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Enhancing Energy Flexibility through the Integration of Variable Renewable Energy in the Process Industry

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Abstract

Energy flexibility plays a crucial role in the current energy transition, as it can contribute to a stabilization of the grid. The integration of electricity from renewable energy sources leads to large fluctuations in power supply, compromising the reliability of supply and the grid stability. Employing surplus of variable renewable energy (VRE) to cover the industrial demand can on one hand reduce the need for grid upgrade on a long term. On the other hand, integrating VRE can contribute to fulfill decarbonisation targets in the industrial sector. As a consequence, the share of renewable energy in the total energy consumption can be increased. This paper aims at assessing the role of VRE integration in the process industry as a mean to leverage energy flexibility. The assessment consists of a scenario-based evaluation, complemented by a simulation model, able to quantify the reduction of specific CO_2 emissions. The developed approach is demonstrated within a case study in the paper industry.

Keywords: Energy flexibility; renewable energy; process industry; sustainable manufacturing

1. Introduction

Within the ambitious goal of reaching a major share of renewables in the energy mix, new challenges have arisen in the operation of the energy systems worldwide [1]. Power generated from variable renewable energy (VRE) sources, such as wind and solar, is not continuous, but rather variable over time, resulting in large fluctuations on supply side. In order to further encourage a high penetration of renewables, operational changes are thus required [2]. Improving the flexibility of energy systems is one of the targets of the current energy transition, as a mean to match supply and demand [1]. Flexibility can be reached through sector coupling, smart grids, energy storage, flexible power plants and demand side management (DSM), among other measures [3]. On demand-side, manufacturing systems can contribute to grid stability by exploiting their flexibility potential, i.e. the ability to adapt to variations in electricity supply. Demand response strategies aim at reshaping the load profile of the consumer [4].

As described in previous research work [5], energy flexibility can be more challenging in the process industry, as the production process is mostly continuous and so is the energy consumption pattern. The continuity and intensity of the energy demand can be valorized as a positive feature, when it comes to balancing generation and demand. Process industry has the potential to serve as energy sink for VRE surplus in the power system [6].

The state of art and research is discussed in section 2. In section 3 a methodology to evaluate the integration of variable renewable energy (VRE) in the process industry to leverage energy flexibility is proposed, taking into account relevant challenges associated to renewable energy supply. The developed approach is applied to a case-study in the paper sector (section 4).

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2. Background

2.1. Variable renewable energy and the energy transition

Renewable energy can be defined as a free available source of sustainable and clean energy. In the past decades, it has been gaining prominence as an alternative energy source, to reduce the reliance on fossil fuels [7]. In the context of the energy transition, wind and solar energy sources are particularly promising, due to their competitiveness compared to conventional power generation options [8]. Both sources are however strongly influenced by weather conditions, such as solar radiation, wind speed and direction, resulting in fluctuating power supply [9]. In its current status, the energy system cannot rely solely on VRE and renewable energy generation is still coupled with conventional generation [7].

The main challenges connected to the deployment of VRE can be summarized as follows [3,10]:

- Temporal variability: wind energy is characterized by short (minute range), medium (hour range) and long (daily) fluctuations; solar energy is more stable than wind energy on a long term perspective, during daylight. Both wind and solar energy sources present also a strong seasonal variability;
- Geographical variability: VRE are influenced by weather conditions, such as wind intensity and solar radiation, thus the geographical location of the generation unit influences the power output;
- Non-dispatchable: the generation can only be reduced or curtailed. Increasing the power output to a defined value is not feasible;

In order to balance the variability resulting from the integration of VRE and ensure the security of supply, an increased flexibility of the energy system has become a relevant target within the energy transition [1].

2.2. Dimensions and strategies of energy flexibility

Energy system flexibility is defined as the ability to keep the balance between demand and supply [11] and can be increased directly through energy grid flexibility or indirectly through supply or demand side flexibility.

