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A B S T R A C T

The conscientious use of energy progressively gains importance in society and the pressure on manufacturing companies to use energy more efficiently increases from an economical, ecological, and social perspective. Since on-site energy conversion has been identified as a measure to increase energy efficiency, manufacturing companies often operate on-site energy conversion systems (ECS) to provide the energy required by their production processes. These production processes cause (strongly) varying energy demands, which can have a huge negative influence on the efficiency of an insufficiently designed ECS. This reason combined with the various design possibilities and the high complexity of ECS design in general, lead to numerous publications addressing specific ECS design problems. These numerous publications make it laborious to identify adequate design approaches for individual application cases, especially due to the lack of an established research framework for this area. Therefore, we present a concept-centric ECS design framework (ECSDF) to classify existing and upcoming publications about the design of on-site ECSs for manufacturing companies. The introduced ECSDF enables the identification of relevant design approaches from an industrial perspective, the identification of opportunities for future research from a scientific perspective, and unifies the understanding of the crucial ECS design aspects in general.

Keywords:
Energy conversion system
On-site
Classification
Research framework
Manufacturing

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1. Introduction

The conflict between globally rising energy demands (Upadhyay and Sharma, 2014) with the inherently scarce resources for demand fulfillment (Gahm et al., 2016) and continuously increasing fuel costs (Al Moussawi et al., 2016) calls for action. With the industrial sector being one of the main users of energy in the European Union (Eurostat, 2019), manufacturing companies have an immense impact on the global energy usage. This results in a great responsibility for manufacturing companies to use energy conscientiously. With energy as a non-substitutable and indispensable production factor (Gahm et al., 2016), it is vital to use energy as efficiently as possible to preserve resources from an ecological perspective and to save costs from an economical perspective.

Regarding energy provisioning in general, decentralized on-site energy conversion (for example by cogeneration and trigeneration systems) has been identified as one of the main measures to improve energy efficiency (cf., e.g., Liu et al., 2014 or Keshavarzzadeh et al., 2020). Other measures are for instance, general energy saving measures (Abdelaziz et al., 2011), the usage of renewable energy sources (Bukar and Tan, 2019), or efficiency increases for installed ECSs (Rashid et al., 2019). To fully benefit from the efficiency potentials of on-site energy conversion, energy conversion systems (ECSs) have to be accurately designed under consideration of the most relevant design parameters (e.g., size, system type, energy sources, operational range, …) as these parameters have an immense influence on an ECSs overall efficiency (Ghadimi et al., 2014). This influence on the overall efficiency increases even drastically, when the applied energy sources demand is varying over time (Yokoyama et al., 2002). Thus, regarding the ECS's efficiency, an accurate design is especially important for on-site ECS in manufacturing companies as their energy demands vary strongly depending on the operation of their production system.

To accurately design a highly efficient and individualized on-site ECS for a manufacturing company, the state-of-the-art of this research field should be taken into account. But in the current literature, the considered parameters have become more and more diversified (Yokoyama et al., 2015) and the increasing number of proposed ECS design approaches focus on various different aspects. Therefore, the identification of the most related ECS design approaches for a specific design problem is a great challenge. To essentially support researchers and decision makers in this, we propose a new research framework to classify existing and upcoming ECS design approaches in a concept-centric manner (i.e., structured in categories (logical groups) (Webster and Watson, 2002)). The main goal of the concept-centric ECS design framework (ECSDF) is to define a domain specific ontology in the context of ECS design to enable subsequent concept-centric literature reviews and the evaluation of design approaches on a conceptual level.

The values added by our proposed ECSDF are manifold. The ECSDF

- builds a knowledge base for decision makers to identify relevant design approaches.
- facilitates the search within existing design approaches.
- comprises the most relevant aspects to be considered by ECS design approaches (for manufacturing companies) and helps to analyze and structure individual planning problems.
- forms the base for empirical analyses of the research field.
- can disclose research gaps and provide insights for future research.

As this paper focuses on the development of the ECSDF, it is not going to provide a review or classification of the existing ECS design literature. Note that the ECSDF is tailored on ECS designs for manufacturing companies by considering the complex relation of their energy demanding production system and the energy providing ECS. Thus, the ECSDF is most likely to be transferable to other company types or application areas but adaptations may be necessary.

The paper is organized as follows. Section 2 contains an analysis of literature reviews and related work conducted in the research field. Afterwards, section 3 describes in detail the methodology applied for the development of the new concept-centric ECSDF. Then, section 4 defines and elaborates the categories and attributes of the framework. Section 5 concludes the article.

2. Related work

In literature, the dimensioning of on-site ECS for manufacturing companies is continuously discussed. Besides complex solutions for individual planning problems, authors review existing literature to analyze and structure design approaches and to simplify the finding of adequate literature (Cho and Lee, 2014). During our performed structured literature search, we identified 32 reviews and frameworks on the design and operation of on-site ECSs. These reviews/frameworks mainly focus on specific aspects. Therefore, they can be distinguished in reviews/frameworks on design- and/or operation-based ECS approaches, on ECS configuration possibilities, on specific types of ECS with different energy sources as input (e.g., cogeneration, or trigeneration systems with renewable or hybrid renewable energy sources), and on applied methodologies (e.g., solution methods) for different ECS types with different energy sources. In the following we summarize and differentiate existing reviews and frameworks about on-site ECS design and carve out the necessity of our concept-centric framework.

Some reviews distinguish between design-based, operation-based, and design-and-operation-based ECS approaches. Note, that for the design of an ECS mainly the design-based and design-and-operation-based ECS approaches are relevant, but for the sake of completeness, the determined operation-based reviews will also be briefly discussed here. O'Brien and Bansal (2000) focus on a design-based approach and additionally classify the existing literature according to the three basic types. A pure design-based review is provided by Biezma and Cristóbal (2006). It focuses on the economical view of ECS design and presents objectives used to optimize the selection of cogeneration systems. This review is exclusively about economic objectives and neglects other design aspects. In contrast, other reviews focus strictly on the operation-based approaches. Padhy (2004) published a survey on the unit commitment problem in the power industry and gives an overview of the operational characteristics of ECSs. Another review on the operation of ECSs was published by Xia and Elaiw (2010), in which they focus on the difference between two operational strategies. Additionally, both Xia and Elaiw (2010) as well as Padhy (2004) analyze applied solution methods. Furthermore, Cho et al. (2014) published an operation-based review on performance improvements and optimization of ECSs in form of combined cooling, heating, and power systems. Herein, they name publications on adequate ECS design and focus on the enhancement of already existing ECSs.

Regardless of whether approaches are design-based or design-and-operation-based, some reviews differentiate approaches according to their components (e.g., types of conversion units) and configuration possibilities. For example in order to adequately design an ECS, Cho and Lee (2014) classify energy conversion systems according to their components. Similar to that, but with a defined focus on trigeneration plants, Al-Sulaiman et al. (2011) and Jradi and Riffat (2014) conduct a review related to their installed prime movers and corresponding selection criteria. Hereby, Jradi and Riffat (2014) further investigate system configurations and the latest operational strategies.

A third group of reviews focuses on specific types of ECSs (e.g., cogeneration or trigeneration systems). For instance, Liu et al. (2014) provide a literature survey addressing cogeneration and trigeneration systems. The survey comprises ECS types, CU types, operational strategies, and optimization methods for the sizing of cogeneration systems. Liu et al. (2014) depict the identified CU types and give a textual summarization of the identified solution methods. Al Moussawi et al. (2016) published a concept-centric review about trigeneration technologies. Within this framework, the authors focus on trigeneration systems and use the classification categories prime movers, CU types, energy storage systems, and heat recovery systems. They provide information about all possible combinations of the elements of these categories. Furthermore, the authors give an overview of solution methods used for trigeneration system design. Al Moussawi et al. (2017) published a continuing review, which emphasizes the importance of the distinction between cogeneration and trigeneration systems during the design process as well as the differences between cogeneration and trigeneration CUs. Additionally, Al Moussawi et al. (2017) provide a selection table to choose adequate CUs depending on specific, application case related parameters.

