary to ensure production at all times, which in turn provides autonomy and security.

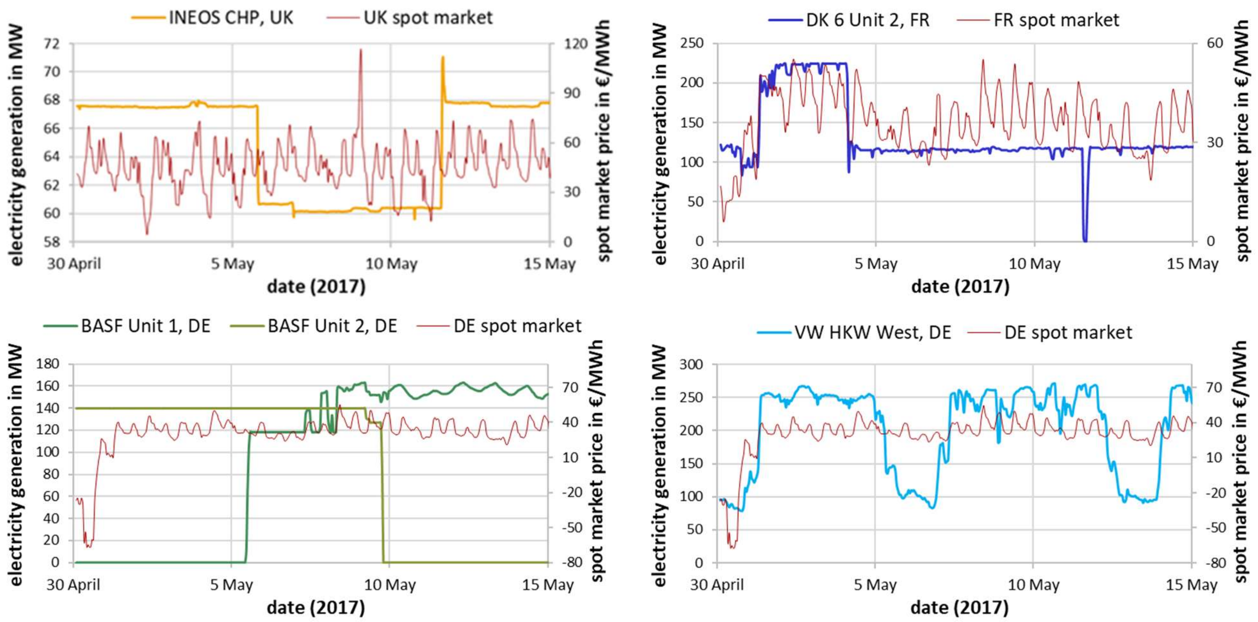

Figure 9: Curves of industrial on-site generation of electricity in contrast to the national day-ahead market prices for electricity illustrated for a typical timespan of two weeks in 2017.

The power curve of the IPP DK 6 Unit 2 highlights an additional aspect of possible modes of IPP operation. This example is one of the few IPPs which does not represent a CHP-system. Again, a relatively constant electricity production rate is observed. However, the power output sharply increases around the second day of May, stays at a constant level for approximately three days and subsequently decreases back to the previous power level. During the time of increase electricity generation, the IPP is operated in full load. At all other times, part load operation prevails. A short power drop occurs at the 12th of May reducing the power to zero for two hours.

In the case of DK 6 Unit 2 it is important to notice that the power unit is operated primarily with furnace gases. These gases, which accrue during the steel production process, compose of greenhouse gases to a large extent. In most countries, disposal costs rise for every unit of gas emitted into the atmosphere. However, if furnace gases are used for on-site electricity generation, such disposal costs are omitted thus bearing a substantial financial benefit. For this reason, all arising furnace gases should be used for on-site electricity generation at all times. As the amount of electricity produced by furnace gases is generally lower than the production site's demand, all electricity is directly consumed on-site most of the time. Even when the steel production might not require the amount of electricity produced at every time, such electricity can be sold to be fed into the national grid. Due to the relatively low energy content of furnace gases, DK 6 Unit 2 is used for electricity production only without any co-generation process.