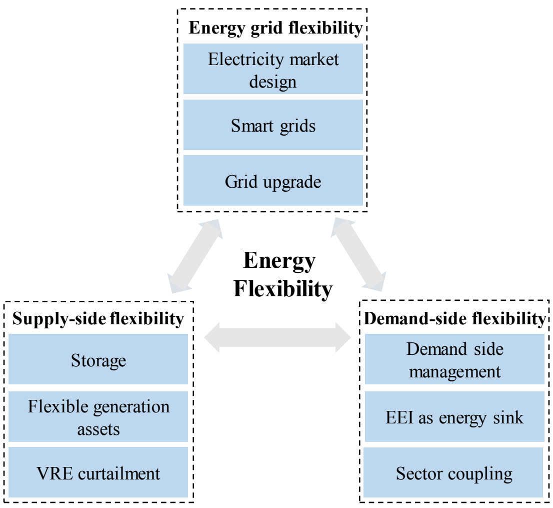

Figure 1: Dimensions and strategies of energy flexibility

As shown in Figure 1, energy flexibility strategies can be categorized according to their dimension into [1,12,13]:

1) Energy grid flexibility
    - Electricity market design, i.e. the introduction of VRE forecasting and the balancing market, the modification of market rules and support schemes;
    - Smart grids, integrating distributed energy sources among the grid;
    - Grid infrastructure upgrade, i.e. the expansion of transmission lines;
2) Supply side flexibility
    - Storage (pumped-hydro, batteries, thermal storage), to compensate the variability of renewable energy supply, avoiding curtailment of wind and solar power;
    - Flexible operation of the generation assets, by modifying the output of single generation units to maintain the power balance in the grid;
    - VRE curtailment, by decreasing the load of renewable generation assets;
3) Demand side flexibility
    - Demand side management, a set of strategies aiming at adapting the end-use electricity consumption;
    - Energy-intensive industries (EEI) as energy sink, valorizing the surplus from VRE through a direct utilization in large-scale industries;
    - Sector coupling, the conversion of energy between different energy sectors, such as power-to-X (P2X) or vehicle-to-grid (V2G);

Those strategies result however in a flexibility gap, that must be compensated. Flexibility shall be thus enhanced at all levels of the system, including also the consumer side. All actors of the energy system play a relevant role as enablers in the achievement of the targets set within the energy transition. The more flexible industrial consumers are, the more flexible the system can be [11].

A consumer can be considered flexible if it is able to adapt to the supply, in a cost and time effective way. If we shift the focus to the production sector, a flexible production system must rapidly react to changes in the electricity supply, with a minimum financial effort and without compromising the output quality [14].

A production system can increase its own flexibility through the implementation of different strategies [15]:

- Power-to-battery, through the installation of batteries to store energy;
- Power-to-storage, through the conversion and storage of energy into other energy forms;
- Power-to-product, through production shifting;
- Power-to-system, by switching the energy source of the supply system;
- Flexible supply, by installing decentralized energy sources.

Integrating single flexibility strategies requires however a thorough evaluation on a technical, environmental and economic perspective. Taking as an example "Power-to-battery" relevant influencing factors are the battery technology, the environmental impact of the chosen technology, including end-of-life, and costs.

2.3. Integrating VRE in the process industry

Energy-intensive industries are already used as capacity reserves in Europe [1,16]. Their potential to serve as energy sink, though the integration of renewable energy, is currently under investigation [4,6].

The process industry is characterized not only by an energy-intensive demand, but also by a nearly constant and continuous power load. As a consequence, the industry relies to a large extent on fossil power stations to cover the electricity demand, resulting in high CO_2 emissions in the production stage. Process industry has the greatest economic potential for demand side management among the industrial consumers; its integration is however more challenging and requires a detailed evaluation on process chain level [1,6].

Among the process industry, the so-called heavy industries dominate the production of CO_2 emissions worldwide: iron and steel, cement, plastic, paper and aluminum production.

Particularly in the case of paper production, not only the electrical but also the thermal energy demand is highly intensive. Energy is typically produced on-site in high-efficient cogeneration systems, such as fuel-based combined-heat and power plants (CHP). In Germany the government is already pushing a modernization of CHP units towards a substitution of fossil fuels, through bio or renewable fuels. Bio-fuels are however limited and expensive [17]. The integration of VRE to partially or fully replace the fossil-fuel based generation represents a promising solution towards carbon reduction.

3. Methodology

The methodology proposed in the current study consists of four-steps (see Figure 2).

