Locating Experts and Carving Out the State of the Art: A Systematic Review on Industry 4.0 and Energy System Analysis*

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Abstract

As Germany's manufacturing industry highly depends on international competitiveness, German companies must rapidly assimilate to current processes of digitization and so-called 'Industry 4.0'. These processes will also affect the German energy system. Understanding and predicting the implications of these changes is one of the core elements of energy system analysis. To address this issue, herein we present a structured and systematic review of literature within the intersection of industrial digitalization in the sense of Industry 4.0 and scientific energy system analysis. The goals of this study are 1) to reveal the locations and institutions of relevant experts and 2) to carve out the current state of the art with regard to technologies that enable (digitized) industries to interact with the energy system in order to contribute to a smart energy system. Our approach is based on a systematic and reproducible keyword search using the scientific literature database Scopus. Both a quantitative evaluation and a qualitative evaluation of the relevant literature are conducted. The quantitative results are presented using GIS-based visualizations. This facilitates us to identify the European Union as main contributor on a global level and the United Kingdom as the most prolifically publishing country within the European Union. Focusing on Germany, we find North Rhine-Westphalia to be the most scientifically active area and Aachen/Dortmund to be the cities where most publications originate. In the qualitative, content-based part of this review, we show that in particular sector coupling and the integration of distributed energy prosumers can lead to a working smart energy system. We demonstrate that industrial digitalization processes in the sense of Industry 4.0 can serve as enabling factor in this respect. Further, we provide extensive summaries regarding both the technological and economic potentials and challenges of different technologies in future smart energy systems. Taking all of the results into account, we outline a framework to connect the highly discussed topics of digitalized industries and smart energy systems to corresponding experts.

Keywords: Energy system analysis; Industry 4.0; Systematic review; GIS-based visualization

1 Introduction

Being one of the world's leading exporters, Germany highly depends on the international competitiveness of its industrial sector. Therefore, German industry will need to quickly adopt processes linked to "Industry 4.0", as they promise competitive advantages. After the implementation of: (1) mechanical means of production with the help of steam and hydropower; (2) the assembly line work through the electrification of production plants; and (3) the further automation of production using electronics and information technology, the fourth industrial revolution is currently taking place based on digital networking of intelligent objects (Wolter *et al.*, 2015). The term "Industry 4.0" (or its German equivalent "Industrie 4.0") originates from the government of Germany and was presented at the Hannover Messe trade fair 2011 in order to describe this process (Kagermann *et al.*, 2011; Botthof 2015). However, a definition of the term with general validity has yet to be found (Bauernhansl *et al.*, 2014; Drath and Horch, 2014; Hermann *et al.*, 2016). For this reason, Nolting *et al.* (2019) investigated the term "Industry 4.0" by conducting a detailed, quantitative literature review with international scope. They found out that Germany is the "sole leader in research under the terminology: 'Industrie 4.0', as well as its equivalent: 'Industry 4.0'" (Nolting *et al.*, 2019).

Digitization processes across industries are likely to affect the German energy system, as the industrial sector accounts for about 30% of the overall energy consumption in Germany (AGEB e.V., 2018). Therefore, we amend the focus of our review by analyzing the interactions between digitized industries and the energy system. As the understanding and prediction of future developments of the energy system represents one of the core elements of energy system analysis (ESA), we analyze experts in the intersection of Industry 4.0 and ESA and the main research topics within these fields.

Using scientific models, simulations and predictions, ESA contributes to both to the estimation of specific developments and to the generation of transparency and comprehension concerning the influence of and interaction with new technologies and the energy system (BMWi, 2016). Developments such as liberalization, energy transition, and digitalization increase system dynamics and complexity. For these reasons, this field of research is growing in popularity, as can been seen in Figure 1.

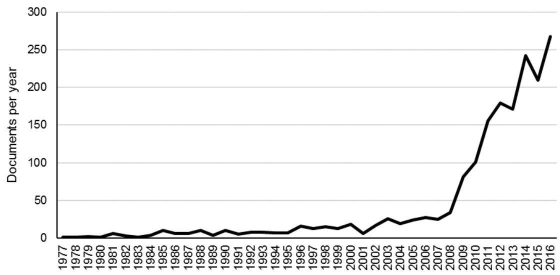

Figure 1: Number of publications per year in the research area of ESA (sources of data: Elsevier B.V. Scopus (2017); Webster and Watson (2002))

Many different technologies comprising all sectors are currently being discussed by researcher from the field of ESA with regard to their potential to contribute to a future SES:

- <u>Heat sector:</u> District heating in local heat markets, heat pumps (HPs), combined heat and power (CHP), thermal energy storages (TES), and power to gas technologies
- <u>Transport sector:</u> Electric Vehicles (EVs)
- <u>Industrial sector:</u> Direct coupling of industrial processes to the energy system to use the flexibility potential

Against this backdrop, we conduct a structured, keyword-based, and reproducible literature review that allows us to:

(1) Reveal the locations and institutions of experts that publish at the intersection of industrial digitalization in the context of Industry 4.0 and scientific energy system analysis using quantitative analysis.

(2) Reflect the current state of the art regarding the main technologies that enable (digitized) industries to interact with the energy system in order to contribute to a smart energy system using qualitative, content-based analysis.

In the quantitative part of our review, we identify and locate the main contributors to the relevant research areas by means of GIS-based visualizations. In the qualitative, content-based part of this manuscript, we provide an up-to-date summary of current scientific debates on both technological and economic potentials and challenges of the main technologies that enable (digitized) industries to contribute to a future SES.

The remainder of this manuscript is structured as follows: In section 2, we provide a detailed description of both research methods, in particular clarifying the literature basis and the systematic approach. We then show our results that were achieved by applying these research methods in section 3. In section 4, a discussion of the results and comparison with the related literature is to be found. We conclude this review in section 5 by providing an overall summary.

2 Methodology

Within this section, our two scientific approaches are described. In order to reach the research goals as defined above, we make use of a literature-based analysis of the research field of ESA and its intersections to Industry 4.0 as an enabling technology for demand flexibility. We apply two different approaches within our study: On the one hand, we analyze the number of papers published within the intersection of these terms quantitatively. This enables us to identify the countries, regions, cities, and universities with high scientific outputs on the corresponding topics. On the other hand, we provide a content-based, qualitative literature review of research published at the intersection of ESA and topics related to Industry 4.0.

To ensure that the results of both methods make a valuable contribution to the development of the research area, it is crucial for the investigation to take into account: (1) the quality of the selected articles; as well as (2) their relevance to the subject to be reviewed; and (3) their completeness (Levy and Ellis, 2006). Advancements in information technology have led to an overwhelming quantity research being quickly accessible. Similar topics have often been studied under different headings, which carries the risk of overlooking significant literature (vom Brocke *et al.*, 2015). Vom Brocke *et al.* (2009) have emphasized the importance of rigorously documenting of the research process. Moreover, there has been a call for a reproducible process to be applied to literature reviews in order to retain scientific quality (Levy and Ellis, 2006; Bandara *et al.* 2011; Wolfswinkel *et al.*, 2013).

It is essential to apply a systematic approach for both the quantitative and the qualitative reviews, as Okoli (2015) and Baker (2000) recommend. Figure 2 shows Okoli's approach for a comprehensible procedure. Okoli focuses on the importance of selecting suitable literature. The application of a practical screen plays a major role in the literature review process, as it determines the documents to be used for further analysis. Moreover, data extraction is indispensable and particular attention must be paid to the quality and suitability of the literature to be examined with regard to the underlying question. Overall, his suggestions reflect a linear approach containing a predetermined sequence of actions when conducting a structured literature review.

