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Characterization of energy consumers in production systems with renewable on-site power generation

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Abstract. The amount of renewable energy is increasing in the German energy system. As a result, grid expansion, consumer regulation (demand response), innovative storage solutions or intelligent grid operation are measures to avoid system instabilities. The development of energy prices and regulatory charges is difficult to predict against this dynamic background. The technological development of small power plants is in progress and many of the offered technologies are reaching grid parity. To increase independency from the grid and to avoid grid supply in periods of high prices, the integration of decentral, renewable power generation technologies is a reasonable solution for manufacturing companies. Therefore, a procedure for industrial companies to use their self-produced energy in a sustainable manner is introduced. This paper focuses on the characterization of industrial energy consumers, which is one of the first steps in the procedure. Different consumer criteria are described to define 48 consumer groups. Certain factories include consumers that can be described by a multitude of these consumer groups.

Keywords: Energy consumption, demand side management, micro-grid.

1 Introduction and State of the art

It has been noted recently that the energy revolution of the electricity system is proceeding ahead in all corresponding fields. Because of their volatile electricity production, the increasing share of renewable energy will challenge grid operators to establish a stable energy supply. So far, there is no economic solution to store electrical power in the utility grid. Therefore, consumption and production need to be balanced at all times. As a result, the instability of the grid could increase the number of power outages. This can lead to high breakdown costs for manufacturing companies caused by interruptions of the production line. Moreover, the volatile power supply has an impact on the electricity market. Fluctuating prices and power quality issues could lead the manufacturer to become more independent from the utility grid. In addition, the customers' demand for environmentally friendly produced products is on the rise. To increase the independency from the utility grid and to meet the costumers' demands, a reasonable solution is to integrate renewables into the industrial grid. A holistic procedure for the integration of suitable technologies within manufacturing companies was introduced recently [1] (**Fig. 1**). Renewable, decentral power generation technologies include tech-

nologies whose energy source is renewable and which are on the scale of the distribution network level. Starting from company-specific goals, the analysis of the consumers, installed in the regarded production systems, is an important step, since its outcome influences all the subsequent activities. The selection and dimensioning of power generation technologies, the choice of the electro-technical micro-grid structure and the development of suitable operation strategies are based on the type of consumers within the system. Against the background of Big Data, several methods from data collection to data processing have also been considered in literature in the field of energy consumption analyses. Liebl et al. [2] provide a review of methods for energy data generation and evaluation differentiated by development depth (concept to prototype) and environmental depth (company to component level). So far, the introduced methods mainly aim at transparency enhancement to improve efficiency and do not pursue the objective of classifying and evaluating individual consumers with regard to the necessary decentral energy supply. Therefore, this paper introduces a qualitative characterization of manufacturing energy consumers considering the subsequent procedure steps.

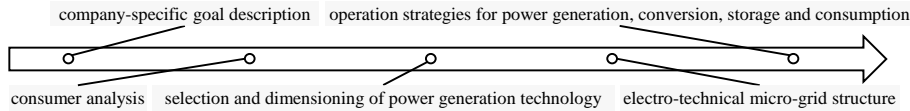


Fig. 1. Procedure for the integration of a renewable, decentral power generation acc. to [1].

2 Electrical and thermal consumers in manufacturing

A broad literature review resulted in the following summary of distinctive criteria of loads in factories divided into functional characteristics and process-related properties.

2.1 Functional characteristics

Compared to the electrical loads of households, the range of **power requirements** in an industrial application is much higher. Devices in industrial micro-grids considerably exceed the values of power consumption in households, where loads such as instantaneous water boilers or charging stations for electric vehicles (up to 22 kW) represent the highest power requirements. Large electrical loads can strongly influence the industrial grid which is exemplarily shown for an arc furnace by Chang et al. [3]. Depending on the maximum power requirement, industrial loads may be operated either at low or medium **voltage level**. Furthermore, in industrial micro-grids, direct current (DC) and alternating current (AC) loads can coexist [4]. Depending on the type and level of operating voltage, industrial grids may have different requirements concerning grid configuration. In AC-grids, the **power factor** (ratio of effective power and apparent power) is an important functional feature. The idle power in industrial micro-grids is higher compared to conventional grids, e.g. due to a high number of electrical machines. The balance of idle and effective power in an industrial grid is of high relevance to ensure a stable grid operation [5]. A large number of inductive **linear** (e.g. transformers, asynchronous machines) and **non-linear** (e.g. power converters, welding equipment, frequency converters) operating devices are used. The current of linear loads runs approximately sinusoidal. The non-sinusoidal current of non-linear loads can be divided into