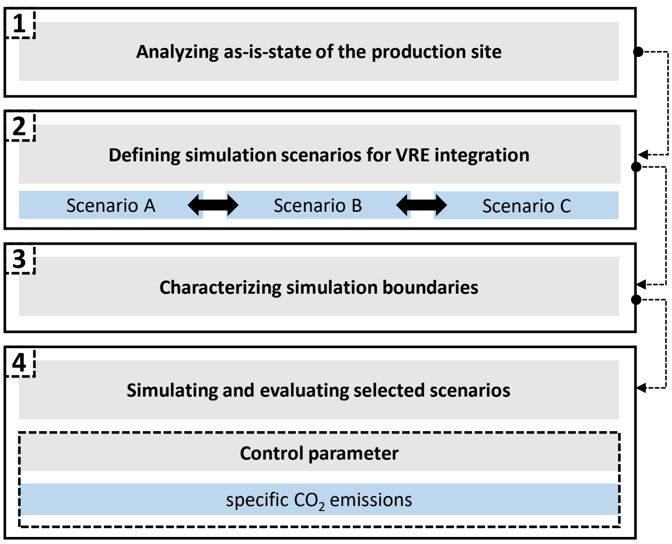

Figure 2: Methodology - Evaluating VRE integration in the process industry

Step 1: in order to get a detailed overview of the energy supply chain of the production site, the as-is-state must be assessed. Different characterization methods and tools can be used, as for instance material and energy flows analysis (MEFA), input-output analysis (IOA) or pinch analysis. The main focus lays on the energy demand and supply.

Step 2: different scenarios can be then pondered, according to the potential for improvement identified in the previous step, in terms of e.g. CHP plant operation and efficiency and the potential to substitute on-site generation.

Step 3: a detailed characterization of the boundaries is then carried out. Relevant factors, such as local weather conditions and the related availability of wind and solar energy, the installed capacity of wind parks and photovoltaic (PV) plants and eventual constraints of the local energy market or the power plant operation, have to be considered.

Step 4: selected scenarios can be simulated in the final step, taking into account the defined boundaries and constraints.

Different methods can be used to model energy supply chains, depending on the detail level and the strived results. In order to model the seasonal availability and the variability of VRE, a dynamic simulation approach is required. The most common approaches are system dynamics (SD), discrete-event simulation (DES) and agent-based simulations (ABS).

SD is used to model global dependencies between elements and their relations through feedback loops. It is employed as decision support at strategical level (long term planning) [18,19]. DES are typically used to model a sequence of events with a higher detail level and are focused on the operational level (short-term planning) [18]. ABS can be used to model the interaction between independent objects (agents) and the influence of the agents' behavior on the entire system. ABS has been widely used for energy management applications and to model decentralized energy systems [20,21]. In [22] ABS is combined with Life Cycle Assessment to evaluate the dynamic impact of VRE on the environmental performance of a production system. Agent-based system can be easily scaled-up [23] and is, for this reason, the preferred paradigm within this research work.

The simulation model has as foreground system a single factory, it can be nonetheless scaled-up to a cluster of factories. The scenarios are assessed on an environmental perspective, using as evaluation criteria the specific CO_2-emissions related to the energy supply of the factory (C_E):

$$C_E = \sum(CI_i * E_i)/Q \qquad (1)$$

where CI_i is the carbon intensity of each supplier i, E_i is the energy (electrical and thermal) dispatched by each supplier and Q the targeted output of product. According to the European Energy Agency (EEA), the carbon intensity (CI) is defined as the ratio of the CO_2 emissions from electricity production and the gross electricity generation. The method used to calculate CI is described in details in the following section.

4. Case Study: Paper Sector

The presented methodology has been implemented in a use-case in the paper sector. The paper industry is responsible for 4% of the global industrial CO_2 emissions [24].

The simulation aims at assessing the possibility to exploit VRE excess available in the region around the paper mill under study, as a first step towards carbon neutrality.

4.1. Analyzing as-is-state of the paper mill

The case-study consists of a paper mill situated in Bayern, Southern Germany. The mill has an intensive demand of both electrical and thermal energy. The most power intensive units are the paper machines and the fiber production process. Thermal energy is required in the drying process to dry the paper-web through evaporation. A detailed assessment of the as-is-state has been performed in previous research work [5].

The factory operates a CHP plant consisting of a gas turbine, a steam turbine for heat recovery and supplementary firing. The system operation is heat driven, reaching an efficiency up to 85% in terms of primary energy use. The power plant runs at its optimum capacity and is currently able to cover around 90% of the electricity demand of the mill. To fulfill the total demand, power is additionally supplied by the public grid. Purchased electricity has a 20% renewable share.