As the investigation of the production curve of DK 6 Unit 2 shows, a weak fluctuation is present at all time in the magnitude of a few MWs. This fluctuation in electricity generation is caused by the fluctuation in steel production i.e. the fluctuation in furnace gases. As for the period of full load operation, even though the electricity production rate does not relate to the French spot market prices in general, it appears that for the hours between 2nd of May and 4th of May it becomes beneficial for the power plant operator to produce more electricity than before by using the additional option of natural gas firing. Either a rise of on-site demand caused by some production peak causes this characteristic, or the surplus of electricity is fed into the electric grid due to some bilateral contract the plant owner has with the grid operator. Hence, the electricity production rate of IPPs can change substantial over time, but is seldom driven by general market mechanisms.

The analysis of the BASF IPP intends to clarify the utilization of two power units for on-site generation. In general, the mode of operation of the total IPP is similar to the INEOS CHP. Natural gas driven turbines are used to generate electricity and heat to directly power the chemical processes of BASF at this site. The power station consists of two units of equal nominal power (180 MW each). Instead of combining both power outputs in figure 9, the electricity generation of both units is presented on the bottom left. It can be seen yet again that the generated power output of each unit is approximately constant if not zero. No correlation to the German spot market price exists. The important thing to observe is that both units serve as back-ups for each other. Apart from the time between 5th of May and 10th of May, only one unit operates at a time while the other one is shut down. This operation extends each turbines operating live, leaves capacity for increased production and protects the power station against total failure. Hence, it appears that the additional investment costs accompanying two separate units in shift operation are justified by the listed advantages, as such systems are most common for large scale IPPs.

The last of the four discussed IPPs is the VW HKW West, which is mainly run by hard coal. On the bottom right of figure 9, the hourly power generation of VW HKW West consisting of two similar power units is shown. A weekly profile is evident in this case, where the power generation varies over time in a repeating pattern every week. For normal weekdays, the electricity generation happens at full load, whereas on the weekend the power output diminishes by approximately 60 %. Some additional fluctuation can be seen over the course of one day.

It is intuitive that this electricity production rate neatly follows the demand caused by the manufacturing process, which is why market prices and electricity production are not related in any way. The daily fluctuations in power output are also due to daily manufacturing patterns. In comparison with the INEOS CHP and the BASF IPP, the VW HKW West is electricity-driven. Its primary purpose is to provide a 100 % of the demanded electricity for the car production, which is the reason why a fossil energy source is employed. Due to the high total efficiency of CHP-systems, heat is co-generated and partially used to satisfy the demand of the production site. Yet, as the plant is electricity-driven and heat demand for a car manufacturer is relatively low, a substantial surplus of heat is supplied to the near city of Wolfsburg to provide private households which district heat. In this mode of operation, the IPP operator guarantees the on-site generation of electricity and at the same time creates an added value due to the CHP-usage.

The comprehensive analysis of all four IPP power curves in combination with previously elaborated results and an interview series [8] facilitates to develop a list of the most important motives for industrial on-site generation of electricity on a European scale. For most companies, the main drive to operate an IPP is a combination or variation of this five motives:

- Cost advantage through the usage of waste, residuals, furnace gases, biofuels/ renewables and other cost-effective energy sources
- Cost advantage by co-generation of heat through CHP-systems
- Cost advantage due to national exemption clauses for on-site generation
- Cost stability, reduced dependency from electricity wholesale price fluctuations
- Autonomy and security of supply

First, the cost advantage of minimized energy source costs concerns the group of IPPs powered by must-run energy sources. Their share is displayed in figure 10, where huge national differences are observable. As explained before, the usage of waste and furnace gases bears the great benefit of not only saving fuel costs but additionally saving disposal costs, which makes such forms of on-site generation most appealing and reasonable. In the case of biofuels/ renewables, the European Union Emissions Trading System (EU ETS) in combination with national incentives regarding renewables ensures the cost-efficiency of these energy sources. Hence, companies operating IPPs based on must-runs normally exhaust all their energy sources for on-site generation.