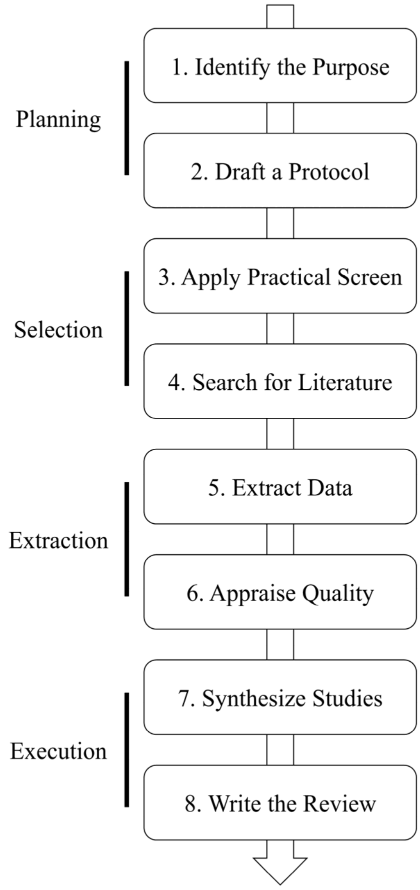

Figure 2: Linear approach toward a standalone systematic literature review (own representation based on Okoli (2015))

In contrast, Baker (2000) recommends a circular framework as can be seen in Figure 3. This approach offers the advantage that a very deep background of the research object under investigation can be explored. In addition, the rapid change in the field of research can be taken into account and contemporary keywords can be determined and considered for the work.

In order to address the aforementioned caveats, we combined the guide for a "Standalone Systematic Literature Review" published by Okoli (2015) and Baker's concept of circularity for generating suitable keywords (Baker, 2000). This approach promises rectification, as it is:

- Systematic and explicit by using a clearly defined method and explaining all necessary steps;
- Comprehensive regarding the scope and inclusion of all material with relevance to the field;
- And thus reproducible by other researchers.

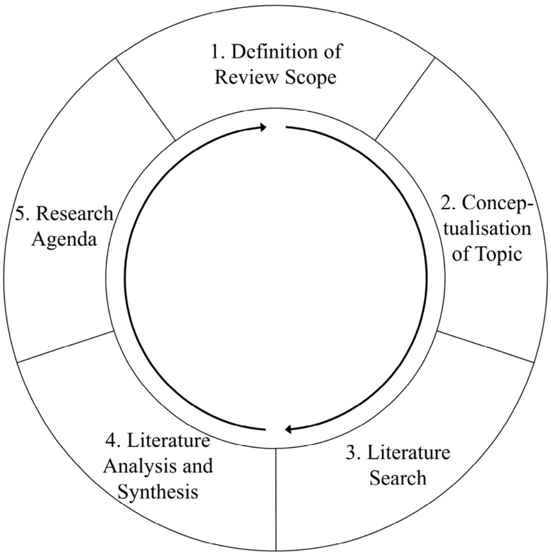

Figure 3: Circularity framework for literature reviews (own representation based on Baker (2000))

To achieve the goal of providing a well-documented and reproducible review, special attention was paid to choosing an adequate database. A systematic literature review must ensure that the collection of relevant literature is as comprehensive as possible (Webster and Watson, 2002). A frequent mistake is to refer to one database exclusively to discover relevant papers without taking into account the possible shortcomings of such an approach, such as database bias, for example. This often results in a literature background that has neither the depth nor the breadth that is appropriate for a high-quality literature review (Levy and Ellis, 2006). To address this issue, the three providers for databases Scopus, Web of Science and ScienceDirect were considered in our analysis. In order to investigate which database is most suitable for this review, the three databases were compared regarding their coverage of the 100 best-ranked journals in the research area energy. For this purpose, the journals were sorted according to their Scimago Journal Rank (SJR) index (Scimago Lab, 2017). For a scientific evaluation of the validity of this journal rank index, see Falagas *et al.* (2008). It was shown that Scopus covers 96, Web of Science covers 66 and ScienceDirect covers 40 of the 100 top-ranked journals. Furthermore, it turned out that Scopus covers – with a single exception – all journals that are also available within ScienceDirect and Web of Science (see Figure 4). Therefore, the review was conducted using Scopus as single source of data.[1] As the coverage of the best-ranked journals within Scopus is as high as 96 %, a database bias can be excluded for our analysis.

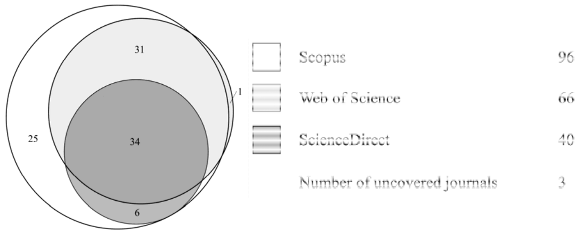

Figure 4: Coverage of journals in different databases (sources of data: Elsevier B.V. Scopus (2017), Scimago Lab (2017), Clarivate Analytics (2017), Elsevier B.V. Science Direct (2017))

For the remainder of this review, we therefore focus on the investigation of 96 of the 100 top-ranked journals within the energy research area, using Scopus as the single data source. The benefits of using the top-ranked journals are

1. Coverage of the central contributions11 and
2. A peer-review process that guarantees high quality standards.

As their articles are independently evaluated, peer-reviewed journals exclude inadequate manuscripts of research. The review process ensures that scientists can rely on a certain quality standard, which is especially relevant for literature analyses (Davison *et al.*, 2005)[2].

After a suitable literature basis was identified, two different steps for the quantitative analysis on the one hand and the qualitative analysis on the other were applied. For this reason, the following paragraphs separately illustrate the chosen methodologies.

[1] The four journals that are not covered by Scopus and that were thus neglected for further analysis are namely (rank in brackets): 1. 2012 2nd International Conference on Applied Robotics for the Power Industry, CARPI 2012 (39), 2. Energy and Fuels (50), 3. ACS Sustainable Chemistry and Engineering (51), 4. Chemical Engineering and Processing (90).

[2] In addition to the 100 top-ranked journals, papers published in conference proceedings of the Institute of Electrical and Electronics Engineers (IEEE) were added to the literature basis because of their high relevance to the subject under investigation. Furthermore, their high ranking according to the SJR index can be seen as proof of their quality.

2.1 Quantitative Analysis

As stated above, a quantitative literature analysis must ensure the quality, completeness and relevance of the counted articles. Both the quality and completeness of the counted articles are therefore assured by an adequate literature basis. Therefore, it is necessary to filter relevant papers for our quantitative analysis as a next step. This is achieved by adopting the following three techniques (Webster and Waton, 2002; Levy and Ellis, 2006; Vom Brocke, 2009):

1. Keyword searching: This approach refers to the search for scientific publications in databases using certain keywords. The basis for generating these keywords is the literature based on the respective research area.
2. Backward searching: This technique describes the process of analyzing the articles identified by the keyword search to determine further relevant articles on the basis of additionally identified keywords that might be relevant to the work.
3. Forward searching: Within this method, articles are reviewed, that have cited the article under investigation in order to further expand the literature basis toward more recent publications.

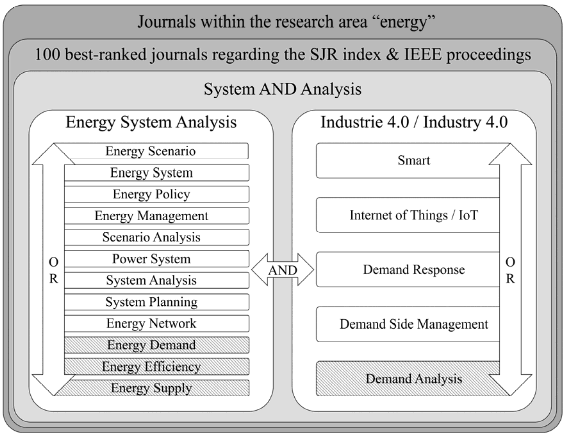

Figure 5: Search scope and combination matrix of keywords

To generate keywords with high relevance for the research area of ESA as well as for the field of Industry 4.0, these three techniques were applied starting the keyword search with two initial search runs using the terms "Energy System Analysis" and "Industry 4.0". Then, several queries were carried out applying the forward and backward searching techniques to collect keywords that represent the research topics under investigation. This approach led to 12 keywords for the ESA category and five keywords for the research field Industry 4.0. This can be seen in Figure 5.