With regards to process steam, the CHP plant meets the full demand and excess heat is provided as district heating to external parties for farming purposes. In case of failure of the power plant, the required process heat can be generated in back-up boilers, formerly used for steam generation.

The company has sustainability targets focused on a continuous improvement of its environmental impact, through the use of CO_2 neutral energy sources and the maximization of renewable fuels and is committed to support the German *Energiewende*. The mill is offering secondary control reserve, through a flexible operation of the CHP plant, which was assessed in detail in [25].

Analyzing the as-is-state, it emerges that the paper mill has a great potential to integrate renewable energy, as it currently runs 100% on fossil fuels.

In proximity of the mill a surplus of power generated in large-scale photovoltaic plants is available and can be used by energy-intensive consumers. As regards wind energy, since most wind mills are rather located in Northern Germany, the possibility of exploiting excess wind energy is neglected.

4.2. Defining simulation scenarios and constraints

In the local grid around the mill there is an excess of solar energy equal to 300 MW. The production facility is able to accommodate 100 MW by substituting electricity purchased from the power grid or a specific amount of electricity generated in the CHP plant. The CHP plant can be operated at a lower capacity than in the current configuration, resulting though in lower efficiency and higher carbon intensity. A reduction of the CHP operation capacity below 60% of its maximum value is not technically feasible.

The only constraint to be considered is that the capacity decrease of the CHP plant should not compromise the heat supply, e.g. the demand for process heat must be ensured.

Three scenarios are chosen for the simulation: scenario 1 (reference), scenario 2A (winter), scenario 2B (summer).

4.3. Simulating and evaluating the scenarios

The simulation is built in AnyLogic, as depicted in Figure 3: each object is modeled as an independent agent. The factory is represented as *Consumer*; three *Supplier* options are included: the CHP plant, the PV surplus and the power grid.

The input data of the simulation are listed in Table 1. For the consumer the power and heat demand as well as the final product output are required. For the CHP plant, the thermal and electrical capacity and the resulting efficiency must be given. The available surplus of PV is calculated according to the simulation scenario (winter/summer) and given as input. The grid is assumed to have an unlimited dispatch capacity (i.e. the capacity is higher than the electricity demand of the mill).

Table 1: Agent-based simulation: structure of the multi-agents system

Item	Description	Input Data
Paper mill (Consumer)	Has a defined demand to produce the output.	Paper output (Q_p) power demand (Dem_P) heat demand (Dem_H)
CHP (Supplier)	Generates process heat and electricity on-site.	Electrical capacity ($maxP_{CHP}$) thermal capacity ($maxH_{CHP}$) carbon factor gas (C_{gas}) system efficiency (η)
PV (Supplier)	Generates PV power off-site; has a variable surplus.	Available surplus ($maxP_{PV}$) carbon factor PV (C_{PV})
Grid (Supplier)	Supplies electricity; has an infinite capacity.	Dispatch from grid ($maxP_{grid}$) Carbon factor grid (C_{grid})

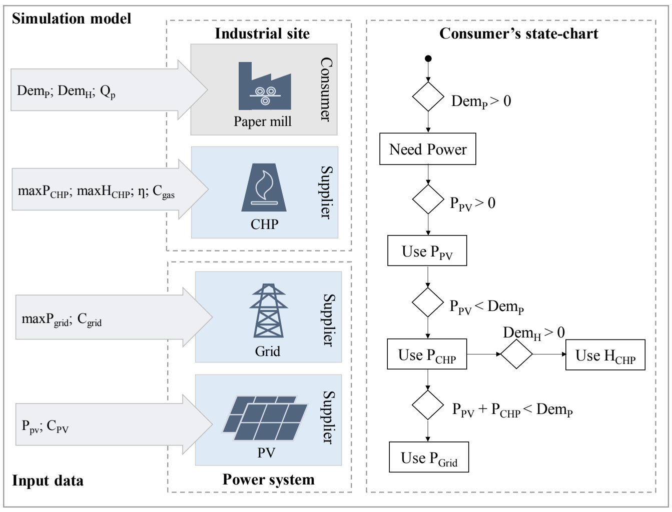

Figure 3: Overview of the simulation model and the state-chart

Table 2: CO_2 emission factors of the three suppliers

Fuel/Power source	CO_2 factor [tCO_2/MWh]	Source of data
Natural gas	0.219*	[26]
Photovoltaic	0.063*	[26]
Purchased electricity	0.671	UPM environmental product declaration

*including upstream emissions and auxiliary energy

The consumer's behavior is defined by a state-chart (Figure 3, right side), where the choice for the supplier is driven by the CO_2 emission factors, listed in Table 2. Preference is given to the supplier with the lowest emissions.