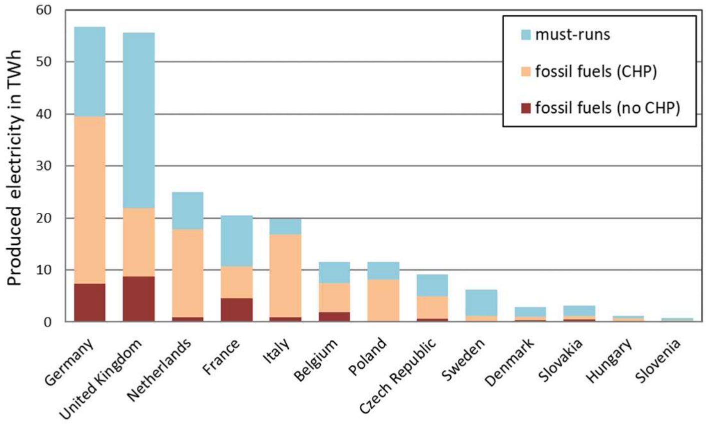

Figure 10: National industrial on-site generation of electricity divided into must-run energy sources, fossil fuels in CHP-systems and fossil fuels without CHP-systems for 2017.

Second, the cost advantage derived from CHP-systems plays a major role in most European countries, as on average 70 % of the on-site generated electricity includes the co-generation of heat. As exemplified by the power production curve of INEOS CHP, many of such CHP-systems are heat-driven thereby making the production of process heat the primary goal. Since the overall efficiency increases substantially when using a CHP-system, the co-generation becomes easily economically beneficial even if the generation of electricity is not a priority. As long as both heat and electricity is demanded, CHP-systems are advantageous to separate production. Since industrial on-site generation vastly depends on a reliable, responsive power supply to react on production changes, combustible energy sources, which match the requirements for CHP-usage, are most common.

As for the third motive, some countries consider it beneficial to included exemption clauses in their national policy for industrial on-site generation. Such exemptions usually serve national interests such as the preservation of the country as a location for industry. For the companies operating an IPP, the cost advantage can be substantial so that even if the first and second cost advantage are not given, this advantage alone may justify the investment in on-site generation. One example of the effects of exemption clauses is the VW HKW West, as in Germany levies are reduced for on-site generation of electricity, grid fees are omitted and CHP-systems are remunerated in different ways.

As analyzed in section 3.1, the overall share of fossil fuel based on-site generation is 59 %, out of which 80 % are CHP-systems. As a consequence, 20 % out of the 59 % are systems which neither have the advantage of highly efficient heat co-generation nor the benefit of free or cheap fuel supply by waste, furnace gases or biofuels/

renewables. This share of 12 % must have other motives for on-site generation of electricity. Besides the mentioned cost advantage of national exemption clauses, which do not apply in a profitable way to all IPPs in all 13 countries, psychological motives play a decisive role for IPP operators. Even if annual electricity costs would be approximately similar for electricity supply through the grid and through on-site generation, the factor of cost stability appears to motivate companies to operate IPPs. The psychological effect of loss aversion if electricity prices are high and no IPP is operated as well as the uncertainty regarding future price developments triggers a general favor for on-site generation in industry.

Even more visible becomes this psychological aspect when speaking about autonomy from external events and increased security of supply. Although companies are aware of the fact that they are not immune against most external events, it still is in the interest of most firms to reduce the damage such events might have to a minimum at great costs. Even though a grid connection still exists in most cases, which exposes the site to power fluctuations in the grid, the aspect of autonomy and security of supply is of major concern for most companies [8].