Not only cogeneration and trigeneration systems are discussed in reviews, but also energy systems with renewable or hybrid renewable energy sources as input, called renewable or hybrid renewable energy system (RES/HRES). For example, Upadhyay and Sharma (2014) published a review on the configurations, operation, and design methodologies of hybrid systems. They classify according to four aspects that need to be considered during the design and implementation of hybrid energy systems: configuration, evaluation criterions, sizing methodologies, and operational strategies. Similar to Upadhyay and Sharma (2014), Al-Falahi et al. (2017) provide a review on optimization methodologies for the sizing of HRES. They consider three aspects which comprise the configuration, the assessment parameters (comparable with goals and objectives) and sizing methodologies found in literature. For each aspect they provide an extensive concept-centric overview.

Next to the different system types, a widely analyzed topic in reviews are the applied solution methods for solving the ECS design (decision) problem. Regarding energy systems in general, Bazmi and Zahedi (2011) published an author-centric literature review about the role of optimization modeling techniques in power generation. They summarize the content of each considered author's publication in the energy and power sector as well as for decentralized energy generation systems. Zeng et al. (2011) conducted a textual author-centric review about the optimization of energy system planning and greenhouse gas emission mitigation under uncertainty through the application of inexact optimization modeling methods and model-based decision support tools. Bargos et al. (2018) examined computational tools and operations research methods for the design and optimization of industrial cogeneration systems. Frangopoulos (2018) analyzed the current state, recent trends, and challenges in sizing and operation methods of energy systems in general.

Next to solution methods for ECS in general, also solution methods related to RES and HRES are subjects of reviews. Baños et al. (2011) provide a literature review on applied solution methods in the context of RES. To that, they structure their review according to the types of renewable primary energy sources (PES; e.g., wind power or solar energy) and provide a text-based and author-centric listing for each type of PES. Similar to that, but in a concept-centric manner, Iqbal et al. (2014) examine RES with respect to different types of renewable PES, and additionally investigate different modes of operations and types of objective functions. In contrast to an overview of diverse PES as input Yilmaz and Selim (2013) published a review on methods of HRES design that are specialized on ECS that especially include biomass as energy source. Regarding solution methods on optimum design of HRESs, Erdinc and Uzunoglu (2012), Luna-Rubio et al. (2012), and Chauhan and Saini (2014) published reviews on sizing methods applied on HRESs in general, whereas the reviews of Zhou et al. (2010), Sinha and Chandel (2015), Khare et al. (2016), and Bukar and Tan (2019) are specialized on the current state and recent trends of optimum sizing methods specifically applied for wind and photovoltaic based HRESs. Additionally to the sizing methodologies, Sinha and Chandel (2015) and Khare et al. (2016) provide an overview of operation optimization techniques, whereas Bukar and Tan (2019) added a fuel cell to their stand-alone photovoltaic-wind energy systems and investigated the latest developments in operational strategies. Furthermore, Khare et al. (2016) included reliability aspects into their review. Also concerning solution methods for specific renewable systems, Scott et al. (2012) focus on multi-criteria decision making for bioenergy systems, Lin et al. (2014) study wind power ECSs and reliability based

Table 1
Investigated aspects of existing reviews and frameworks.

Reviews & frameworks	Considered aspects											
	Design of ECS	Operation of ECS	ECS configuration	Cogeneration systems	Trigeneration systems	HRES	RES	Restricted by specific ECS/PES	Solution methods	Objectives of design	Reliability aspects	Interdependencies with Production system
Al-Falahi et al. (2017)	x		x			x			x	x		
Al-Sulaiman et al. (2011)	x		x		x							
Al Moussawi et al. (2016)	x		x		x				x			
Al Moussawi et al. (2017)	x		x	x	x							
Bahramara et al. (2016)	x					x			x			
Baños et al. (2011)	x						x		x			
Bargos et al. (2018)	x	x		x					x			
Bazmi and Zahedi (2011)	x								x			
Biezma and Cristóbal (2006)	x									x		
Bukar and Tan (2019)	x	x				x		x	x			
Chauhan and Saini (2014)	x					x			x			
Cho and Lee (2014)	x	x	x									
Cho et al. (2014)		x			x					x		
Erdinc and Uzunoglu (2012)	x					x			x			
Eriksson and Gray (2017)	x	x				x		x		x		
Frangopoulos (2018)	x	x							x	x		
Iqbal et al. (2014)	x	x					x		x			
Jradi and Riffat (2014)	x	x	x		x							
Khare et al. (2016)	x	x				x		x	x		x	
Khatib et al. (2016)	x		x					x		x		
Lin et al. (2014)	x							x	x		x	
Liu et al. (2014)	x	x	x	x	x				x			
Luna-Rubio et al. (2012)	x					x			x			
O'Brien and Bansal (2000)	x	x										
Padhy (2004)		x							x			
Scott et al. (2012)	x	x						x	x	x		
Sinha and Chandel (2015)	x	x				x		x	x			
Upadhyay and Sharma (2014)	x	x	x			x			x	x		
Xia and Elaiw (2010)		x							x			
Yilmaz and Selim (2013)	x					x		x	x			
Zeng et al. (2011)	x								x			
Zhou et al. (2010)	x					x		x	x			
ECSDF	x	x	x	x	x	x	x				x	x

system planning, and Khatib et al. (2016) concentrate on technical, economic, and social objectives for photovoltaic systems with batteries. In comparison to the reviews just mentioned, Bahramara et al. (2016) reversed the review process and investigate publications which apply one specific optimization method (the software HOMER) for the design of any HRES.

Other reviews do not focus on applied solution methods but on specific ECS types and their representation in literature. Eriksson and Gray (2017) for instance critically review current approaches on design and optimization of HRES with a hydrogen fuel cell and propose criteria addressing economical and socio-political design objectives. In Table 1, all previously discussed reviews and frameworks on ECS design are depicted with regard to their addressed aspects. For the sake of completeness, the last row allows a comparison of all reviews/frameworks with our proposed ECSDF.

Summarizing, most of the discussed publications are reviews with a very specific focus (e.g., certain aspects or types of ECSs) and lack a general applicability and a comprehensive consideration of all relevant aspects crucial for ECS design. In addition, the specific requirements of manufacturing companies are hardly considered. This means, to the best of our knowledge, there is no appropriately comprehensive concept-centric framework supporting an accurate ECS design for manufacturing companies. This confirms the need for our new ECSDF in order to facilitate the search for adequate literature and to analyze and structure design approaches and problems. Of course, concepts, aspects, categories, etc. that are used by the previously described reviews are analyzed and incorporated into our framework whenever appropriate. In the last row of Table 1, the uniqueness and the completeness of our developed ECS design framework is emphasized. Note that the ECSDF concentrates on the ECS related aspects but not on solution methods or objectives because these aspects are not necessarily ECS related. Of course, when conducting a literature review, these aspects should also be considered.

The complete methodology for the development of our ECSDF is described in the following section.

3. Methodology and literature scope

The methodology to develop the ECSDF follows a combination of recommendations on literature reviews and the development of research frameworks from Salipante et al. (1982) and Gahm et al. (2016) (which itself is based on the processes proposed by Webster and Watson (2002), Seuring and Müller (2008), and Vom Brocke et al. (2009)). According to these authors, literature should be categorized concept-centric instead of author-centric, because an author-centric categorization fails to analyze the literature systematically, whereas a concept-centric categorization structures literature in a research area in logical groups (Webster and Watson, 2002). For this reason, the concept-centric design of a research framework should be understood as a minimum requirement, which is also considered in the design of our ECSDF.