Afterwards, keywords that proved to lead to either too few or to inappropriate results during the search procedure were excluded from further investigations. For the purpose of visualization, these keywords are represented in the grey striped boxes in Figure 5.

In order to create suitable search terms, the words "System" and "Analysis" were declared obligatory to appear within the title, abstract or keywords of the filtered papers within the energy subject area. Thereafter, each phrase in one of the left boxes relating ESA was linked to one of the phrases within a white box on the right-hand side relating to the topic of Industry 4.0 using the logical AND operator. Therefore, only papers that cover topics within the intersection of both fields of research were taken into further consideration. Due to the intensified research in the area of ESA and the massive increase in published papers since the year 2008 (see Figure 1), onlypapers published after 2007 were included in this study. The described approach led to the following search term:

(TITLE-ABS-KEY ("system" AND "analysis")) AND (TITLE-ABS-KEY ("energy system" OR "energy policy" OR "scenario analysis" OR "system planning" OR "power system" OR "energy management" OR "system analysis" OR "energy scenario" OR "energy network")) AND (TITLE-ABS-KEY ("smart" OR "IoT" OR "internet of things" OR "demand side management" OR "demand response")) AND (SUBJAREA (ENER)) AND (PUBYEAR > 2007)

Entering this search term into the Scopus database filter yielded a total amount of 2695 papers for further investigation. This search term will be referred to as the "general search term" in the remainder of this manuscript.

Besides the general search term, two modified terms were applied in order to generate even more transparency in the usage of Industry 4.0 in the energy research area. The first modified search term is meant to reveal papers that directly link flexibility to the research field of ESA, as Industry 4.0 can be seen as enabling process for flexibility in the future energy system. Therefore, the general search term was extended by the condition that relevant papers must contain the word flexibility within title, abstract or the keywords. This approach led to the following, extended search term that will hereinafter be referred to as “flexibility search term”:

(General search term) AND (TITLE-ABS-KEY (“flexibility”))

The flexibility search term reduced the total number of papers to 399 for further investigation.

The second modification to the general search term was made in order to unveil papers that directly address with the link of Industry 4.0 and energy system analysis. For this reason, the general search term was extended by the keywords “Industry 4.0” and “Industrie 4.0”. However, this search led to a total number of twocan papers passing the filter. As quantitative explorations need to be based on broad population, the filter was moderated. This led to the following search term, which directly links “Industry 4.0” to the research area of energy. It will be referred to as “Industry 4.0 search term” in the remainder of this manuscript.

(TITLE-ABS-KEY ("industrie 4.0" OR "industry 4.0")) AND (TITLE-ABS-KEY("energy")) AND (PUBYEAR > 2007)

Applying the Industry 4.0 search term, 48 papers were identified for further investigation.

The papers resulting from the three different search terms were then segregated by region. This enabled an analysis on an international basis, a German national basis and a regional basis, with a focus on North Rhine-Westphalia. In addition, the contribution of single universities to the scientific discussion was analyzed. The results were further visualized using QGIS (QGIS Development Team, 2017). The visualizations can be seen in the results section (Figures 6 to 10).

2.2 Qualitative Review

After the quantitative analysis was described in detail, the qualitative part of this literature review is presented within the following paragraphs. The pure counting and visualizing of papers within the intersection of ESA and Industry 4.0 was attended by an in-depth analysis of the content of the most relevant literature. Therefore, the 2695 papers that build the basis of the quantitative analysis must be post-processed and screened further in order to obtain a manageable number of papers for content analysis. To extract the most relevant research topics, we only analyzed the content of papers with five cites or more per year. This once again supports the high quality of the reviewed literature. Furthermore, only English papers were considered, as these can be assumed to have international relevance. The implementation of these two additional filters to the general search term led to a total amount of 369 papers for content analysis.

In a next step, the title, abstract and list of content of the filtered papers was assessed. Publications that were found to have a close link to the research fields under investigation were then clustered and their content and findings were summarized and contrasted. In order to provide a structured overview, the potentials and challenges of single technologies, as discussed in the literature across different sections of the energy system, were finally drawn together in Tables 3 to 12. Thereby both, the technological and economic potentials and challenges as were considered.

3 Results

In this section, the results achieved by applying the aforementioned methods are shown. The following paragraphs are structured according to Section 2, starting with the results of the quantitative analysis and describing the results of the qualitative, content-based analysis thereafter.

3.1 Results of the Quantitative Analysis

This section contains both the quantitative results of the general search term as well as of the two modified search terms. The counts of the general search term are demonstrated first, starting with an international scope and zooming in to a national analysis for Germany. The same procedure is conducted for the two modified search terms.

As can be seen in Figure 6, most papers within the intersection of ESA and Industry 4.0 are published within the European Union (EU). All regions of the world relate most to the topic “Power System” within their publications.[3] Thereby, most papers (675) originate from institutions of the European Union, while China produced 377 and the United States 416. Comparing the number of articles concerning “Energy System”, China (32) and the United States (65) have published far fewer papers than the EU (276). Regarding the keyword “Energy Policy”, the results are similar: the EU (180) published more papers than the United States (70) and China (35). Also, with respect to "Energy Management", significant differences between regions can be detected. While Chinese institutions published 57 papers, American researchers (117) published more than twice as many, while members of the EU (241) then again published more than twice as many as the United States. Overall, it can be stated that all regions of the world have a similar focus within their research in the field of ESA. Most importance is attached to the topic "Power System", followed by the topic "Energy Management". Concerning the word phrases "Energy Policy" and "Energy System", only EU member states published a comparable number of papers while those fields seem to be of less interest in China and the United States. However, in all fields, the EU is a leader in corresponding publications. For this reason, a more detailed analysis of the European publications is presented in the following.

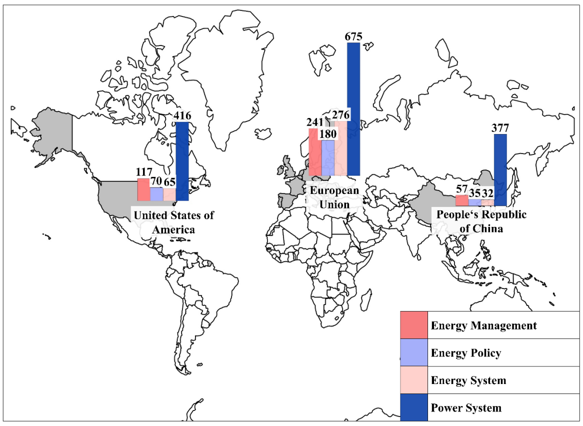

Figure 6: Papers identified using the general search term, worldwide scale (own representation using QGIS Development Team (2017), Natural Earth (2017))

Figure 7 depicts the distribution of papers published within the EU within the research field under consideration. The eastern member states of the EU[4] were conjoined under the term "Eastern Europe" for reasons of clarity. Taking the resulting figures into account, the United Kingdom (UK), Germany and Italy can be identified as European leaders in the area of research. While all European countries have the highest scientific outcome regarding the keyword "Power System" (UK 125, Italy 91, Germany 85), it turns out that Italy has also specified its research concerning the topic "Energy Management" (51 papers), whereas Germany (21) and the United Kingdom (35) have fewer publications in this field. Examining the papers published incorporating the term "Energy Policy", the United Kingdom is the sole leader, with 43 articles. Germany, which represents the second most publications (18), produced than half as much publications as the United Kingdom. The number of manuscripts in Germany (36), Italy (30) and the United Kingdom (53) within the field "Energy System" is similar. In addition to those three key players, Spain, Denmark, and the etherlands contribute a considerable amount to the aforementioned fields of research.