It is highly important to bear these motives in mind when speaking about on-site generation of electricity, as they represent the perspective of the industrial sector, where sensitivity is crucial. As for now, a combination or variation of these motives seems to enable companies to operate their IPPs in the manner described in this section.

3.4 Future potential and drawbacks

With the end of section 3.3, the comprehensive analysis of the status quo of industrial on-site generation of electricity is completed. The detailed findings of this analysis allow to look into the near future and evaluate drawbacks and potentials, which might gain in importance. For this holistic analysis, the five perspectives defined in section 2.4 are taken into account.

First, the motives discussed in the previous section are linked to benefits of industrial on-site generation on a national and a European scale are discussed. It is intuitive that the usage of waste, residuals, furnace gases and biofuels/ renewables does not only bear the mentioned cost advantage for industrial companies operating IPPs. On a national scale, it is beneficial to employ such energy sources for electricity generation, as overall emissions are reduced since waste products are not disposed but their energy content is exploited. Countries, which profit from this benefit to a large extent, are the United Kingdom (61 % must-runs), Sweden (80 % must-runs), Denmark (63 % must-runs) and Slovakia (63 % must-runs). On a European scale, 41 % of the on-site generated electricity is due to must-run energy sources implying that this motive constitutes a major benefit not only for industry but for the entire electricity generation system.

A second benefit, which arises from the advantageous position of many IPPs is the high total efficiency of CHP-systems in industry. For many countries, such as the Netherlands, Italy, Poland, Czech Republic and Sweden, this benefit of high efficiency compared to a separate generation of heat and electricity constitutes the main reason for industrial on-site generation. Again, on a national as well as on a European scale, emissions are generally reduced by this advantage. If no CHP-on-site generation would be conducted, companies would purchase electricity on the electricity market and produce heat on-site. Depending on the national energy mix, emissions are increased if these two advantageous are not exploited.

If companies would only operate must-run IPPs and/ or CHP-system without additional incentives, other electricity generators or participants of the electricity wholesale market would not be disadvantaged. The circumstances of such IPPs would simply be more beneficial so that on-site generation is the reasonable choice from an economic view. However, the cost advantage for industrial on-site generators arising from national exemption clauses for on-site generation displays that the first two advantages are not sufficient enough to empower industrial on-site generation in Europe's market-based electricity system. With the rise of cost-efficient renewable energies, electricity generation costs are too high for many IPPs in comparison with most generators of public supply [2].

National policies granting special rights to IPPs are mostly motivated by two drives. First, the benefit of reducing national emissions by operating CHP and/ or must-run IPPs should be ensured. Second, large-scale companies of national importance should be kept within the country thereby preserving competitiveness and know-how.

Thus, on a national scale, such exemption clauses are reasonable to protect the national interests. On a European level, however, these policies can cause imbalance and a country-specific extent of on-site generation, as discussed in section 3.2. Industrial on-site generators definitely benefit from these exemption clauses, whereas electricity generators of public supply are less favored. When many companies produce their own electricity, participants of the wholesale market benefit, as demand is reduced. For the general system of electricity generation, consequences are ambivalent. On the one hand, the mentioned advantage of reduced emission due to highly efficiency CHP-systems often operating with must-run energy sources prevail. On the other hand, market mechanisms are not reaching the entire electric system, which is why total electricity generation costs are not minimized.

From the evaluations in the last paragraph it can be seen that the complexity of the topic rapidly increases as soon as several perspectives are taken. Some aspects which are benefits from one perspective are drawback from another. It is concluded that on a national scale the main benefit of industrial on-site generation is the preservation of locational advantages for electricity-intensive industries, which is also a Europe-wide benefit. The overall reduction of emissions through high shares of must-run energy sources and CHP-systems might constitute another benefit.