For the development of the ECSDF for manufacturing companies, the current state of science has to be considered by a comprehensive literature sample (because we cannot guarantee that all high-quality articles are considered, it is always a sample). To determine a comprehensive literature sample, we follow the iterative research procedure of Gahm et al. (2016) (cf., Fig. 1).

Note, that the steps II., III., and VI. of the research process are slightly adapted compared to Gahm et al. (2016): phase II. and VI. were renamed and in phase III., the identified publications from the forward search are additionally considered within the backward search process. Following a defined and structured research procedure proofs the credibility of the review due to its transparency (Vom Brocke et al., 2009) and ensures the objectivity of the research process (Seuring and Müller, 2008).

3.1. *Definition of scope and purpose*

First, the thematical scope of the research field and thus, of the literature sample for the development of the ECSDF must be defined. To that, a clear definition of the research field covered by the literature sample and the framework is set up. Based on this definition, a guideline for the relevance assessment of journals and articles is defined (further referred to as *scope and purpose criteria*).

3.1.1. *Definition of the research field*

To define the research field of the ECSDF, we start with an analysis of the possibilities of energy procurement for manufacturing companies. Regarding energy procurement in general, Rager et al. (2015) and Gahm et al. (2016) describe three main procurement cases (A, B, and C) together with the relevant systems and entities, which are depicted in Fig. 2 and described in the following.

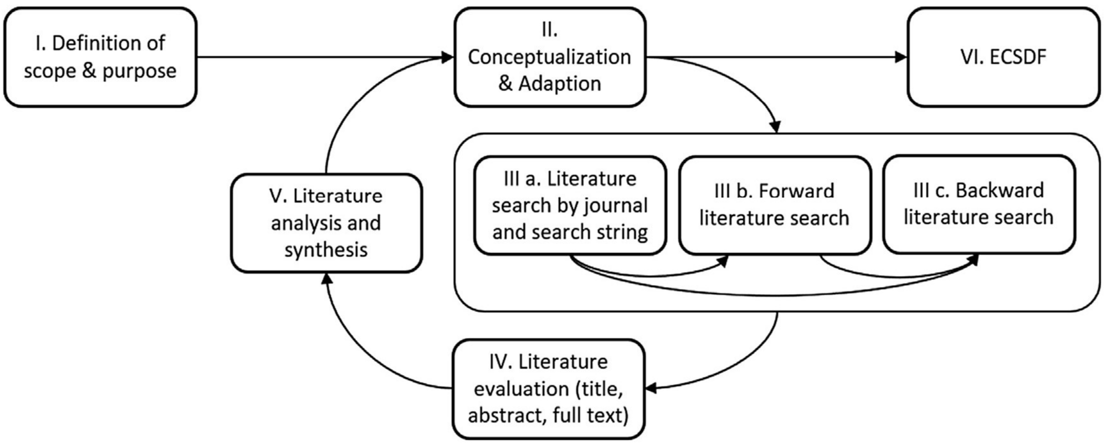

Fig. 1. ECSDF development based on a structured literature search.

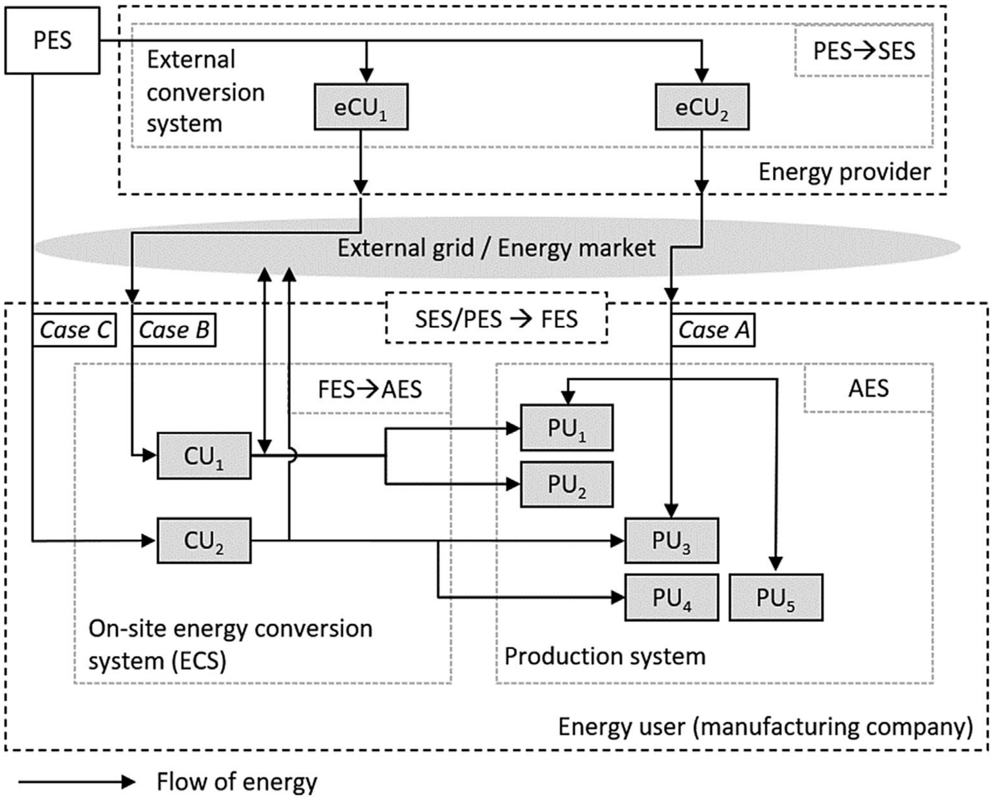

Fig. 2. Procurement of energy sources in manufacturing companies - relevant systems and entities.

Energy is transported or stored by energy sources (also called energy carriers). Energy providers transform primary energy sources (PES) (e.g., solar or wind energy) with external conversion units (eCU) into secondary energy sources (SES) (e.g., power). At the moment the ownership of SES is transferred to the energy user (the manufacturing company), they are referred to as final energy sources (FES).

These FES can either be directly used as applied energy sources (AES) by the production units (PUs) of a manufacturing companies' production system (cf., Case A: flow of energy from eCU_2 to PU_1, PU_3, or PU_5 in Fig. 2) or need to be converted before being applied. In the latter case, the FES is the input for an on-site energy conversion system's conversion unit (CU). Hereby, an ECS can comprise an individual number of CUs. The CUs convert the FES into the desired AES before it can be used by production units (cf., Case B: flow of energy from eCU_1 over CU_1 to PU_1 and PU_2 in Fig. 2). Additionally, the flow via an external conversion system can be avoided by using the PES directly as input for an on-site CU. In this case the PES serves as FES and is directly converted into the AES (cf., Case C: flow of energy from CU_2 to PU_3 and PU_4 in Fig. 2). In addition, the ECS can interact with the external grid and/or energy market. Our ECSDF classifies and structures approaches, which design ECS for manufacturing companies as in cases B and C.

3.1.2. Scope and purpose criteria

Based on the definition of the research field, the *scope and purpose criteria* for the journal and article selection is defined in this section.

The focus of the ECSDF is on the design of ECS and therefore, only publications dealing either with the design or with the design and operation of ECSs are relevant. Consequently, articles dealing exclusively with the operation of ECSs (e.g., the energy flow, inlet pressure, or operational temperature of CUs) are excluded. Furthermore, to focus on the ECS design for manufacturing companies, an article is considered as relevant when it designs on-site ECSs in a manufacturing context (for a definition of the

Table 2
Considered sub-areas and sub-categories for journal selection.