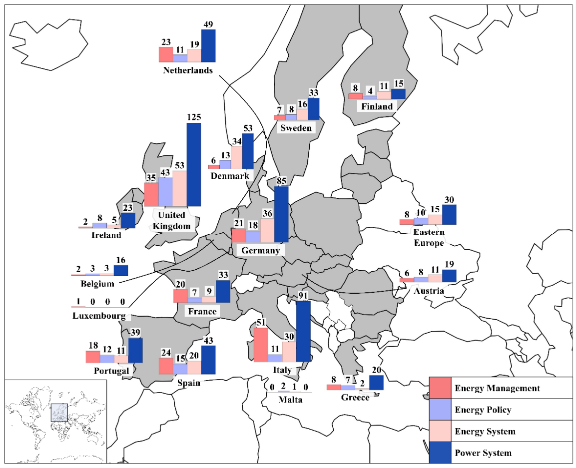

Figure 7: Papers identified using the general search term, European scale (own representation using QGIS Development Team (2017), Natural Earth (2017))

Zooming in on a national scale in Germany (see Figure 8), North Rhine-Westphalia (62) and Baden-Württemberg (48) can be identified as key players. Both states published most within the term of "Power System" (North Rhine-Westphalia 37, Baden-Württemberg 24). Regarding the keywords "Energy Management" and "Energy Policy", North Rhine-Westphalia published more papers (nine and eight, respectively) than Baden-Württemberg (seven and four, respectively) whereas for the keyword "Energy System", the number of papers from Baden-Württemberg (13) exceeded the number of papers from North Rhine-Westphalia.

Focusing on North Rhine-Westphalia (see Figure 9), the leading role of RWTH Aachen (15 papers) is apparent. Furthermore, TU Dortmund (14) significantly contributes to the research area of ESA. Both, Aachen (11) and Dortmund (nine), intensified their work under the term of "Power System". Dortmund published three papers utilizing the phrase "Energy System", which seems to be of less interest in Aachen (zero). However, concerning the terms

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[3] In the following, the number of published papers per region/country is given in brackets.

[4] Namely: Poland, Hungary, Bulgaria, Croatia, Slovenia, Czech Republic, Latvia, Estonia, Cyprus and Romania.

"Energy Management" and "Energy Policy", Aachen (three and one, respectively) published more frequently than Dortmund (two and zero, respectively).

In order to allocate the locations of scientific experts to their research institutions, an evaluation of the most important universities was conducted as well. This approach yielded the results shown in Table 1.

After the results of the general search term were presented in detail for different local scales, the outcomes of the two modified search terms are shown in the following paragraphs. For reasons of clarity, they are summarized in Figure 10. The third bar serves as a reference to the general search term in order to classify the results of the modified search more accurately. The results of the flexibility and Industry 4.0 search term in the context of energy sciences can be condensed as follows:

- Compared with the general search term, fewer results are achieved because of the more specified fields of research.
- On an international scale, Europe is the leader concerning flexibility in the field of ESA, as well as in examining methods of Industry 4.0 in the energy sector.
- Within the EU, the key players (UK, 41; Germany, 31; Italy, 27) of the general search confirm their position regarding research about flexibility in ESA. Moreover, the Netherlands (30 papers) and Denmark (26 papers) can be added to the list of key players.
- Looking at the Industry 4.0 topic on the European scale, it becomes clear that Germany is the sole leader with 15 publications over the last decade in this field of research.

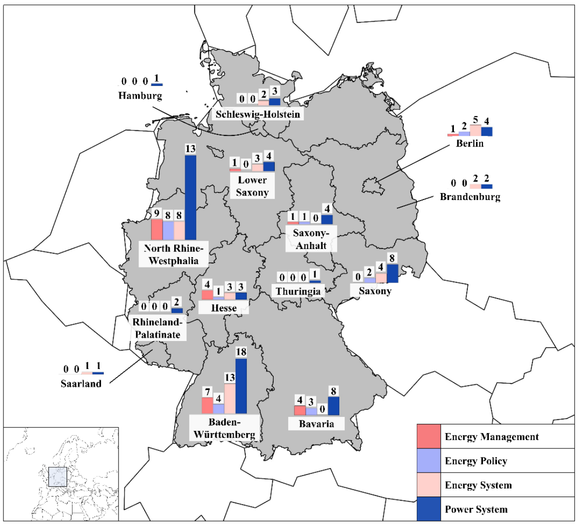

Figure 8: Papers identified using the general search term, German scale (own representation using QGIS Development Team (2017), Natural Earth (2017))

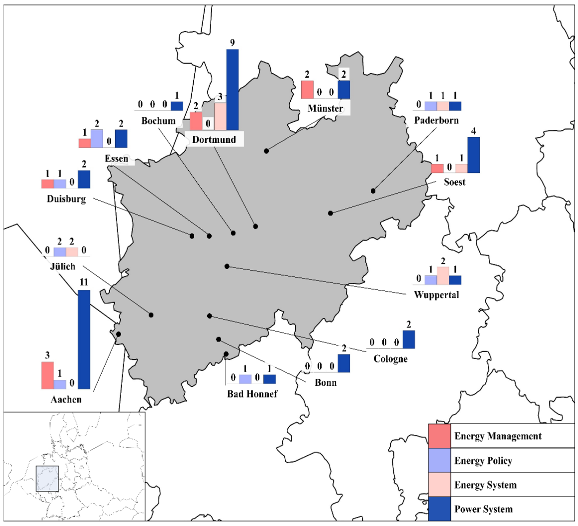

Figure 9: Papers identified using the general search term, North Rhine-Westphalia (own representation using QGIS Development Team (2017), Natural Earth (2017))

Table 1: Most publishing regions, countries, cities, and universities based on the general search term

Scope	Most publishing regions, countries,and cities	Most publishing universities
World	EU (1162), USA (598), China (457)	Danmarks Tekniske Universitet (45), Pacific Northwest National Laboratory (29), Tsinghua University (50)
Europe	UK (221), Italy (162), Germany (134)	Imperial College London (32), Politecnico di Milano (15), RWTH Aachen University (14)
Germany	North Rhine-Westphalia (54), Baden-Württemberg (41)	RWTH Aachen University (14), Karlsruhe Institute of Technology (12)
North Rhine-Westphalia	Aachen (15), Dortmund (14)	RWTH Aachen University (14), TU Dortmund (12)