Yet, the financial incentives for IPP operators provided by national exemption clauses bear the danger of making industrial on-site generation a measure of first choice for companies even if the benefit of emission reduction is not given. The share of fossil fuels used for on-site generation without CHP-usage, which exists in every country to a certain extent, confirms this effect. Moreover, for countries with high shares of renewables used for public supply even the usage of CHP-systems in industry might not be beneficial during times of high solar radiation and high wind velocities. During such times, fossil fuel based IPPs operate for long hours even though sufficient renewable energy would be available.

Thus, a major drawback of the current situation of industrial on-site generation is the insufficiently differentiated promotion of IPPs especially with regard to the rising share of renewables in many European countries. This tendency holds true for countries of high shares of renewables in the electricity sector and high shares of fossil energy sources in on-site generating industry, such as Germany or the Netherlands. Another important drawback is the disconnection of on-site generators from generator of public supply, where total electricity generation costs are not minimized from a holistic system perspective. Instead, the liberalized electricity market determines the selling and buying prices for generators of public supply, whereas most on-site generators produce regardless of market prices on a constantly high level throughout the year.

Since both benefits and drawbacks of on-site generation are identified, the next paragraphs aim on combining these aspects to point out the future potential of industrial on-site generation. A general trend of Europe’s electricity generation system is to gradually increase the share of renewables. Yet, as discussed in section 3.1, the average share of biofuels/ renewables in IPPs is well below the European average in generator of public supply. Since company owners are well aware of their social responsibility and role model function, there is a general willingness to invest in renewables for on-site generation in industry. Even if some companies are not in favor of renewables for on-site generation at the moment, the opposition regarding fossil fuels for electricity generation is rising and will not accept high shares of fossil energy sources for much longer in industry. The volatility of such technology still limits its applicability today, but future advancements in storage systems and flexibility will certainly contribute to increase the share of renewables for industrial on-site generation of electricity. As countries like the United Kingdom demonstrate, renewables can play a major role for industrial companies if applied efficiently. Hence, a generally positive development concerning the share of renewable energies for industrial on-site generation is expected. This implies the future potential that companies will invest in renewables and storage technologies for on-site generation of electricity thereby reducing greenhouse gas emissions. It will also increase or at least not decrease grid stability due to the decentralized nature of on-site generation.

However, the described potential of increased shares of renewables for industrial on-site generation appears to be a cost-intensive venture. It is likely that existing IPPs will remain in-service for some time from now due to their high investment costs. These existing IPPs are also connected to some future potentials. As explained in section 3.3, many of the plants are operated in part load based on fossil fuels. The unused capacities of such IPPs all over Europe can be used to provide control power to ensure the stability of the grid's frequency, which is endangered due to high shares of volatile power producers. If the unused capacities of IPPs are used, the amount of reserve power plants, which must be built to ensure grid stability, will be reduced and so will the costs. Thus, the need for control power represents a chance for fossil fuel based on-site generation to prevail. As companies could even gain some money by providing control power, this aspect increases the potential to keep companies in Europe.

Consequently, there is future potential for industrial on-site generation if the industry is willing to apply some changes such as the investment in renewables and the provision of control power. For national governments as well as for the European Union, it is important to create incentives for companies to start the transformation process. It seems unlikely that fossil fuel based IPPs can continue their on-site generation for long without changing their mode of operation due to national climate goals. Just leaving such IPPs to themselves would increase the danger of losing such companies in Europe.

Instead of supporting on-site generation in general, incentive should only apply to must-runs including renewables, where a balance must be found so that generators of public supply are not discriminated. Such measures could include a reduction of fees and levies for must-run energy sources in IPPs or in turn a charge per unit of emitted greenhouse gas. As for control power, existing market mechanisms are already sufficient to motivate some IPPs to participate in the control power market (for example in Germany). In the future, market incentives will inevitably rise due to an increase in demand.