Sub area	Sub category
Energy	Energy Engineering and Power Technology (En. Eng. & Pow. Tech.)
	Energy (miscellaneous) (En.)
	Renewable Energy, Sustainability and the Environment (Ren. En. Sust. & Environ.)
Engineering	Electrical and Electronic Engineering (Electri. & Electro. Eng.)
	Engineering (miscellaneous) (Eng.)
	Industrial and Manufacturing Engineering (Ind. & Manu. Eng.)
	Mechanical Engineering (M. Eng.)

Table 3
Reviewed journals and identified relevant articles (State: May 2020).

Journal name (initial hits search string search)	SJR index and quartile of sub-categories: SJR-Index	En. Eng. & Pow. Tech.	En.	Ren. En. Sust. & Environ.	Electri. & Electro. Eng.	Eng.	Ind. & Manu. Eng.	M. Eng.	Articles identified by: Keyword search	Forward search	Backward search	Total
Applied Energy* (47)	3,61	Q1	Q1					Q1			2	2
Applied Thermal Engineering* (18)	1,78	Q1					Q1				4	4
Chemical Engineering Science	1,00						Q1				2	2
Computers and Chemical Engineering	1,00									3	5	9
Desalination	1,81							Q1			2	2
Energy* (58)	2,17		Q1		Q1		Q1	Q1	2		3	6
Energy Conversion and Management* (44)	2,92	Q1		Q1					3	2	1	6
IEEE Transactions on Industry Applications* (10)	1,50				Q1		Q1		1			1
International Journal of Hydrogen Energy* (33)	1,14	Q1		Q2					1	3	2	6
Journal of Cleaner Production* (18)	1,89			Q1			Q1			1		1
Renewable & Sustainable Energy Reviews* (7)	3,63			Q1						1		1
Renewable Energy* (32)	2,05			Q1					1	2	1	4
Solar Energy* (9)	1,54			Q1						2		2
Computers & Industrial Engineering* (2), Electric Power Systems Research* (4), Energy & Environmental Science* (5), Energy Economics* (3), Energy for Sustainable Development* (0), Energy Journal* (0), Environmental Research Letters* (2), Experimental Thermal and Fluid Science* (0), IEEE Journal of Emerging and Selected Topics in Power Electronics* (1), IEEE Journal of Photovoltaics* (0), IEEE Power & Energy Magazine* (0), IEEE Transactions on Energy Conversion* (9), IEEE Transactions on Industrial Electronics* (14), IEEE Transactions on Power Delivery* (5), IEEE Transactions on Power Electronics* (8), IEEE Transactions on Power Systems* (21), IEEE Transactions on Sustainable Energy* (14), IET Generation, Transmission & Distribution* (8), IET Power Electronics* (2), IISE Transactions* (1), International Journal of Electrical Power & Energy Systems* (17), International Journal of Engineering Science* (1), International Journal of Heat and Mass Transfer* (7), International Journal of Production Economics* (1), International Journal of Production Research* (4), International Journal of Thermal Sciences* (2), Journal of Modern Power Systems and Clean Energy* (0), Journal of Operations Management* (0), Nano Energy* (4), Nonlinear Analysis: Real World Applications* (0), Production and Operations Management* (0), Production Planning & Control* (0), Progress in Energy and Combustion Science* (0), Progress in Photovoltaics* (0), Solar Energy Materials and Solar Cells* (3), Sustainable Energy Technologies and Assessments* (3), Journal of the Energy Institute* (0)												
Total									8	14	22	44

corresponding industrial sector see section C in United Nations, Department of Economic and Social Affairs, 2008). Consequently, commercial energy production at energy providers; the design and operation of the central grid, its layout, or extensions; and publications on on-site ECSs of city districts and public or private buildings (e.g., administrative offices, hospitals, or households) are excluded. Note, that the ECSDF can be suitable for non-industrial ECS design contexts with similar constraints as in the case of manufacturing companies (e.g., varying energy demands). Furthermore, the mere installation of an energy storage system is not part of the literature sample. Also, publications which have an ECS as a production system (which coincidentally can be an ECS; e.g., a hydrogen production system), are excluded.

3.2. Conceptualization

The iterative part of the research process starts with step II. (Conceptualization & Adaption). During the first iteration of the conceptualization phase the topic of interest is investigated in general. Hereby, a deduction of the first categories and attributes of the ECSDF while analyzing existing reviews and literature of previous publications is undertaken (like proposed by Salipante et al., 1982, Webster and Watson, 2002, and Seuring and Müller, 2008). This results in a first version of the ECSDF.

Further results of the first conceptualization phase are the definition of the scope of journals to investigate and the definition of the keywords (in order for the search procedure to be reproducible).

The definition of the scope of journals is based on the “SCIMAGO Journal & Country Rank”, which provides the SJR-Index. The SJR-index is a number-based score for journals measuring the impact or prestige of its articles (Guerrero-Bote and Moya-Anegón, 2012). The journal selection is based on a journal ranking, because journal rankings identify high-quality journals and, according to Webster and Watson (2002), the most important publications are found in the most renowned journals. In addition to a journal ranking, the

SJR provides sub-areas and sub-categories classifying journals with similar topics.

Within the sub-areas and sub-categories selected for this review (cf., Table 2), we assume that the most quality research is published in scientific journals and thus, exclude books, theses, conference proceedings and trade journals (as done by Rubio et al., 2008 and Gahm et al., 2016). All investigated journals are published in the English language, peer reviewed, and rated with an SJR-index greater than 1 to assure an adequate quality (further revered to as *journal criteria*). Subsequently, journals are excluded if they do not fit the topic according to the scope and purpose criteria (cf., section 3.1) considering their title, contents, and main focus. Finally, 47 appropriate journals have been identified for the aspired literature search. The journals identified in this process phase are listed in Table 3. Next to the journal selection, also the keywords were determined. The complete combination of journals and keywords builds the basis of our structured literature search and defines the so called "search string" depicted in appendix A-1.

3.3. *Iterative framework development*

The iterative framework development process comprises the steps III. a. – III. c. and the succeeding steps IV., V., and II. in an iterative manner (cf., Fig. 1). In the first iteration (starting with step III. a.), a literature search by journal and keywords is conducted in the Web of Science database. This database is used as it hosts all 47 relevant journals. The search string's application (in the advanced search tool in all databases and all years) reveals the "initial hits": a set of 416 articles. This kind of search does not claim to be complete, but it is extensive, structured, transparent and reproducible (cf., Vom Brocke et al., 2009 and Seuring and Müller, 2008).

Within the initial hits, the literature evaluation (IV.) preselects the relevant approaches by reviewing title, abstract, and keywords. Then, all preselected approaches are checked for their relevance by a full text review. In both steps, the articles are identified as relevant (or irrelevant) according to the criteria defined in section 3.1. Regarding the initial hits, 8 relevant articles have been identified.

These 8 articles are analyzed and synthesized (V.) in order to be classified by the incumbent version of the ECSDF. In case approaches address terms or aspects which are not yet represented in the incumbent ECSDF, we adapt the ECSDF (II.).

In the second iteration, the forward search (III. b.) with all subsequent steps is conducted. The forward search is based on the 8 identified publications and is carried out to find literature that cites these publications. Regarding the forward search, only approaches which fulfill the *journal criteria* and *scope and purpose criteria* (cf., sections 3.2 and 3.1) are added to the literature sample. This iteration identifies 14 additional ECS design approaches as relevant.

To get a more comprehensive literature sample, in the last iteration (starting with step III. c.), a structured backward search is performed based on the 22 previously identified approaches. This final iteration leads to 22 additionally identified approaches.

This iterative procedure leads to 44 ECS design approaches to be analyzed. Note that the 44 identified articles are the result of the thorough analysis of titles, abstracts, and full texts of over 600 potentially relevant articles.