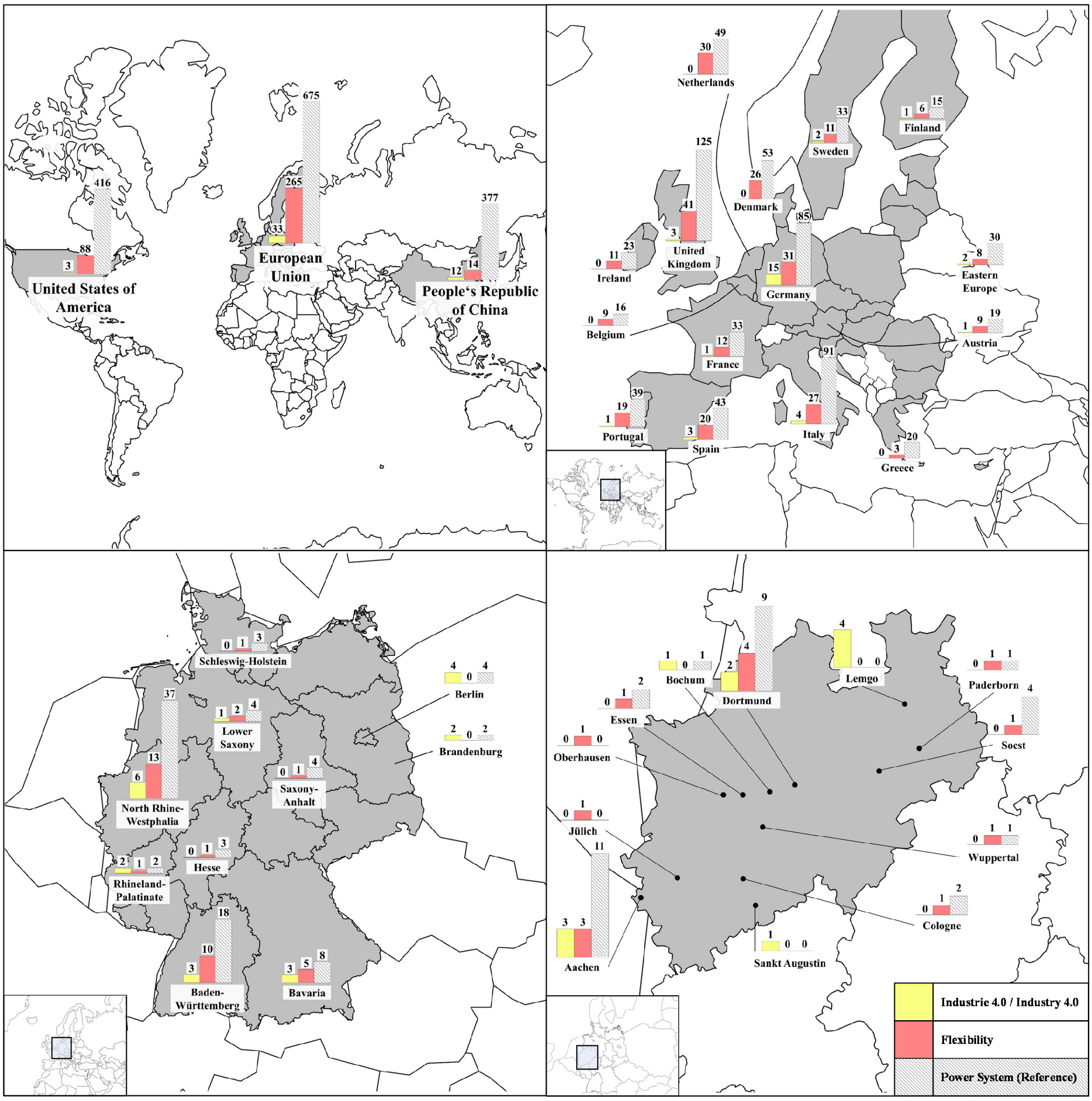

Figure 10: Summary of the results achieved with the modified search term (own representation using QGIS Development Team (2017), Natural Earth (2017))

- Focusing on Germany, the results of the general and the modified search terms highly correspond. Baden-Württemberg has published 13 papers, (10 incorporating the flexibility search term and three regarding the Industry 4.0 search term). North Rhine-Westphalia had 19 publications in total, 13 of which regarding flexibility, six concerning Industry 4.0. Along with Berlin and Brandenburg, they published six papers in the area of Industry 4.0 which makes them one of the key regions regarding this terminology. Furthermore, Bavaria contributed with eight papers, mainly published by researchers situated at TU Munich.
- Aachen and Dortmund are also key players with respect to the modified search term with 6 publications each but differently distributed. Dortmund has an outcome of four papers using the flexibility search term and two in the case of using the Industry 4.0 search term. Aachen however published three papers each. However, the highest number (four) of papers concerning Industry 4.0 were published by institutions located in Lemgo, North Rhine-Westphalia.

Again, an analysis of the most important regions, countries, cities, and universities was conducted, which yielded the following results shown in Table 2.

Table 2: Most important regions, countries, cities, and universities based on modified search terms

Scope	Flexibility: Most important regions, countries, and cities	Flexibility: Most important universities	Industry 4.0: Most important regions, countries, and cities	Industry 4.0: Most important universities
World	EU (265), USA (88), China (46)	Danmarks Tekniske Universitet (17), UC Berkeley (11), Tsinghua University (4)	EU (33), China (12), USA (3)	RWTH Aachen University (3), South China University of Technology (3), UC Berkeley (1)
Europe	UK (41), Germany (31), Netherlands (30)	University of Manchester (11), Karlsruher Institut für Technologie (5), TU Eindhoven (14)	Germany (15)	RWTH Aachen University (3)
Germany	North Rhine-Westphalia (13), Baden-Württemberg (10)	Karlsruhe Institute of Technology (5), TU Dortmund (4)	North Rhine-Westphalia (6)	RWTH Aachen University (3)
North Rhine-Westphalia	Dortmund (4), Aachen (3)	TU Dortmund (4), RWTH Aachen University (3)	Lemgo (4), Aachen (3)	RWTH Aachen University (3), HS Ost-Westfalen Lippe (2)

3.2 Results of Qualitative Analysis

After the results of the quantitative evaluation were presented using GIS-based visualizations, the outcomes of the content analysis are shown within this section. For reasons of clarity, all findings are summarized in Tables 3 to 12.

As the forward and backward search for appropriate keywords revealed, the term “Industry 4.0” is directly linked to the keywords “Smart”, “Internet of Things” and “Demand Side Management”, as well as “Demand Response”. This means that the intersection of “Industry 4.0” and ESA lies especially in SESs with automatically-controlled demand and fully integrated supply. This implies a broad understanding of the term “Industry 4.0” within recently published academic literature. In this context, a SES can be defined as a system that offers energy services to customers in a highly automated way. In the following, it will be defined based on the three core characteristics found in the analyzed literature:

- **First, the electricity, transport and heat sector are coupled to a multi energy system:** To date, 155 parties have signed the Paris Agreement and declared their willingness to pursue massive CO2 reduction (United Nation Climate Change, 2017). The highest potentials for CO2 reduction, similar in size, are found in the electricity, transport and heat sector. For decarbonization, all three sectors must be powered by a large share of intermittent RES. The coupling of energy sectors can increase the flexibility of energy systems, which is in turn required for the integration of intermittent resources (Breyer *et al.*, 2015; Jiang *et al.*, 2014; Lund *et al.*, 2014; Mancarella, 2014).
- **Second, distributed energy prosumers (DEPs) are integrated into the grid.** DEPs are participants of the grid that can act as“Distributed Consumers” and/or “Distributed Suppliers” and/or “Distributed Energy Storages” as shown in Figure 11. Due to the increasing number of DEPs, instead of passive consumers, a multitude of active participants needs to be integrated into the grid. Hence, the growing complexity necessitates information technology solutions (Lund *et al.*, 2014; Houwing *et al.*, 2008; Li *et al.*, 2016; Monti and Ponci, 2010; Wang *et al.*, 2015; Yang *et al.*, 2016; Toledo *et al.*, 2010).
- **Third, Industry 4.0 and Smart Grids (SGs) enable the process:** The term “Industry 4.0” comprises of all concepts for digitized processes within the industrial value chain (Hermann et al., 2016). On the one hand, Industry 4.0 refers to the introduction of cyber physical systems in industrial production systems that can automatically react to data inputs automatically (e.g., adapt production loads to electricity prices in real-time). On the other hand, Industry 4.0 cannot be limited to this and in a broader understanding as the “Industrial Internet”, it includes the implementation of bidirectional communication within SGs (Drath and Horch, 2014), (Monti and Ponci, 2010) In this context, we define SGs as parts of the distribution system that can exchange data in real-time.