3.4.1 Potential of market integration

As the example of the control power market shows, market incentives provide a powerful tool to balance demand and supply when the framework is right. As for the case of industrial on-site generation, another possibility for the future development is pointed out: The potential to use market mechanisms to minimize costs through an integrated electrical system, which includes IPPs and generator of public supply. The idea is to enable industrial on-site generators to participate in the national day-ahead markets. If regulations are altered accordingly, companies could purchase electricity whenever prices are lower than the costs for on-site generation.

During such periods, IPPs will shut down their production. When market prices rise above electricity generation costs, the IPPs will continue their on-site generation. In the case of a CHP-system, a heating plant becomes necessary, which supplies process heat when the IPP is not operating. In this way, costs for electricity of companies operating an IPP are minimized. In addition, such IPPs could offer their free capacities at the market to be sold whenever prices are high enough thereby increasing the market supply and enhancing competition. Thus, such an integrated system would increase both demand and supply thereby minimizing the overall electricity generation costs from a holistic perspective.

To gain an understanding of the consequences such a market integration would have on electricity prices, generation costs and CO_2-emissions, [2] simulates an altered market situation in Germany for the entire year 2017. The integration is conducted by modifying hourly bidding curves of the German spot market, such as the one displayed in figure 11. The details regarding this procedure are explained in [2]. As expected, results show a substantial amount of previously on-site generated electricity which is replaced by electricity bought in the market. The total electricity generation costs are thereby reduced for this situation, whereas spot market prices rise due to the increase in demand. Many of the IPPs, which are hypothetically replaced, are normally operated with natural gas. The market participants, which replace these IPPs, are – in the case of Germany – mainly coal-based plants due to the price level at which the integration is happening. In addition, in the case that CHP-systems are substituted, the alternative way to generate heat is included into the calculations. As a consequence, total CO_2-emissions rise for the investigated setting.

Thus, the potential of a market integration approach is impaired by the negative effects of rising prices and emissions for the case of Germany in 2017. However, the resulting magnitude of costs reduction and emission increase of the [2]-study is relatively small compared to the entire costs and emissions of the electrical sector. Differences in the energy sources structure or the spot market price level would have a substantial impact on the outcome of the analysis. The tendency of increasing CO_2-emissions might be turned into a decrease depending on the circumstances.

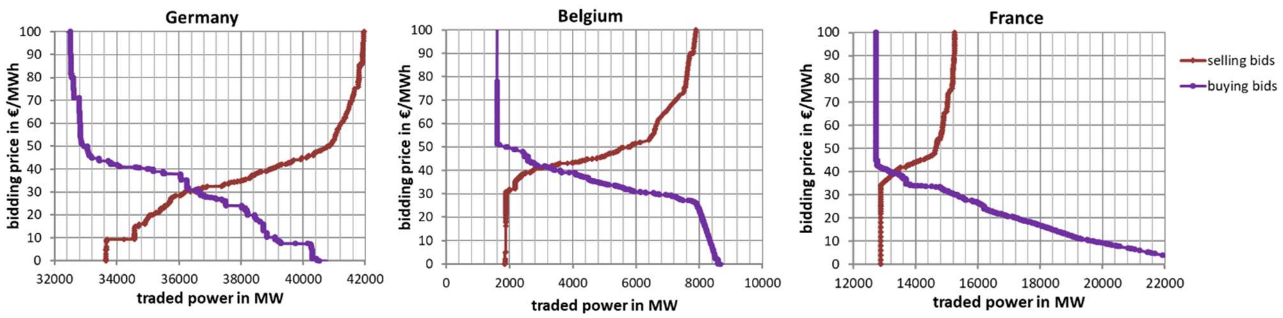

Figure 11: Spot market bidding curves for the 10th of April 2017.