a base current with grid frequency and several harmonics [6]. These harmonics can lead to thermal overloads and disturbances in electrical systems such as control systems, measuring units, capacitors, or circuit breakers [7]. Since almost every device within a production line is integrated into the control system, a failure of this system can affect the entire electrical, thermal and mechanical energy supply [8] and consequently single machines, the entire process or the product quality. Devices for compensation of the harmonics must be taken into account in the grid planning. Especially in industrial grids with large non-linear loads and low-dimensioned power supply, non-linear loads can cause voltage fluctuations and oscillations [7]. Voltage dips may lead to interruptions in process-relevant devices. A large number of **single-phase loads**, typically at low voltage levels, leads to voltage asymmetries. In industrial grids, rotating electrical machines in particular are influenced by these asymmetries. This leads to counter currents, high thermal losses, torque reduction and vibrations [7]. In contrast to conventional consumers, many industrial consumers are **three phase loads**.

2.2 Process-related properties

In micro-grids with a high share of renewable energies and a low share of synchronous generators, the rotating reserve of the grid is low. Therefore, micro-grids are more sensitive to faults than distribution grids. In addition to feed-in voltage and frequency regulation, demand side management is necessary in industrial micro-grids [9]. The potential of consumer-side control in an industrial grid depends, among other things, on the **controllability of the loads**. Controllable loads are characterized, for example, by the adjustment of the power requirement and the starting or shut-down behavior [10]. Energy flexibility describes the ability of production devices to adjust their energy demand to environmental circumstances [11]. Energy-flexible production lines offer organizational energy-flexible measures, whereas single machines provide technical energy-flexible potential for balancing the grid [12]. According to Schenk et al. [13], in a manufacturing factory the energy consumers are considered with different priorities for effective design and planning. Consumers of the first periphery are directly dependent on the production program (e.g. assembling robots, spindle drives). Consumers of the second periphery are not directly dependent on the production program, but on the equipment of the main process (e.g. hydraulic or compressed air units). Within the third periphery, consumers are independent of the production process (e.g. technical building equipment) and are known as cross-sectional technologies as well [14]. Even if their energy demand is mostly lower than the one of the main process consumers, they are considered technologies that are very adjustable and consequently suitable for application in dynamic systems. In these systems, loads have to be specifically removed from the grid in order to avoid load peaks and balance the system [15]. Electrical loads in an industrial environment can have a **uniform** power demand or an **intermittent demand** [16, 17]. Intermittent loads may lead to significant fluctuations in voltage and frequency in the grid, which in turn can lead to instabilities, especially in self-sufficient operation making the integration of distributed energy resources challenging [9]. Electrical loads can cause grid interferences due to functional characteristics and process-related re-

quirements. In contrast, consumers may have certain requirements for **supply reliability** or **voltage quality**. Many consumers, such as motors, just tolerate limited supply quality since fluctuations of the torque can affect the manufacturing process and subsequently the product quality. In addition, low supply quality leads to increased wear or defects of the equipment and may cause decreases in productivity [18].

3 Consumer characterization

Based on the introduced properties of consumers in industrial (micro-) grids, the characterization of the consumers and the formation of consumer groups can be described.