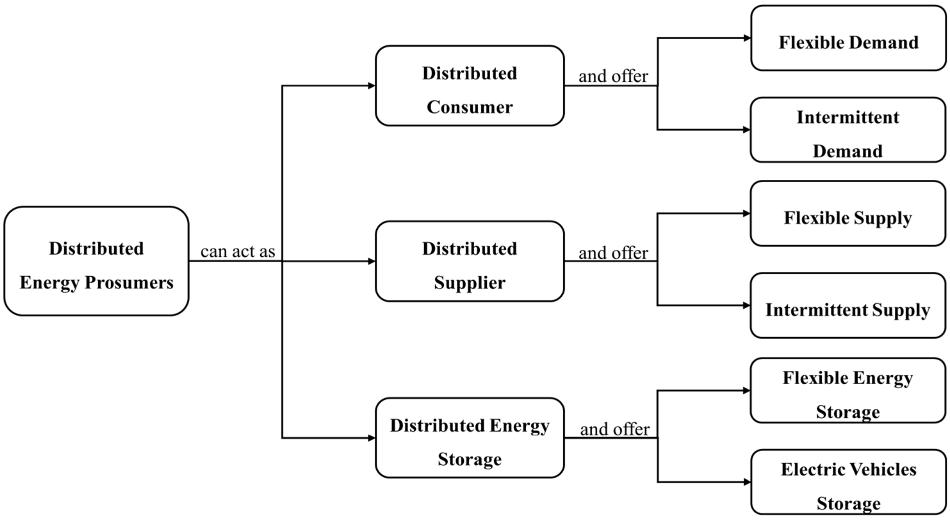

Figure 11: Distributed energy prosumers (own representation based on Li et al. (2016))

It is estimated that investments in SG technologies had reached €3.15 billion in Europe by the end of 2014, underlining their growing significance (Covrig et al, 2014). The impact of SG projects and their suitability for large-scale applications has been investigated, such as by Rodriguez-Calvo *et al.* (2018).

Within SGs the devices of DEPs can be used to provide flexibility by:

- Transferring energy between the energy sectors within the SES
- Controlling the demand, supply and storage behavior of DEPs

The following presentation of outcomes of the content analysis is structured according to the main sectors of the energy system that are discussed in the literature. Within these sectors, the most important technologies and their applications are presented separately. Aside from this analysis of technological potential and challenges, an overview of the economic potential and challenges is provided for the technologies within each sector. The economic potential is evaluated according to different markets (spot and derivatives markets, ancillary markets and local heat markets).

- **Heat sector:** In the following, the most discussed technologies are presented that provide the possibility of coupling the heating/cooling sector directly to the electricity sector.
  - District heating (DH): DH is a system that utilizes a network of pipes for connecting central heat producers with decentral heat consumers locally. DH systems are installed in areas with high special density of heating demand [kWh/m2] or a high amount of industrial surplus heat (Persson *et al.*, 2014). Within the reviewed literature, several heat sources are discussed to feed the DH grid such as combined heat and power units (CHPs), Heat Pumps (HPs), solar and geothermal plants, waste-incineration plants, industrial surplus heat and thermal energy storages (TES) (Lund *et al.*, 2014; Connolly *et al.*,2014). Persson *et al.* (2014) state that the economic potential of DH is to cover 50% of the European heat demand. Moreover, several studies emphasize the importance of radically extending low-temperature DH (50°C-70°C) (Lund *et al.*, 2014; Connolly *et al.*, 2014; Brand and Svendsen, 2013; Fang *et al.*, 2013; Lund *et al.*, 2010; Rezaie and Rosen, 2012). Both low-level DH and conventional DH increase the flexibility of SESs: Once converted from electrical power to heat, energy can be stored and transmitted flexibly between DEPs (Persson *et al.*, 2014; Rezaie and Rosen, 2012; Salpakari *et al.*, 2016). The technological potentials and challenges of DH are summarized in Table 3.
  - Heat pumps (HPs): HPs are devices that use electricity to increase the temperature level of environmental heat. One possible application is the use of

industrial waste heat. HPs can offer flexibility by storing heat in TES and buildings, an approach that makes it possible to shift their electrical loads in time. Nonetheless, the replacement of conventional heating systems by HPs increases the total amount of electrical energy required to a significant extent (Pudjianto et al., 2013). Table 4 provides an overview of the technological potentials and challenges of HP systems.

- Combined heat and power units (CHPs): CHPs are (often small) power plants that simultaneously provide electricity and useful heat. On the basis of their very high overall efficiency, they may play an essential role in decarbonization (Ghavidel *et al.*, 2016). CHPs can be categorized into six major technologies: fuel cells, micro turbines, small steam turbines, sterling engines, reciprocating engines and small gas turbines (Alipour *et al.*, 2014). Many CHPs are currently operated in a heat-driven manner; however, CHPs can provide flexibility to the electrical grid due to a controllable heat-electricity ratio and modulation range. A summary of advantages and drawbacks of CHPs is shown in Table 5.

Table 3: Technological potentials and challenges of district heating within a SES

Potentials	References (Potentials)	Challenges	References (Challenges)
• Cost-effectiveness and low future capital costs	Jiang *et al.* (2014); Lund *et al.* (2012); Persson and Werner (2011)	• Cost-effectiveness in areas with low heating demand density	Persson and Werner (2011)
• Enabling the integration of RES, especially PV • Effective power sink for periods with surplus electricity production • Thermal storage opportunities for load shifting	Connolly *et al.* (2014); Brand and Svendsen (2013), Rezaie and Rosen (2012); Salpakari *et al.* (2016); Persson and Werner (2011); Sayegh *et al.* (2017)	• Requirement of front-end investments • Rarity of appropriate sites in populated areas • Possible emergence of local heating supply monopolies	Rezaie and Rosen (2012)

Table 4: Technological potentials and challenges of heat pumps within a SES

Potentials	References (Potentials)	Challenges	References (Challenges)
• Support of RES integration if controlled flexibly • Support of wind integration even if not controlled flexibly	Lund *et al.* (2014); Hedegaard and Balyk (2013); Hedegaard and Münster (2013); Carmo *et al.* (2014)	• Causation of more frequent and higher peaks • Least-cost operation results in less RES friendliness	Pudjianto *et al.* (2013); Carmo *et al.* (2014); Blarke (2012)
• Load shifting possibilities if operated flexibly • Reduction of required reserve capacity	Hedegaard and Balyk (2013); Hedegaard and Münster (2013)	• Dependency on storage type and size, control strategy and building physics	Hedegaard and Balyk (2013); Carmo at al. (2014); Fischer and Madani (2017)
• Voltage regulation • Increased efficiencies in virtual power plants	Drath *et al.* (2014), Hermann *et al.* (2016), Covrig *et al.* (2014), Persson *et al.* (2014), Brand and Svendsen (2013)	• Suitability limited to low-temperature heat markets in DH	Nastasi and Lo Basso (2016)
• High efficiency • Increased flexibility in DH	Lund *et al.* (2014); Hedegaard and Münster (2013); Blarke (2012); Fischer and Madani (2017); Moura and de Almeida (2010); Kato and Suzuoki (2014)	• Efficiency losses caused by flexible HP operation	Fischer and Madani (2017); Nolting *et al.* (2018)

Table 5: Technological potentials and challenges of CHPs within a SES

Potentials	References (Potentials)	Challenges	References (Challenges)
• Integration of RES	Lund *et al.* (2014); Lund and Mathiesen (2015); Lund *et al.* (2012)	• Not suited for wind power integration	Blarke (2012); Mignard *et al.* (2007)
• Increase in supply security	Ghavidel *et al.* (2016); Alipour *et al.* (2014); Samad and Kiliccote (2012)	• Risk averse operation of CHPs causes less profit through flexibility programs	Alipour *et al.* (2016)
• Voltage and frequency regulation • Reduction of system operation cost • Decrease in grid requirements with decentralized CHPs	Lund *et al.* (2012); Lundström and Wallin (2016); Wolisz *et al.* (2016); Pazouki and Haghifam (2016); Østergaard (2012)		

Table 6: Technological potentials and challenges of TESs within a SES

Potentials	References (Potentials)	Challenges	References (Challenges)
• Support of PV power integration by seasonal TESs • Load shifting, particularly with periodic RES • Increase in the flexibility provided	Lund *et al.* (2014); Salpakari *et al.* (2016); Pudjianto *et al.* (2013); Nuytten *et al.* (2013); Kitapbayev *et al.* (2015); Tehrani *et al.* (2013)	• Less flexibility offered by decentralized TESs • Limited influence on the integration of wind power • Coupling with HPs insignificantly increases flexibility	Hedegaard and Balyk (2013); Carmo *et al.* (2014); Østergaard (2012); Nuytten *et al.* (2013)
• Enhancement of HP efficiency • Reduction of HPs' required size	Pardo *et al.* (2010)	• No cost-effective control	Hedegaard and Münster (2013); Hedegaard *et al.* (2012); Oldewurtel *et al.* (2013)