Such differences in energy sources structure and spot market price exists between the European countries. A different outcome of a simulated market integration could be the result of this considerations. The effect of such differences is perhaps best demonstrated through the bidding curves. If comparing, for instance, the three different graphs of three different countries in figure 11, it becomes obvious that the slope and curvature of the bidding curves is fundamentally different for each country. The buying bids, which approximately represent the merit order of electricity generators participating at the market, of Germany form a much wider range of moderate increase than the buying bids of France. Hence, in France the amount of electric power generated at intermediate costs is relatively low compared to the German electricity generation structure. A lot more information can be drawn from these curves, but would go beyond the scope in this paper.

To investigate the different outcomes of a market integration for various countries and circumstances, several sources of data are needed for each case. Unfortunately, the data basis is not sufficient to allow for a Europe-wide market integration simulation. In fact, it is not sufficient to allow for any market integration apart from the one in Germany. Hence, one can only analyze the possible outcome in a qualitative manner. Generally speaking, some basic rules exists, which are prerequisites for a market integration of on-site generation to be beneficial from a systemic perspective including an emission reduction:

- The amount of fossil fuel based IPPs should be relatively high so that such systems are vastly replaced by other market participants
- The market prices level should be considerably high so that IPPs are repeatedly replaced
- Generators of public supply, which would replace IPPs at the prevailing price level, should on average emit less CO_2 than the IPPs they are substituting
- If free capacities of IPPs are available to be additionally offered in the spot market, only such IPPs with low CO_2-emissions should be applied.

These rules show that some countries are more likely than others to be suited for a market integration. In countries such as Poland or Czech Republic, a mix of IPPs based on coal and natural gas is most likely substituted by coal based power plants achieving little advantage. A relatively high potential is identified for the United Kingdom, Italy and Belgium, where comparably large amounts of industrial on-site generation are based on fossil energy sources, which can be replaced by biofuels/ renewables especially during summer. Another special case is France, where fossil fuel cased IPPs might be substituted by nuclear power for long hours of the year. If one considers nuclear power a clean energy source, France may hold the greatest potential of all European countries. Yet, the full scope of potential is only achieved if fossil fuel based IPPs are repeatedly replaced by renewables, which would today not be the case in any country.

Apart from these possible national outcomes, it is important to bear in mind that future development would influence the results of a market integration. If the present trend of rising CO_2-certificate prices (ETS) continues, the market price level will soon be very different from today. In the merit order of market participants, where renewables are already at the lower end of the order for most European countries, coal might move beyond natural gas. In addition, the general share of renewable energy sources will inevitable increase. As a consequence, for a simulation of a market integration in the future, costly IPPs will most likely be replace either by natural gas or renewable energy based power plants. Despite of the still increasing wholesale market prices, CO_2-emissions are likely to drop for a future scenario. This reasoning holds true for all European countries, even for such as Poland, which are not the most eager to increase their share of renewables.

Hence, the option of integrating IPPs into the European markets of electricity can eventually become advantageous, where existing IPPs remain in operation and companies might profit from the new situation. Again, the exact outcome depends on the circumstances created by the governments. The balancing act between the support of national on-site generating companies and the contentment of all other market participants must be performed with utmost finesse. A national policy should surely include some incentive or at least the reduction of obstacles to participate on the spot market. It might even comprise an obligation for certain IPPs. Apart from that, country-specific regulations are too diverse to be discussed here in detail.

To sum up, market integration of IPPs represents one of multiple potential ways to continue industrial on-site generation in the future. The analysis of this particular approach intents on underlining the interdependence of the topic with the result, that only future attempts of testing such ideas will lead to development in the sector. If no innovative process is started, operators of industrial on-site generators put themselves in the dangerous position of being dependent from political decisions.

4 Conclusions and outlook

This paper presents an overview of the current status quo of industrial on-site generation of electricity on a European scale, where multiple aspects are taken into consideration to identify benefits, drawbacks and potentials for future developments.