PV is chosen as the best supply option, since it has the lowest (nearly zero) carbon factor. The PV surplus is estimated using the solar irradiation values of the area. The CHP plant has a defined electrical and thermal capacity, which can be reduced according to the demand and to the availability of photovoltaics. Depending on the amount of electricity and heat to be generated, a relative input of natural gas is needed. This is associated to a specific carbon factor. It is assumed that the plant operates without failures throughout the year, i.e. back-up boilers are not included in the model. Purchased electricity (20% renewable share) is the last viable option to cover the electricity demand of the mill, having the highest emission factor.

To simplify the simulation, the mill demand for electricity and heat is assumed to be constant over the year.

In order to evaluate the simulation results, the specific CO_2 emissions related to the energy supply of the factory can be estimated using Eq. (1), i.e. for the case study:

$$C_E = \frac{CI_{CHP}*(P_{CHP}+H_{CHP}) + C_{PV}*P_{PV} + C_{grid}*P_{grid}}{Q_P} \quad (2)$$

where CI_{CHP} is the carbon intensity of the CHP plant, P_{CHP} the generated power, H_{CHP} the generated heat, P_{PV} the power supplied from the virtual PV plant, P_{grid} the electricity purchased from the grid, C_{PV} and C_{grid} the carbon factors of PV and the grid, respectively and Q_p the produced paper.

The carbon intensity of a CHP plant (CI_{CHP}) can be calculated as follows [27]:

$$CI_{CHP} = \sum(C_{gas} * I_{gas})/\sum(P_{CHP} + H_{CHP}) \quad (3)$$

The results depicted in Figure 5 demonstrate that the available excess of solar energy has the potential to fully replace power supply from the grid both in winter and in summer months.

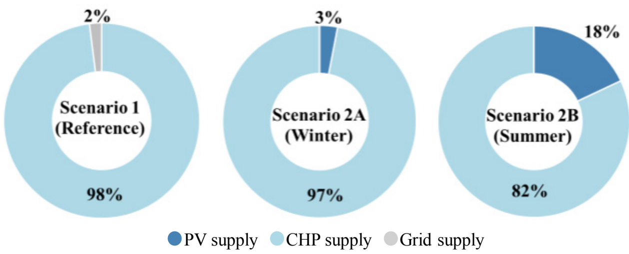

Figure 5: Simulation results – Share of the three suppliers on the mill's electricity supply

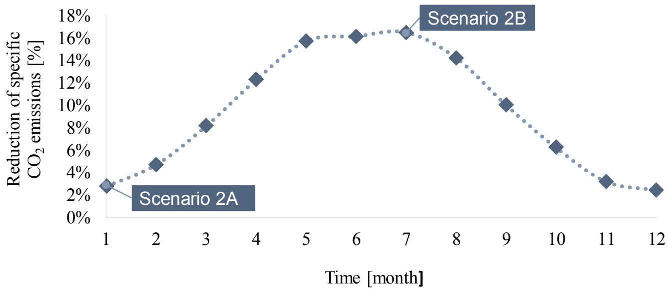

Figure 4: Simulation results – Reduction of specific CO_2 emissions

In Figure 4 the time performance of the control parameter, i.e. the specific CO_2 emissions, is plotted over the simulation timeframe, to show the impact of scenario 2A and 2B, in comparison to the reference scenario. In the winter scenario (2A) the gas demand for the CHP plant decreases by 1%, in summer (2B) by 16%, resulting in a reduction of the specific carbon emissions by 2.5% and 16%, respectively.

Due to the assumptions made in the simulation model, the results provide only an estimation of the decarbonisation level that can be reached through the integration of PV excess.