Table 7: Technological potentials and challenges of P2G within a SES

Potentials	References (Potentials)	Challenges	References (Challenges)
• Integration of RES • Seasonal storage for PV integration	Nastasi and Lo Basso (2016); Sternberg and Bardow (2015); Lund *et al.* (2015); Bocklisch (2015); Jacobson and Delucchi (2011); Connolly *et al.* (2016); Green *et al.* (2011)	• Requirement of further efficiency and cost improvements • Costs of low-carbon electricity • Costs of large-scale hydrogen storage	Lund *et al.* (2015); Götz *et al.* (2016); Dodds *et al.* (2015); Hajimiragha (2007)
• Seasonal load shifting • Reduction of required reserve capacity • Improvements in system cost and efficiency	Bocklisch (2015); Dodds *et al.* (2015)	• Non-existence of hydrogen grid	Nastasi and Lo Basso (2016)

- Thermal energy storages (TESs): TESs are devices that are able to store and transfer the thermal energy of heating or cooling units. Thereby the technology can facilitate the temporal decoupling of heat demand and supply, thus providing flexibility to the SES. One main application is flexible HP control methods. Moreover, buildings can be used as passive TES, generating additional flexibility potential. More detailed information is provided in the following Table 6

- Power to gas (P2G): The term P2G describes technologies that convert electrical energy (e.g., surplus electricity produced by renewables) into chemical energy contained in a gaseous fuel. A suitable technology to convert electricity into hydrogen is the proton exchange membrane electrolysis (Starnberg and Bardow, 2015). Hydrogen can be transported via the existing gas grid to a small extent without affecting conventional combustion. Alternatively, hydrogen can be converted into methane in an additional step. The re-electrification of hydrogen or methane that is produced using electrolysis is seen to be economically infeasible because of very low round trip efficiencies (Lund *et al.*, 2015). P2G is considered as storage technology that is especially well-suited for long-term storage, as no energy losses accrue over time (Breyer *et al.*, 2015). However, extra conversion must be conducted, thus causing efficiency losses. All information on P2G in energy systems that was found in the reviewed literature is summarized in Table 7.

After the technological potential of different technologies within the heating sector was shown above, a condensed analysis of their economic potentials and challenges follows in Table 8.

- **Transport sector:** Within the transport sector, electric vehicles (EVs) constitute the most discussed technology to connect the electricity with the transport sector. The batteries of EVs can provide flexible charging or energy storage. However, the potential of EVs to provide flexible charging rather than to serve as real energy storages is seen higher due to warranty issues (Oldewurtel *et al.*, 2013; Kristoffersen *et al.*, 2011). Industrial car fleets are large enough to exploit the economic potentials of cost-effective EVs (Zhang *et al.*, 2013). For further information, please refer to Table 9.

Again, the economic potentials and challenges as reported in the literature are summarized in the following Table 10.

- **Industrial sector:** According to Aghaei and Alizadeh (2013), industrial and commercial customers are more likely to facilitate flexibility provision than residential consumers. Yet, quality and throughput are top-priority constraints for industrial processes that cannot be affected by the flexibility provision. Industrial electricity consumers are not sufficiently motivated in a financial way to provide flexibility services (Shoreh *et al.*, 2016). Within the industrial sector, the potentials of conventional industry sectors, energy intensive industries and the possibilities based on approaches related to Industry 4.0 must be delineated. The main potentials and challenges in each of these sub-sectors are displayed in the following Table 11.

The review of the economic potentials and challenges within the industrial sector revealed the results as summarized in Table 12.

Table 8: Economic potentials and challenges of different technologies within the heat sector

Technology	Market	Potentials and Challenges	References
Heat Pumps	Spot Markets	• Non-cost-effectiveness of investments in flexible operation	Hedegaard and Münster (2013)
	Ancillary Markets	• Higher efficiency than conventional balancing methods • Operation in virtual power plants possible	Hedegaard and Münster (2013); Wang *et al.* (2012); Oldewurtel *et al.* (2013); Vrettos and Andersson (2016); Biegel *et al.* (2014); Papaefthymiou *et al.* (2012)
	Local Heat Market	• Participation in low-temperature markets • Possibility of coupling with CHP	Jiang *et al.* (2014); Lund *et al.* (2014); Salpakari *et al.* (2016); Hedegaard and Balyk (2013)
Combined Heat and Power Units	Spot Markets	• Participation possible for all CHP sizes	Lund *et al.* (2014); Lund *et al.* (2012); Alipour *et al.* (2016); Streckienė *et al.* (2009)
	Ancillary Markets	• Provision of automatic primary reserve possible • Low investment costs for participation in primary reserve market	Lund *et al.* (2014); Houwing *et al.* (2008); Alipour *et al.* (2014); Lund *et al.* (2012)
	Heat Market	• Participation in high-temperature markets possible • Support of operation of DH by decentralized CHP	Lund *et al.* (2014); Lund and Mathiesen (2015); Lundström and Wallin (2016); Kitapbayev *et al.* (2015); Tehrani *et al.* (2013)

Table 8: Economic potentials and challenges of different technologies within the heat sector (continued)

Technology	Market	Potentials and Challenges	References
Thermal Storages	Local Heat Market	• Hot water tanks for central storage	Salpakari *et al.* (2016); Hedegaard and Balyk (2013); Nuytten *et al.* (2013); Kitapbayev *et al.* (2015)
Power to Gas	Ancillary Markets	• Provision of regulation reserve on annual and hourly markets	Breyer *et al.* (2015); Green *et al.* (2011)
	Local Heat Market	• Usage for DH with central hydrogen storage	Bocklisch (2015)

Table 9: Technological Potentials and Challenges of Electric Vehicles

Potentials	References (Potentials)	Challenges	References (Challenges)
• Low storage losses • High storage capacities	Mwasilu *et al.* (2014); Zhang *et al.* (2013); Tie and Tan (2013); Dallinger *et al.* (2013)	• Posing of battery guarantee issues and social burden	Oldewurtel *et al.* (2013); Zhang *et al.* (2013); Dallinger *et al.* (2013)
• Participation in building energy management systems • Avoidance of investment costs through fleet storage	Weiller and Neely (2014); Antunes *et al.* (2013)	• Essential need for wide-spread charging infrastructure • Necessity of "critical mass" of EVs • Further optimization of EV charging required	Oldewurtel *et al.* (2013); Weiller and Neely (2014); Mwasilu *et al.* (2014)
• Integration of RES through flexible charging demand • Load shifting	Mwasilu *et al.* (2014); Ipakchi and Albuyeh (2009); Wang *et al.* (2011); Rotering and Ilic (2011); Dallinger *et al.* (2013); Pillai *et al.* (2011); Borba *et al.* (2012)	• Need for standards for software and communication networks • Privacy issues due to data submission	Oldewurtel *et al.* (2013); Weiller and Neely (2014); Mwasilu *et al.* (2014)
• Compensation of wind fluctuations	Streckienė *et al.* (2009)		
• Voltage control and frequency regulation • Reduction of grid ramp rates • Increase in grid efficiency	Mwasilu *et al.* (2014); Dallinger *et al.* (2013); Pillai *et al.* (2011)	• Coincidence of direct charging demands and system peak load • Increased peak load by maximization of range • Rise of grid capacity requirements by extra demand	Pudjianto *et al.* (2013); Mwasilu *et al.* (2014); Zhang *et al.* (2013); Dallinger *et al.* (2013)

Table 10: Economic potentials and challenges of electric vehicles (EVs)