Table 3 summarizes the reviewed journals and the number of relevant articles (depicted according to their publishing journals after each search iteration) from the iterative framework development. Note, that the 47 journals from the structured literature search are marked with an asterisk (*). Furthermore, Table 3 shows in which quartile (Q1-Q4) each journal is ranked by the SJR. It stands out, that journals with an SJR >1 are most of the time considered to be in the top 25% of journals within each subcategory. The number of 51 journals in total (only 4 more than in the search string) indicates that the research field is analyzed in a sufficient manner, as not many further journals were identified through the forward and backward search of the search process.

Of course suitable articles from the initial conceptualization phase and the related work section are included in the ECSDF development. Finally, over 76 articles (design approaches, reviews, frameworks etc.) form the literature sample to develop the ECSDF.

The described methodology results in the ECSDF which is described in the following section.

4. The concept-centric ECS design framework

The developed concept-centric *ECS design framework* consists of eight main categories with several sub-categories and attributes by which any ECS design approach for manufacturing companies can be classified. The main categories of the concept-centric framework are the *Basic design approach*, *ECS type*, *ECS operation*, *Energy sources*, *CU types*, *CU operation*, *AES demand/FES supply*, and *Relations to other systems* (cf., Fig. 3).

Each of these main categories can consist of multiple sub-categories (groups of attributes) and attributes that are explained in detail in the following sections. To that, each section contains one or more figures, which illustrate the category to be explained (highlighted in a light grey) with its sub-categories and corresponding attributes. Whenever the category or its attributes are related to one of the previous frameworks or reviews, these are acknowledged and cited within the descriptions.

Note that a complete classification of the analyzed ECS design approaches is provided within the supplementary material. Therefore, to keep the text clear, we omit a complete list of references for each attribute but provide most informative references wherever it is appropriate.

4.1. *Basic design approach*

The first main category *Basic design approach* categorizes publications according to their treated decisions. To that, the category is subdivided into *Scope* and the *Decision field* (cf., Fig. 4).

4.1.1. *Scope*

During the design of an ECS for manufacturing companies, the relation between the ECS and the production system (PS) is an integral part as this relation strongly influences the ECS design. As a result, the sub-category *Scope* differentiates between the attributes

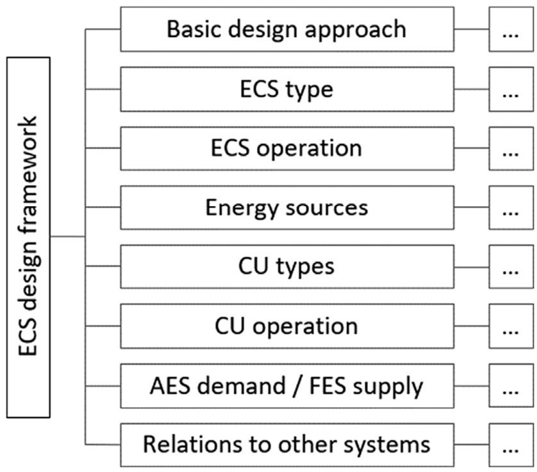

Fig. 3. Main categories of the ECS design framework.

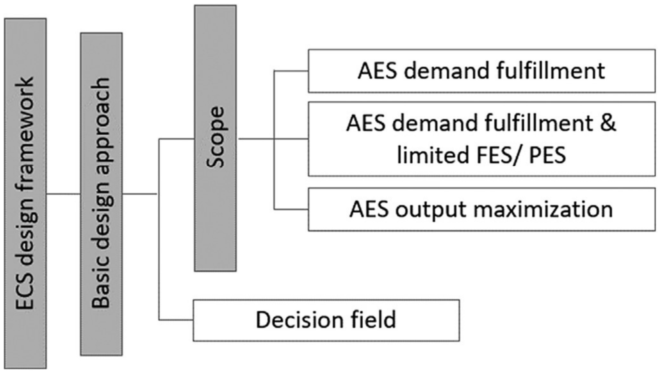

Fig. 4. Sub-category scope.

AES demand fulfillment, *AES demand fulfillment & limited FES/PES*, and *AES output maximization* (cf., Fig. 4).

The category *AES demand fulfillment* classifies approaches which design the ECS with the main goal to fulfill the AES demand of the PS (e.g., Leif Hanrahan et al., 2014 or Rad et al., 2016). The attribute *AES demand fulfillment & limited FES/PES* is similar, but classifies approaches which additionally consider a limited availability of FES/PES (e.g., when the FES/PES is a renewable energy source like solar or wind energy) (e.g., Amusat et al., 2016 or Campana et al., 2019). For both attributes, the AES demand can be static or varying. The third attribute *AES output maximization* classifies approaches which design ECS not with the goal to fulfill a given AES demand, but with the goal to maximize the ECS's possible AES output. In this setting, the PS's output relies on the amount of AES the ECS provides (e.g., Ahmadi et al., 2015; Bhattacharyya et al., 2017; Keshavarzzadeh et al., 2020). An example is the hydrogen production with renewable energy sources as FES. Here, the optimized design of an ECS defines the AES output und therefore, the hydrogen production volume.

4.1.2. *Decision field*

The category *Decision field* describes the details of what (e.g., size of CUs) and how (e.g., a selection from a predefined set) major decisions regarding the ECS design are made. For that purpose, the category is divided into the two sub-categories *Decision topic*, i.e., what is decided, and the *Decision type*, i.e., the how is it decided (cf., Fig. 5).

One way to differentiate ECSs is by the parameters number, size, and type of installed CUs (cf., Cho and Lee, 2014). Within the category *Decision topic*, we accordingly differentiate approaches by the *Size of units*, *Number of units*, *Type of units*, *Superstructure*, *System selection*, *ECS expansion, and System configuration*.

The attribute *Size of units* refers to the maximum capacity of CUs (e.g., Chitgar and Moghimi, 2020), *Number of units* refers to the quantity of installed CUs (e.g., Keshavarzzadeh et al., 2020), and *Type of units* refers to the selection of different technologies (e.g., a selection between gas-fired or coal-fired boilers; e.g., Aguilar et al., 2008; Sun and Liu, 2015; Alirahmi et al., 2020a). The attribute *Superstructure* means that selectable units (e.g., with distinct sizes and/or types) are considered as candidates for an ECS. The real structure of the ECS is created by selecting some units from the suggested superstructure candidates (e.g., Voll et al., 2013; Andiappan et al., 2015; Yokoyama et al., 2015). The attribute *System selection* classifies approaches in which complete ECSs (not individual CUs) are compared to one another. There is no decision on the number, size, and type of any CU but just the decision between complete, discrete systems (e.g., Pendergrass, 1983; Yokoyama et al., 2014; Campana et al., 2019; Abbasi and Pourrahmani, 2020). The attribute *ECS expansion* classifies approaches which extend already existing ECSs (e.g., Roy, 2001; Voll et al., 2012; Shamsi et al., 2019). The attribute *System configuration* classifies approaches which, in addition to design aspects, optimize “operational” design variables. Examples for these operational design variables are the turbine inlet pressure, the operation temperature, or the orientation angle of the photovoltaic system. Approaches can only be classified by the attribute *System configuration* when they also optimize at least one of the other decision topics (e.g., Najafi et al., 2014; Khanmohammadi et al., 2017; Alirahmi et al., 2020b). Nonetheless, we found this additional decision topic worth adding to the framework as it provides additional information about the planning approach. Note that these attributes are non-exclusive.