5. Conclusions & Outlook

In the current study a methodology to evaluate the integration of VRE in the process industry is proposed as a mean to reduce the need for grid upgrade. Through their intensive and nearly continuous demand for energy, process industries represent an opportunity to serve as energy sink in the system by exploiting available excess energy, avoiding curtailment of VRE and reducing industrial carbon emissions.

The case study is focused on the paper sector. The simulation scenarios encompass the integration of surplus photovoltaic power available in the local grid of the factory under study. The methodology can be adapted to other industrial sites or to other EEIs (with comparable CHP potentials) and can be even scaled-up, by adjusting the boundary conditions and constraints. The model aims at an environmental improvement of the energy supply chain; the economic advantages associated to PV integration must be assessed in detail, taking into account the natural gas prices, the variable costs of the CHP plant, the price of purchased electricity and the costs associated to the procurement of PV surplus, through a power purchase agreement (PPA).

Challenges related to the integration of excess PV power are the need for reliable forecasting of VRE due to the seasonality of PV and the fluctuating power supply. A full reliance on VRE is currently not feasible in the process industry: a hybrid solution, as the one proposed in this paper, is hence the only viable option at the moment.

Future work will strive for a reduction of the time resolution in the simulation models, to assess the seasonal influences more in depth, as well as an increase of the detail level to evaluate the implementation of demand side management strategies within the production chain. Further activities to be carried out include the development of new decarbonisation scenarios, integrating the heat supply chain in the simulation model, to evaluate the possibility of shutting down the CHP plant.

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References

[1] Lund, P. D., Lindgren, J., Mikkola, J., Salpakari, J., 2015, Review of energy system flexibility measures to enable high levels of variable renewable electricity, Renewable and Sustainable Energy Reviews, 45:785–807, DOI:10.1016/j.rser.2015.01.057.

[2] Denholm, P., Hand, M., 2011, Grid flexibility and storage required to achieve very high penetration of variable renewable electricity, Energy Policy, 39/3:1817–1830, DOI:10.1016/j.enpol.2011.01.019.

[3] Huber, M., Dimkova, D., Hamacher, T., 2014, Integration of wind and solar power in Europe: Assessment of flexibility requirements, Energy, 69:236–246, DOI:10.1016/j.energy.2014.02.109.

[4] Beier, J., Thiede, S., Herrmann, C., 2017, Energy flexibility of manufacturing systems for variable renewable energy supply integration: Real-time control method and simulation, Journal of Cleaner Production, 141:648–661, DOI:10.1016/j.jclepro.2016.09.040.

[5] Pierri, E., Schulze, C., Herrmann, C., Thiede, S., 2020, Integrated methodology to assess the energy flexibility potential in the process industry, Procedia CIRP, 90:677–682, DOI:10.1016/j.procir.2020.01.124.

[6] Riese, J., Grünewald, M., Lier, S., 2014, Utilization of renewably generated power in the chemical process industry, Energy, Sustainability and Society, 4/1:1–10, DOI:10.1186/s13705-014-0018-4.

[7] Wee, H. M., Yang, W. H., Chou, C. W., Padilan, M. V., 2012, Renewable energy supply chains, performance, application barriers, and strategies for further development, Renewable and Sustainable Energy Reviews, 16/8:5451–5465, DOI:10.1016/j.rser.2012.06.006.

[8] Kost, C., Schlegl, T., Thomsen, J., Nold, S., Mayer, J., et al., 2018, Fraunhofer ISE: Levelized Cost of Electricity - Renewable Energy Technologies, March 2018, Fraunhofer ISE: Levelized Cost of Electricity - Renewable Energy Technologies, /March.

[9] Saavedra M., M. R., Cristiano, C. H., Francisco, F. G., 2018, Sustainable and renewable energy supply chain: A system dynamics overview, Renewable and Sustainable Energy Reviews, 82/September 2017:247–259, DOI:10.1016/j.rser.2017.09.033.

[10] Beier, J., 2017, Simulation Approach Towards Energy Flexible Manufacturing Systems, Berlin Heidelberg: Springer International Publishing, DOI:10.1007/978-3-319-46639-2.

[11] Taibi, E., Nikolakakis, T., Bank, W., Gutierrez, L., Fernandez Del Valle, C., 2018, Power System Flexibility for the Energy Transition IEA Task 25-Design and Operation of Power Systems with Large Amounts of wind power View project Cyprus National Energy Roadmap View project. .