Market	Potential and Challenges	References
Spot Markets	• Achievement of "critical mass" (500 - 1000 EVs) necessary	Oldewurtel *et al.* (2013); San Román *et al.* (2011); Schäuble *et al.* (2017)
Ancillary Markets	• Provision of direct load control • Valuable resources for secondary balancing power	Oldewurtel *et al.* (2013); Lund *et al.* (2015); Weiller and Neely (2014); Mwasilu *et al.* (2014); Koohi-Kamali *et al.* (2013); Ipakchi and Albuyeh (2009); Wang *et al.* (2011); Rotering and Ilic (2011)

Table 11: Potentials and challenges of different areas of the industrial sector

Sub Sector	Potentials	References (Potentials)	Challenges	References (Challenges)
Conventional Industry	• Integration of RES via flexible demand • High flexibility potential, although fewer in number than the residential sector	Aghaei and Alizadeh (2013); Shoreh *et al.* (2016)	• Electricity is bought with long term fixed prices • Electricity price risk is financially hedged • Ambition to run production on a continuous basis	Lund *et al.* (2015); Bröckl *et al.* (2011)
	• Possible avoidance of grid security measures by "load shedding"	Praktiknjo (2016)		

Table 11: Potentials and challenges of different areas of the industrial sector (continued)

Sub Sector	Potentials	References (Potentials)	Challenges	References (Challenges)
Energy Intensive Industry	• Cost-effectiveness of shifting production in time	Torriti *et al.* (2010)	• Balancing services compete with storage and residential demand side management	Paulus and Borggrefe (2011)
	• Load shifting • Cost-effective without reduction of quality and throughput • Potential of covering 50% of tertiary reserve market	Alcázar-Ortega *et al.* (2012); Rodríguez-García (2016); Babu and Ashok (2008); Paulus and Borggrefe (2011)	• Processes have critical temporal dependencies	Samad and Kiliccote (2012); Li *et al.* (2012)
			• Throughput is the constraint with the highest priority • Necessity of accurate throughput risk evaluation tool • Lack of energy control module within most systems	Alcázar-Ortega *et al.* (2012)
Digitized Industrial Sectors (Industry 4.0)	• Cost-effectiveness of increasing flexibility by additional storage • Significant peak-load reduction through inventory storage	Samad and Kiliccote (2012); Keller *et al.* (2014); Fernandez *et al.* (2013); Wang and Li (2013)	• Necessity of real-time decision making • Need for online data access • Progress of real-time implementation lags far behind	Li *et al.* (2012)
			• Mainly positive reserve capacity	Paulus and Borggrefe (2011)
	• Flexible shut down without affecting throughput	Wang and Li (2013)		

Table 12: Economic potentials and challenges within the industrial sector

Technology	Market	Potentials and Challenges	References
Conventional Industry	Local Heat Market	• Feed-in of waste heat	Lund *et al.* (2014); Salpakari *et al.* (2012)
Energy Intensive Industry	Spot Markets	• Provision of load shedding	Paulus and Borggrefe (2011)
	Ancillary Markets	• Participation in tertiary market • Direct load control is unsuitable • High investments for participation in primary and secondary reserve markets	Samad and Kiliccote (2012); Shoreh *et al.* (2016); Rodríguez-García *et al.* (2016); Paulus and Borggrefe (2011)
Digitized Industrial Sectors (Industry 4.0)	Spot Markets	• Short-term production planning for balancing day-ahead trades	Keller *et al.* (2014)
	Ancillary Markets	• Participation in secondary and minute reserve is profitable • Real-time production management for ancillary markets	Rodríguez-García *et al.* (2016)

4 Discussion

In the following paragraphs, we discuss and contrast our results against the background of the related literature (Nolting *et al.*, 2019).

In the quantitative part of this review, we locate experts and institutions that contribute in the intersection of energy system analysis and Industry 4.0. Thereby, we amend the focus of Nolting *et al.*(2019), as they have solely focused on generating transparency with regard to Industry 4.0. Demonstrating GIS-based visualizations of key players that conduct research on (digitized) industrial processes within a future SES, we provide further insights.

Regarding the content-based, qualitative part of our review, we contribute to the scientific discussion by further enhancing the focus and providing a more extensive overview. While existing reviews have focused on single technologies such as the operation and implementation of SGs (Camarinha-Matos, 2016; IqtiyaniIlham *et al.*, 2017; Leiva *et al.*, 2016; Zhou *et al.*, 2016; Anjana and Shaji, 2018), possible applications for heat pumps in future energy systems (Fischer and Madani, 2017; Chua *et al.*, 2010), the assessment of different storage technologies to provide sustainable energy (Koohi-Kamali *et al.*, 2013; Akinyele and Rayudu, 2014; Gallo *et al.*, 2016; Zakeri and Syri, 2015; Zhao *et al.*, 2015; Acar, 2018; Rosen and Dincer, 2003; Liu *et al.*, 2018), or district heating systems (Perez-Mora, 2018), our contribution is to provide a structured overview about ongoing discussions on the potentials and challenges of different technologies and different market applications. We thereby provide a comprehensive summary regarding the current state of the art at the intersection of Industry 4.0 and technologies in a future SES as analyzed by ESA.

In terms of methodology, our approach differs from already published reviews not only in the breadth of content, but also in the structured, keyword-based approach that guarantees the reproducibility of our results. Additionally, the combination of GIS-based visualizations to locate experts in the field with a content-based, qualitative review has not yet been published by other authors to the best of our knowledge. Therefore, we provide a unique framework to connect experts in the field with state-of-the-art research. Further, our techno-economic approach to assessing both technological and economic potentials and challenges for future SESs enhances the common technological focus of reviews regarding future energy systems.

5 Conclusion

Within this manuscript, we derived an approach to conducting a systematic, keyword-based and therefore transparent literature review guaranteeing: (1) a high-quality literature basis; and thereby (2) high quality results. We then applied this approach to topics related to the intersection of ESA and Industry 4.0. The corresponding literature was analyzed quantitatively to determine and visualize scientific experts and qualitatively to summarize the current state of the art in the corresponding fields of research. Thereby, our review creates transparency within the analyzed fields of literature.

In terms of the locations of scientific experts, our results indicate that key players with regard to publications within the intersection of ESA and Industry 4.0 are to be found within Europe. At European level, the United Kingdom emerges as main contributor. Zooming-in on the German national scale, we find North Rhine-Westphalia to be the most prolific area and Aachen/Dortmund to be the cities with the most publications. Applying the modified search terms, the perception of a European leadership regarding scientific publications in the corresponding field of research grows. Considering the Industry 4.0 search term (i.e., the explicit usage of the term “Industry 4.0” or its German equivalent “Industrie 4.0” within title, abstract or keywords), the international leadership of German institutes within this research area becomes apparent. This finding corresponds to the results reported by Nolting *et al.* (2019).

Focusing on the content-based analysis, we can state that the intersection of industry 4.0 and ESA covers different fields of research. We show that in particular the provision of flexibility by means of sector-coupling and the integration of DEPs can lead to a working smart energy system. We further demonstrate that industrial digitalization processes in the sense of Industry 4.0 can serve as an enabling factor in this respect. Most of the studies investigated are not limited to industrial processes per se, but rather show the potential and challenges connected to single technologies within different market applications.

From the sheer amount of discussions shown in Section 3, as well as from the partly opposing results regarding the challenges and potentials of different technologies within recently published literature, a compelling necessity for further research within the corresponding areas can be concluded. In particular, research evaluating the potential of Industry 4.0 processes to provide flexible demand has not yet been covered extensively, as many authors in the field of energy system analysis tend to focus on non-industrial processes. Our results indicate that the challenges and potentials for different technologies to contribute to a future smart energy system with flexible industrial processes highly depends on the underlying market mechanisms. Thus, future research on potential business models that enable (digitized) industries to provide flexibility in a profitable way needs to be conducted.

Combining the results of the qualitative and quantitative approach, we provide a framework of key players and highly discussed research topics that can help identify scientific experts at the intersection of ESA and Industry 4.0. The knowledge of these experts will be required to close existing research gaps in the near future.

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