Because the decision on the previously described decision topics can have different degrees of freedom, the category *Decision type* depicts whether the decisions are *Free*, restricted by a *Predefined*

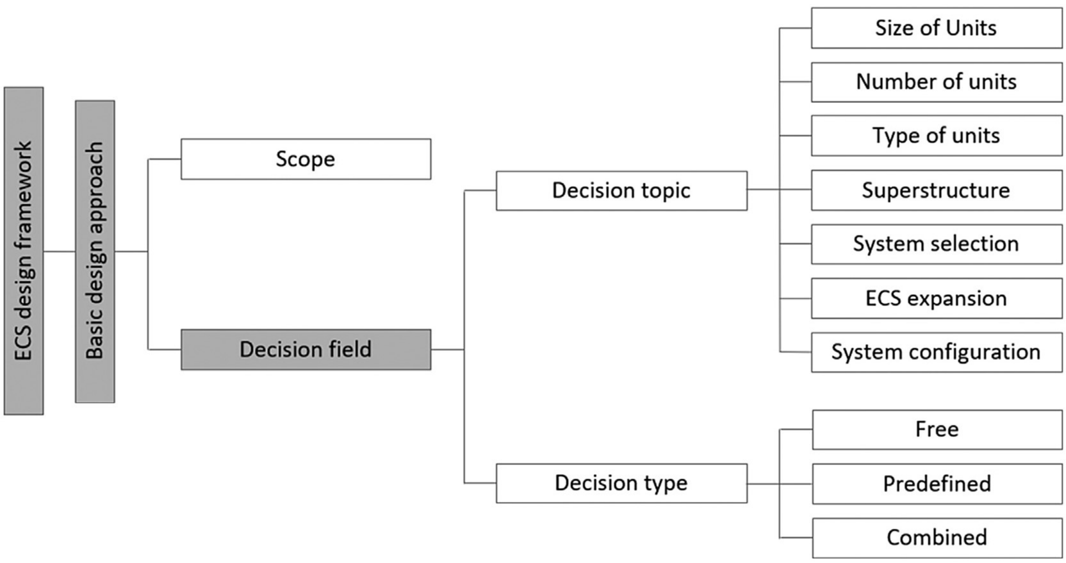

Fig. 5. Sub-category Decision field.

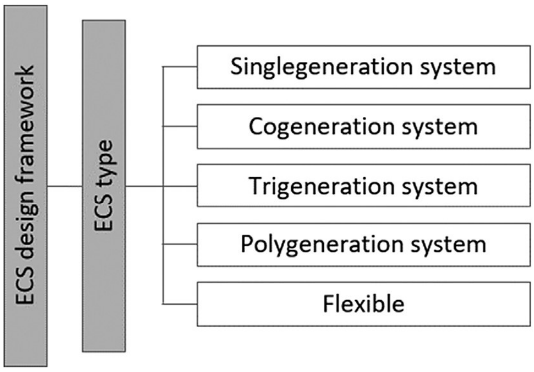

Fig. 6. Category ECS type.

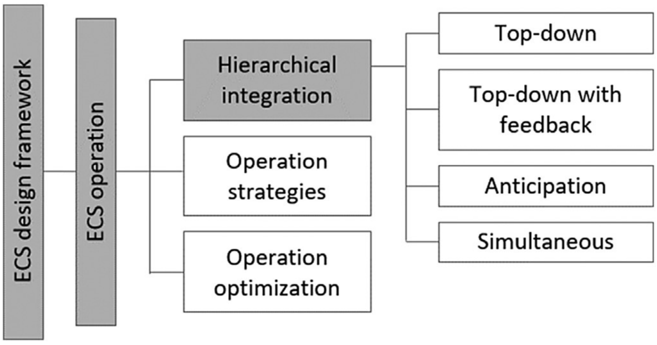

Fig. 7. Sub-category Hierarchical integration.

set, or a combination of both (*Combined*).

If an approach determines all considered *Decision topics* not from a limited amount of discrete options, but optimizes the considered decision topics during the design process, it is categorized as *Free* (e.g., Emadi and Mahmoudimehr, 2019; Chitgar and Moghimi, 2020). In contrast, if an approach determines all considered decision topics by choosing between discrete options, it is categorized as *Predefined* (e.g., Marechal and Kalitventzeff, 1998; Won et al., 2017; Ghorbani et al., 2019). When more than one decision topic is determined, the degree of freedom can vary between and within each decision topic. Therefore, the attribute *Combined* is necessary in the case that within one approach some decision topics are determined *Free* and some others are *Predefined* (e.g., Papoulias and Grossmann, 1983; Luo et al., 2014; Kazi et al., 2015; Campana et al., 2019). Note that these attributes are exclusive.

4.2. ECS type

The main category *ECS type* classifies ECSs according to their basic type by classifying them by the number of provided AES (cf., Andiappan et al., 2014). To this, we differentiate between the attributes *Singlegeneration system*, *Cogeneration system*, *Trigeneration system*, *Polygeneration system* and *Flexible* (cf., Fig. 6). Some attributes of this category have also been used by Liu et al. (2014) and Al Moussawi et al. (2016, 2017).

In order to create an unambiguous definition of the ECS types, the attribute *Singlegeneration system* classifies an ECS which converts FES into a single AES. A *Cogeneration system* (*Trigeneration system*) is an ECS which converts FES into two (three) AES. A *Cogeneration system* is most commonly a combined heating and power (CHP) system, whereas a *Trigeneration system* is usually a combined cooling, heating, and power (CCHP) system (cf., Andiappan et al., 2014; Al Moussawi et al., 2017). When an ECS converts FES into more than three energy sources, it is categorized as a *Polygeneration system* (e.g., Papoulias and Grossmann, 1983; Carvalho et al., 2014). In case, approaches can design multiple kinds of ECS types (e.g., CHP and CCHP), they are classified as *Flexible* (cf., Azit and Nor, 2009).

The strict categorization and clear definition into the different *ECS types* proves necessary, as so far, some authors use the definitions in different contexts. For instance, occasionally authors talk about cogeneration systems although they provide more than two AES (e.g., Azit and Nor, 2009). Other approaches group heat and cold into one thermal energy source. Afterwards, they generate cold and/or heat by further processing the thermal energy sources provided by CUs (e.g., Yokoyama and Ito, 2002; Benam et al., 2015). In this case also no unified definition is used for the corresponding ECS types. Thus here, an ECS is categorized depending on whether it processes the thermal energy sources into just heat or cold (cogeneration system), or both (trigeneration system). Note, that the attributes of the category *ECS types* are usually mutually exclusive but in case of a comparison between different *ECS types*, they can be non-exclusive.

4.3. ECS operation

The literature analysis carved out that, during the design of an ECS, the operation of the prospective ECS is considered in different ways. Thus, the main category *ECS operation* categorizes approaches according to the way the prospective operation is considered during the design phase. Therefore it classifies approaches according to the sub-categories *Hierarchical integration* and *Operation strategies* with their attributes and the attribute *Operation Optimization* (cf., Fig. 7).

4.3.1. Hierarchical integration

The sub-category *Hierarchical integration* consists of attributes explaining the interdependencies of design decisions and operational decisions, as it is important to take their hierarchical relationship during design into account (Ghadimi et al., 2014). A detailed description of hierarchical planning in general can be

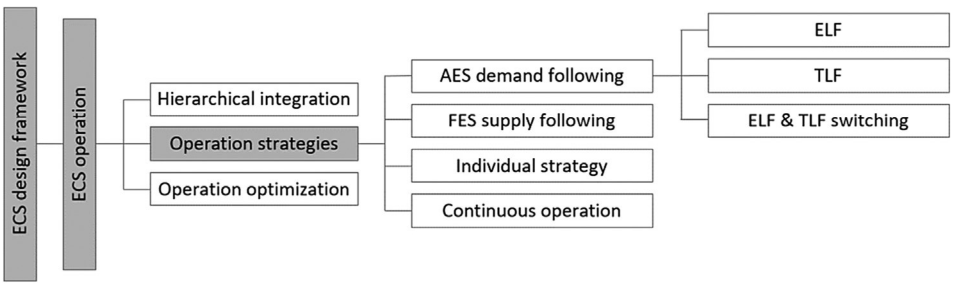

Fig. 8. Sub-category Operation strategies.

found in Schneeweiss (2003) and of hierarchical interdependencies during ECS planning in Yokoyama et al. (2014). In literature, some authors (implicitly) differentiate between a separate (Aguilar et al., 2007), iterative (Aguilar et al., 2007), anticipating (Aguilar et al., 2008), or a simultaneous (Aguilar et al., 2008) optimization of the design and the operation of an ECS. Accordingly, the category *Hierarchical integration* classifies the different integration types of an ECS's operation by the mutually exclusive attributes *Top-down*, *Top-down with feedback*, *Anticipation*, and *Simultaneous* (cf., Fig. 7).