Industrial on-site generation is undeniably a relevant part of the electricity sector. The study concludes that on average 9 % of national electricity production is due to IPPs, which are 2,459 TWh of electricity in 2017 for the 13 investigated countries. In general, the on-site generation of electricity in industry involves some unique features, which are fundamentally different than the generation of electricity for public supply. Such differences are the uncommonly large share of CHP-systems, the large share of fossil energy sources used for electricity generation, which is more than twice the share of fossil fuels used for public supply, and the large share of natural gas.

On a national level, the general trend of high shares of CHP-usage and fossil energy sources continues. Yet, the magnitude of on-site generation varies within the countries due to the different industrial prerequisites. In countries with a strong domestic industry and large local companies, such as Germany, the United Kingdom or the Netherlands, on-site generation places an important role generally speaking.

The structure of energy sources used in IPPs differs considerably between the countries, as does the usage of CHP-systems. This finding is mainly due to the resources available in each country, where Eastern European countries and Germany rely partly on coal, whereas the Netherlands and Italy meet the demands with natural gas. The different shares of must-run energy source, which vary from 15 % to 80 %, explains the variation in CHP-usage. Again, the availability of must-run energy sources determines the extent of national on-site generation.

In terms of characteristic modes of operations of IPPs, some universal observations are summarized:

- Little to no relation between wholesale electricity market prices and electricity generation exists if the IPP is used for on-site generation only.
- Instead, electricity generation rate or rate of co-generated heat follows the demand caused by manufacturing or production processes.
- If waste or furnace gases are utilized, the energy sources are employed for electricity generation up to the last bit.
- Most IPPs operate in part load to allow for a production increase if needed.
- Many large-scale power stations consist of at least two units to ensure production in the case of failure, where either both units operate at the same time or one at a time.
- For CHP-systems, the potential surplus of electricity or heat is fed into the public grid.

When summarizing the main motives for on-site generation, two aspects are identified to be of mayor importance. First, cost advantages due to beneficial circumstances such as the efficient usage of CHP-systems, must-run energy sources and national exemption create an added economical value for IPP operators. Second, psychological advantages such as security of supply, autonomy and cost stability facilitate most companies to convince investors and increase planning security.

These motives for individual IPPs imply some benefits on a national scale. National electric grids are less loaded, waste and furnace gases is energetically exploited and important companies are kept within the country. These benefits also hold true on a European scale. Yet, on-site generation is not free of drawbacks. The unequal distribution of incentives accompanying on-site generation, where IPPs profit but generators of public supply and electricity consumers pay part of the price, represents one of these drawbacks. Another one is the high share of fossil energy sources used in IPPs, which is not appropriate to the current situation of global warming.

The knowledge of such benefits and drawbacks enables to advise on appropriate changes, which might unlock the future potential of industrial on-site generation. Most importantly, changes in national policies concerning IPPs will become inevitable in the future. Visionary policies should encourage companies to base their on-site generation on renewable energies and should discourage the usage of fossil fuels. For existing IPPs, the future potential can be to provide reserve capacity to ensure grid stability thereby reducing the amount of newly build back-up power plants. Whether a high share of on-site generation compared to generation of public supply will prove to be advantageous in the future is difficult to predict, as is the general trend of the magnitude of industrial on-site generation.

Another way of harvest the potential of industrial on-site generation for the future is the integration of IPPs in national spot markets, where companies would purchase electricity if their own electricity generation costs become higher than market prices. As calculations for Germany show, such an integrated system would yield higher market prices but lower total electricity generation costs and a generally reduced share of fossil fuel based IPPs. However, for the current situation in Germany, emissions are not found to decrease. For other countries, this tendency can change as other electricity generators would replace the IPPs. The change of emissions is thus subject to a degree of uncertainty. It is concluded that for the future development of substantial shares of renewable energies in the electric grid, the market integration of industrial on-site generation of electricity can reduce greenhouse gas emissions for most European countries.

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