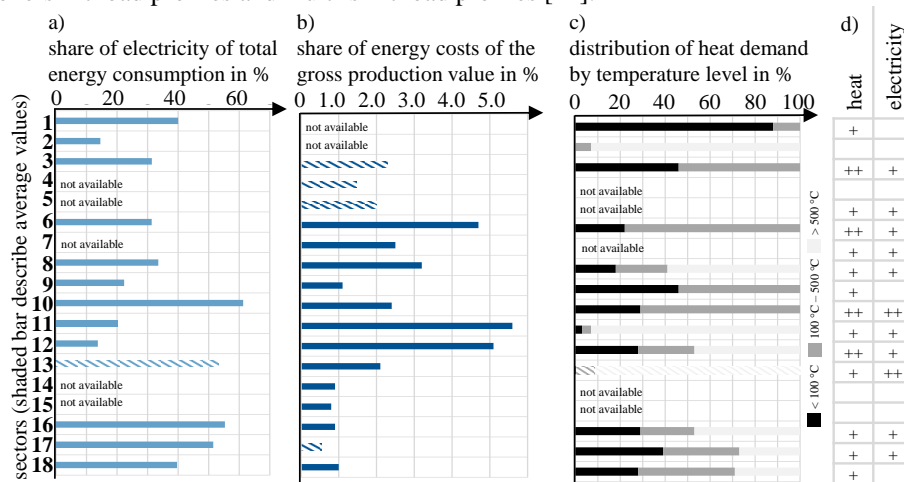
3.1 Overall classification

Before characterizing the consumers within production systems, the area of application of the procedure has to be defined. First, the different **industry sectors** are analyzed regarding important features. Gaining independency from the varying and non-transparent electricity price for industry may be one reason for on-site generation. While the electricity price for households undergoes only small price differences, these differences can be significantly higher for industrial customers. This is mainly due to the exemption from various taxes, which relieves the energy-intensive industry in particular. In addition, the absolute electricity consumption and the full-load hours influence the electricity price [19]. The share of energy costs in the gross production value (**Fig. 2b**) allows more significant conclusions because others than electricity costs are considered and related to the produced outcome. The higher this share, the greater is the incentive for a company to find a more cost-effective alternative than grid procurement. In addition to the energy costs, the share of electricity or heat in the company's energy consumption can be considered as criteria (**Fig. 2a**). Regarding the required heat, the temperature level is of particular importance since many decentralized and regenerative heat generation processes work at a low temperature level (**Fig. 2c**). Based on the described criteria, the possibilities for on-site power generation for each industry sector can be evaluated. **Fig. 2d** gives a qualitative evaluation of the sectors regarding the on-site generation of heat and electricity. The qualitative evaluation is based on the data given for each sector. If the electricity share is higher than 50 %, the sector is valued with electricity +. If the temperature level is mainly < 500 °C, the sector is valued with heat +. The share of electricity costs increases the valuation in positive direction if the share is > 2.0 %.

Sustainable decisions take economic efficiency, the security of supply and the environmental impact into account. In order to assess the economic viability of a power plant, a comparison of energy production costs and the procurement costs of electricity and heat is usually carried out. In case of a grid-connected plant, a possible feed-in as well as the associated payments have to be considered in addition [20]. The manufacturing industry in Germany is strongly characterized by medium-sized companies that represent 97.2 % of all companies [21]. Despite the dominant number, only about 40 % of the total energy consumption in the manufacturing industry is caused by them [22]. Energy costs play a subordinate role for small companies due to their small share in total costs. Energy measures are usually given lower priority than investments in the

core business. Therefore, small to medium-sized companies often avoid investing in their own power generation facilities due to a lack of the necessary capital [22]. It can be assumed that the **willingness to invest** in the integration of on-site, renewable energy generation does expand with increasing company size. For high-revenue companies, there are different possibilities for the self-production.

About a quarter of the companies in the German manufacturing sector work in shifts due to high fixed costs for plant and machinery or due to continuous processes [23]. Different **working hours** cause high varying **load profiles** among companies. The range from smaller companies in one-shift operation to large companies in three- to five-shifts and weekend operation are summarized in standard load profiles divided into one-shift load profiles and multi-shift load profiles [24].



1 mining; 2 quarrying of stone and earth; 3 nutrition, beverage and tobacco; 4 textiles, clothing, leather, leather goods and shoes; 5 wood, wicker and cork products, furniture; 6 paper, cardboard and articles thereof; 7 printed matter, duplication of recorded audio, video and data media; 8 chemical products; 9 other chemical industry (e.g. pharmaceutical products); 10 rubber and plastic goods; 11 glass and glassware, ceramics, stone and earthwork; 12 metal production; 13 metal working and metal products; 14 data processing equipment, electronic and optical products; 15 electrical apparatuses; 16 mechanical engineering; 17 automotive engineering; 18 other sectors.

Fig. 2. Sector-wise characterization for Germany regarding **a)** the share of electricity of total energy consumption according to [27], **b)** the share of energy costs of the gross production value according to [28], **c)** the distribution of heat demand by temperature level according to [29] and **d)** evaluation of the sectors regarding the on-site generation of heat and electricity (sectors are valued as very suitable (++), suitable (+) for on-site renewable power generation).

Renewable power generation technologies have various requirements. Depending on the industrial company, the **available areas** can vary. According to VDI 3644 [25], only undeveloped green and open spaces, or reserve areas on factory sites, are relevant for the integration of renewable energies. Suitable roof structures can also be used [26].