The integration type *Top-down* means a strict top-down relationship between ECS design and ECS operation, i.e., the ECS operation is only used for evaluating the preceding, independent design decision (cf., e.g., Varbanov et al., 2005; Ghadimi et al., 2014; Alirahmi et al., 2020a). However, no design decisions are changed due to the evaluation, but one ECS design can be compared to another ECS design and the best design can be chosen. Hereby, exemplary evaluation criteria can be operational costs, investment costs, or energy consumptions.

In contrast, approaches to be classified by the integration type *Top-down with feedback* use feedback information resulting from ECS operation related to a specific ECS design to adjust the incumbent ECS design in an iterative manner (cf., e.g., Roy, 2001; Amusat et al., 2017). Hereby, a definition of the feedback information and the procedure on how to integrate this feedback is mandatory.

The third integration type *Anticipation* directly integrates some aspects of the ECS or CU operation into the ECS design. In doing so, some aspects and/or simplified (relaxed) aspects of the subordinate ECS or CU operation are integrated and others are not (otherwise, the ECS design might be getting to complex). The concrete ECS and CU operation aspects can be considered in individual detail and combinations during the ECS design. An Example for a CU operation aspect is the compliance with minimum time intervals between which a CU can be switched on and off (cf., e.g., Aguilar et al., 2008; and section 4.6). An Example for the anticipation of ECS operation is the usage of an operation strategy (e.g., Smaoui et al., 2015; Morais et al., 2020). By using such an operation strategy, an ECS's operational behavior is integrated without optimizing it.

Last attribute of hierarchical integration is called *Simultaneous* and classifies design approaches, which determine the design and operation of an ECS at the same time. Note that hereby the complete relevant subordinate ECS operation problem must be considered.

4.3.2. Operation strategies

To take the interdependencies between the design and operation during the design stage into account, operation strategies simulate the prospective behavior of the ECS in a simplified way, i.e., by following strategy-specific rules. The difficulty hereby is that not every strategy does necessarily exploit all benefits of every ECS and thus, has to be selected carefully (Kavvadias and Maroulis, 2010).

The sub-category *Operation strategies* comprises typical representatives as sub-categories and attributes. We propose to distinguish strategies according to the sub-category *AES demand following* and the attributes *FES supply following*, *Individual strategy*, and *Continuous operation*.

The sub-category *AES demand following* comprises approaches where the ECS operation is directly coupled to the AES demand and consists of the attributes electrical load following *(ELF)*, thermal load following *(TLF)*, and the attribute *ELF & TLF switching* (cf., Fig. 8). When following the *ELF* strategy, the priority of the ECS operation is to provide the electrical load demand as exactly as possible, independent of whether a deviation from this demand

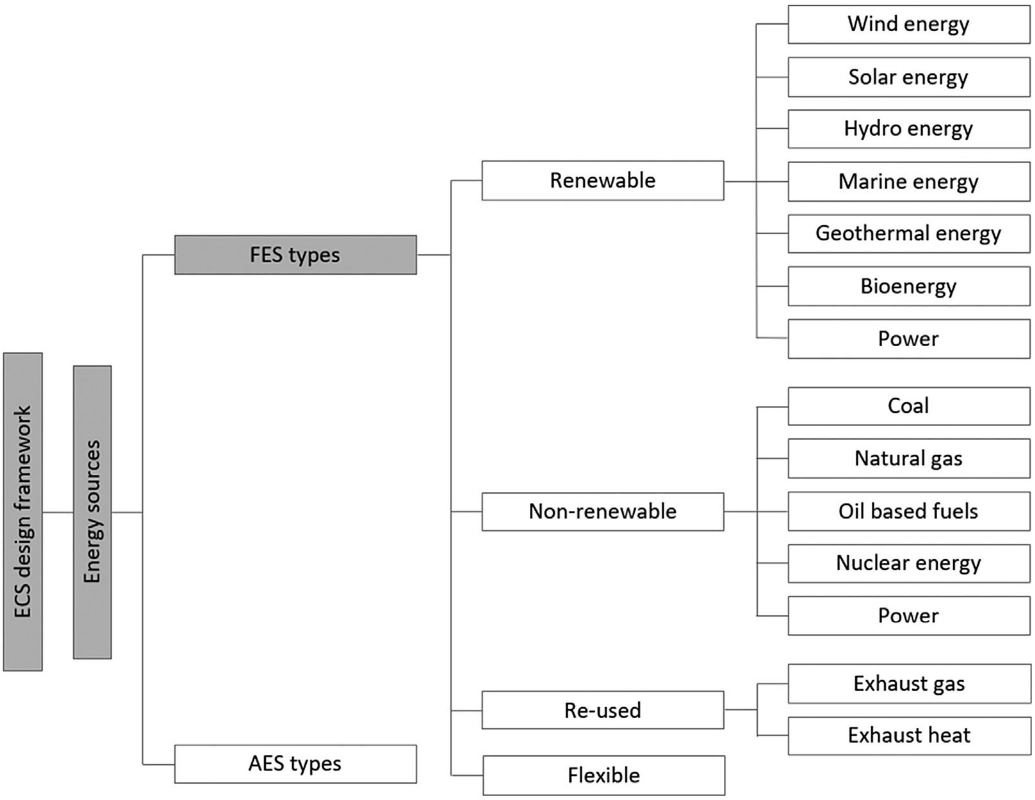

Fig. 9. Sub-category FES types.

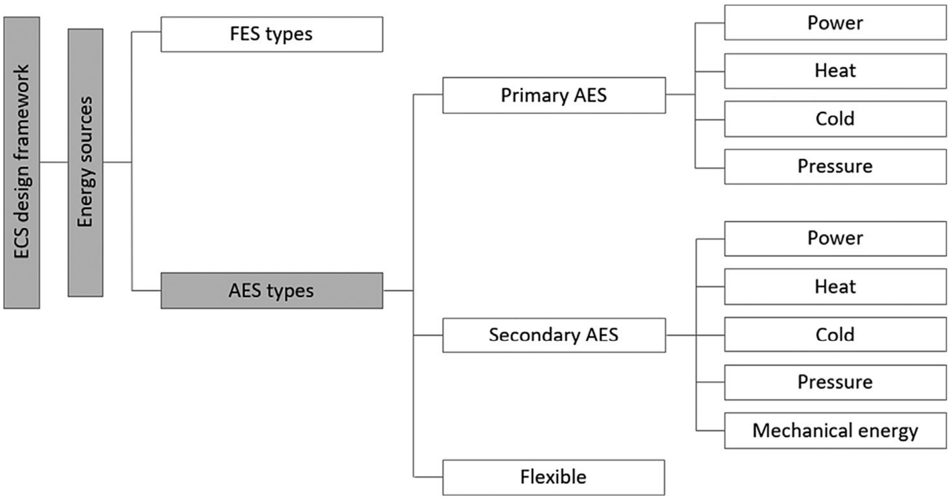

Fig. 10. Sub-category AES types.

following would be beneficial (cf., e.g., Ghadimi et al., 2014; Al Moussawi et al., 2017; Morais et al., 2020). The strategy TLF is similar to ELF, but with the priority to follow the thermal load demands as exactly as possible (cf., e.g., Ghadimi et al., 2014; Al Moussawi et al., 2017; Shamsi et al., 2019). In both strategies additional recovered heat during ELF or generated electricity during TLF can occur, but is treated as a byproduct (Ghadimi et al., 2014). The attribute *ELF & TLF switching* classifies approaches in which ECS operation interchanges between the ELF and TLF strategy depending on AES demands (Andiappan and Ng, 2016).