[12] Akrami, A., Doostizadeh, M., Aminifar, F., 2019, Power system flexibility: an overview of emergence to evolution, Journal of Modern Power Systems and Clean Energy, DOI:10.1007/s40565-019-0527-4.

[13] Roesch, M., Bauer, D., Haupt, L., Keller, R., Bauernhansl, T., et al., 2019, Harnessing the full potential of industrial demand-side flexibility: An end-to-end approach connecting machines with markets through service-oriented IT platforms, Applied Sciences (Switzerland), 9/18, DOI:10.3390/app9183796.

[14] Roth, S., Thimmel, M., Fischer, J., Schopf, M., Unterberger, E., et al., 2019, Simulation-based analysis of energy flexible factories in a regional energy supply system, Procedia Manufacturing, 33:75–82, DOI:10.1016/j.promfg.2019.04.011.

[15] Khripko, D., Dunkelberg, H., Summerbell, D. L., Hesselbach, J., 2018, Energy Efficiency and demand side management: A case study of a holistic energy concept in polymer processing, Procedia Manufacturing, 21:702–709, DOI:10.1016/j.promfg.2018.02.174.

[16] Paulus, M., Borggrefe, F., 2011, The potential of demand-side management in energy-intensive industries for electricity markets in Germany, Applied Energy, 88/2:432–441, DOI:10.1016/j.apenergy.2010.03.017.

[17] BMWi, 2017, Concluding paper : Electricity 2030 , Long-trends - tasks for the coming years, Federal Ministry for Economic Affairs and Energy, p. 52.

[18] Antonelli, D., Litwin, P., Stadnicka, D., 2018, Multiple System Dynamics and Discrete Event Simulation for manufacturing system performance evaluation, Procedia CIRP, 78:178–183, DOI:10.1016/j.procir.2018.08.312.

[19] Gravelsins, A., Bazbauers, G., Blumberga, A., Blumberga, D., Bolwig, S., et al., 2018, Modelling energy production flexibility: System dynamics approach, Energy Procedia, 147:503–509, DOI:10.1016/j.egypro.2018.07.060.

[20] Jun, Z., Junfeng, L., Jie, W., Ngan, H. W., 2011, A multi-agent solution to energy management in hybrid renewable energy generation system, Renewable Energy, 36/5:1352–1363, DOI:10.1016/j.renene.2010.11.032.

[21] Woltmann, S., Zarte, M., Kittel, J., Pechmann, A., 2018, Agent Based Simulation Model of Virtual Power Plants for Greener Manufacturing, Procedia CIRP, 69/May:377–382, DOI:10.1016/j.procir.2017.11.054.

[22] Rödger, J., Beier, J., Schönemann, M., Schulze, C., 2020, Combining life cycle assessment and manufacturing system simulation – evaluating dynamic impacts from renewable energy supply on product-specific environmental footprints, International Journal of Precision Engineering and Manufacturing-Green Technology, /0123456789:1–22, DOI:10.1007/s40684-020-00229-z.

[23] Golmohamadi, H., Keypour, R., Bak-Jensen, B., Pillai, J. R., 2019, A multi-agent based optimization of residential and industrial demand response aggregators, International Journal of Electrical Power and Energy Systems, 107/July 2018:472–485, DOI:10.1016/j.ijepes.2018.12.020.

[24] Gutowski, T. G., Allwood, J. M., Herrmann, C., Sahni, S., 2013, A Global Assessment of Manufacturing: Economic Development, Energy Use, Carbon Emissions, and the Potential for Energy Efficiency and Materials Recycling, Annual Review of Environment and Resources, 38/1:81–106, DOI:10.1146/annurev-environ-041112-110510.

[25] Kahlert, S., Spliethoff, H., 2017, Investigation of different operation strategies to provide balance energy with an industrial combined heat and power plant using dynamic simulation, Journal of Engineering for Gas Turbines and Power, 139/1:1–8, DOI:10.1115/1.4034184.

[26] Umweltbundesamt, 2017, Emissionsbilanz erneuerbarer Energieträger, Climate Change 23/2017., pp. 1–147.

[27] Graus, W., Worrell, E., 2011, Methods for calculating CO2 intensity of power generation and consumption: A global perspective, Energy Policy, 39/2:613–627, DOI:10.1016/j.enpol.2010.10.034.