3.2 Relevant distinguishing features

The manufacturing industry comprises very heterogeneous economic sectors with very different operational structures, production processes and energy intensities. Companies are to be classified with regard to possible concepts for the integration of renewable

energies. Small, medium and large industrial plants can differ greatly in their consumer structure. In section 2, it was shown that loads can differ in multiple functional characteristics and process-related properties. To model individual factories, the aim of this section is to identify the characteristics of loads that are crucial for the integration of on-site, renewable power generation. The **power demand** of consumers is an essential parameter for the integration of power generators. A classification of the loads into two groups is sufficient to be able to estimate the voltage hierarchies (low-voltage or medium-voltage level) and grid interferences (strong or weak). Accordingly, required generators or storage units can be optimally selected, dimensioned and placed. Small consumers include all loads with a maximum power requirement of up to $P = 100$ kVA. These loads usually have an operating voltage at the low voltage level (400 V/230 V). The loads have a small tendency towards system interferences, which are very small. Large loads have a maximum power requirement of more than 100 kVA. The operating voltages of these loads are usually at the medium-voltage level (1 kV - 50 kV) and the system interferences may have large effects on the grid. Due to their characteristics, industrial loads can cause **grid interferences** that consequently may have negative effects on the quality of supply. This danger exists particularly in weak grids in isolated operation. Through a suitable integration of generation technologies and storage, negative influences on the supply quality can be eliminated. Impulsive or intermittent loads, non-linear loads and inductive loads with a low power factor have a high potential for system interferences. Accordingly, loads are classified into loads with high risk of interferences and loads with a low risk of interferences. The classification of loads into the two groups is sufficient to assess the extent to which loads are compatible with sensitive loads and whether measures need to be taken to isolate sensitive loads from loads with a high potential for system interferences. The **organizational classification** serves the purpose of estimating the potential of loads with regard to their use for demand side management. A distinction is made between loads of the main process and peripheral loads. The first group contains loads that are directly related to the main process and that will significantly impair the process in case of supply interruptions. The suitability for load shedding and the controllability is low. Therefore, a low potential for demand side management is attributed. The group of peripheral loads is assigned with a medium and high suitability for load shedding. These loads are either always disconnected from the grid in isolated operation or continue to be operated until there is an imbalance between supply and demand. Then they can be temporarily disconnected from the grid without noticeably affecting the production process. Poor supply quality of the grid can have far-reaching consequences in production and must be taken into account accordingly when integrating power generation and storage facilities. Due to diverse requirements of the consumers for **supply reliability**, the selection of power generation technologies has to be adapted. Consumers can be classified into sensitive loads that allow for supply interruptions of less than one second and insensitive loads that allow for supply interruptions of more than one second. The differentiation of the **required voltage quality** is based on DIN EN 61000-2-4 [30]. Sensitive loads have a high demand on the voltage quality of the network, whereas insensitive loads have standard requirements for the necessary voltage quality of the network. Furthermore, the required **temperature level** has to be considered. **Fig. 3** summarizes the defined

criteria and the distinguishing features with their parametrization. Furthermore, it is described which features relate to which next steps in the procedure for integrating renewable power generation.

process-related properties	supply reliability and voltage quality	required temperature level	• on-site heat generation	parameterization	< 100 °C		100 °C – 500 °C	> 500 °C		consumer groups
	uniform/intermittent demand				sensitive loads	insensitive loads				
functional characteristics	load shedding priority	required voltage quality	• on-site electricity generation • structure of industrial micro-grids	relevant for:	sensitive loads	insensitive loads	loads of the main process		peripheral loads	
	controllability	required supply reliability	• on-site electricity generation • structure of industrial micro-grids		sensitive loads	insensitive loads	loads of the main process		peripheral loads	
	single/three/five-phase loads	organizational classification	• potential for demand side management • on-site electricity generation		low risk of interferences	high risks of interferences	loads of the main process		peripheral loads	
	linear/non-linear loads	grid interferences	• supply quality of the grid • compensation by on-site electricity generation		low risk of interferences	high risks of interferences	loads of the main process		peripheral loads	
	power factor	maximum power demand	• on-site electricity generation • grid interferences, voltage level		P > 100 kVA	P < 100 kVA	loads of the main process		peripheral loads	
	power requirement voltage level				P > 100 kVA	P < 100 kVA	loads of the main process		peripheral loads	

Fig. 3. Characterization of industrial energy consumers in consumer groups.

4 Conclusion and further steps

The introduced criteria allow for characterization of the divers consumers in an industrial electrical and thermal grid. Based on the given parametrization, which can be further subdivided, different consumer groups are described. Taking into account invalid combinations of characterization, industrial consumers can be divided into 48 alternative type groups (six features, two or three parametrizations). The consumers within the considered system are typically allocated to several of these groups. Depending on the distribution of consumers among the introduced groups, appropriate generation technologies can be selected and dimensioned. The application of the presented characterization will be carried out exemplarily for a machine tool. Further steps consider a quantitative analysis of the consumers, taking their specific load profile into account.

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