The attribute *FES supply following* classifies approaches in which the conversion process completely depends on the FES supply. This means, the amount of available PES/FES (e.g., mostly in the form of uncontrollable occurrence of wind or solar energy) determines whether or not the ECS is operating and the corresponding amount of AES provided (cf., Bernal-Agustín and Dufo-López, 2010; Behzadi et al., 2019; Waseem et al., 2020). The provided AES are either directly used by the PS or transferred to an energy storage unit. In this case, the PS's production rate is directly influenced by the PES/FES availability and no active decision on the ECS operation is made.

The attribute *Individual Strategy* represents individual tailor-made or modified operation strategies sporadically used by a single or only a few approaches. Examples of such strategies are peak shaving (cf., e.g., Kavvadias and Maroulis, 2010), separate heat/power generation (cf., e.g., Ghadimi et al., 2014), rule based operation (cf., e.g., Mavromatis and Kokossis, 1998; Amusat et al., 2017), and electrical/thermal equivalent demand following (cf., e.g., Kavvadias and Maroulis, 2010). Note that a more detailed discussion on energy management strategies in the context of stand-alone renewable ECSs can be found in Bukar and Tan (2019).

Approaches are classified by the attribute *Continuous operation* whenever the ECS operation is at a constant operation level and is not determined by the availability of PES/FES nor by a given AES demand. This is for instance the case when hydrogen (e.g., Chitgar and Moghimi, 2020) and/or fresh water is produced (e.g., Keshavarzzadeh et al., 2020).

4.3.3. *Operation optimization*

During ECS design, the operation of the ECS can also be part of the optimization. Sometimes this approach is actually called optimization, in other cases, it is called an optimal dispatching strategy (cf., e.g., Ghadimi et al., 2014; Liu et al., 2014). For an approach being classified by the attribute *Operation optimization*, the approach needs to consider design and operational decision variables (e.g., Hui and Natori, 1996; Abbasi and Pourrahmani, 2020). Be aware that optimization not necessarily means that a mathematical optimum is reached, but also suboptimal solutions calculated by heuristics are appropriate. In case the design and operation are optimized at the same time, the approach is also classified as *Simultaneous* (e.g., Shang and Kokossis, 2005; Carvalho et al., 2014; Amusat et al., 2016).

Note, that the attributes within the sub-category hierarchical integration are exclusive. Whereas the attributes of the sub-category *Operation strategies* and the attribute *Operation optimization* are non-exclusive, as for instance, an approach can compare an operation strategy to an optimization procedure or the most suitable operation strategy is selected.

4.4. *Energy sources*

The main category *Energy sources* classifies approaches according to their *FES type* (input energy sources) and their *AES type* (output energy sources) (cf., Figs. 2 and 9, and Fig. 10).

Note that in this section, the term energy sources is used because the final attribute of each sub-category are energy sources (e.g., steam or hot water), even though intermediary sub-categories are common properties of energy sources (e.g., heat) but not energy sources by definition.

4.4.1. *FES types*

The sub-category *FES types* differentiates FES by the sub-categories *Renewable*, *Non-renewable*, *Re-used* and *Flexible* (cf., Fig. 9) because ECS design approaches have to take corresponding aspects (e.g., concerning supply availability) into account.

Renewable energy sources occur in forms of, e.g., *Wind, Solar, Hydro, Marine, Geothermal energy* or *Bioenergy* (cf., Shiun et al., 2012 or Ellabban et al., 2014). Non-renewable energy sources are, e.g., *Coal, Natural gas, Oil based fuels,* and *Nuclear energy* (cf., Shafiei and Salim, 2014). Electric power, has a double position as it can be renewable, non-renewable, or a combination of both, depending on its characteristics. Note, that if an approach does not define if the electric power is renewable or non-renewable, we classify it according to both *power* attributes because the electric power from the grid consists of an energy mix. Furthermore, *Re-used* energy sources are the waste of other systems and are re-used by the ECS, e.g., *Exhaust gas* or *Exhaust heat* (with the energy sources hot water,

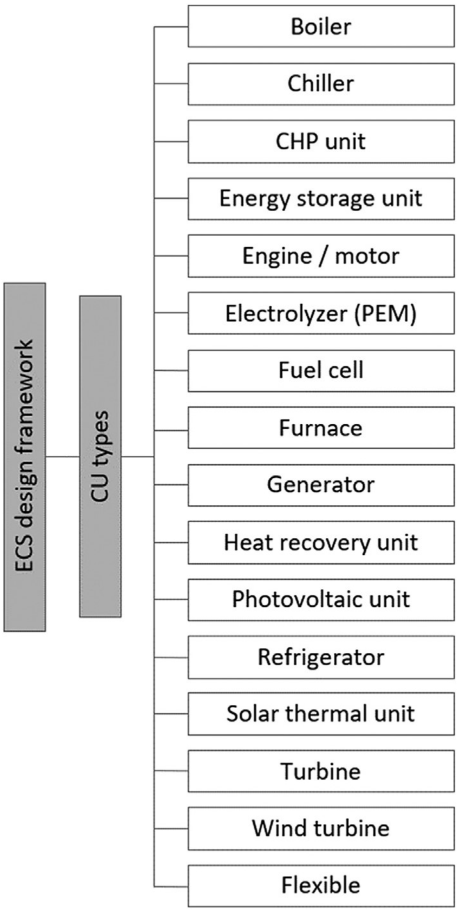

Fig. 11. Category CU types.

air, or steam) (cf., e.g., Roy, 2001). The attribute *Flexible* classifies approaches, which can be applied to different types of FES (e.g., Iyer and Grossmann, 1998; Voll et al., 2013).

The attributes of the category *FES types* are non-exclusive. For instance, more than one attribute of *FES types* can be considered when an ECS consists of more than one CU which use different FES as input.

4.4.2. AES type

The AES is directly applied by the production units of a manufacturing company's production equipment (machines etc., cf., Fig. 2). The category *AES types* differentiates between the two sub-categories *Primary AES* and *Secondary AES* as well as the attribute *Flexible* (cf., Fig. 10). This differentiation is introduced to highlight the AES the ECS is primarily designed for and the AES that result from a combined (secondary) production (e.g., from cogeneration or trigeneration systems).

The attribute *Flexible* classifies approaches, which can be applied to different types of AES (e.g., Iyer and Grossmann, 1998; Voll et al., 2012).

4.4.2.1. Primary AES. The *Primary AES,* specifies the deliberately controlled output of the ECS (e.g., by an operational strategy, see section 4.3). It is called “primary” AES since the whole ECS's design and operation is optimized to fulfill the demand of this AES as efficient as possible. The most common types of primary AESs are classified by the attribute electric *Power* and the sub-categories *Heat* (with the AES attributes hot water, air, or steam), *Cold* (with cold water, or air), and *Pressure* (with steam, air, or oil) (e.g., Aguilar et al., 2008; Tichi et al., 2010; Abbasi and Pourrahmani, 2020; Morais et al., 2020, Fig. 10). If an ECS design approach considers more than one AES (e.g., steam and power) but does not explicitly define which of the AES is the primary one, all AES are considered as primary AES.

4.4.2.2. Secondary AES. The category *Secondary AES* classifies approaches which consider “byproducts” of the conversion process (e.g., within CHP or CCHP systems) and thus, a second (or third) AES. Be aware, that the provided amount of *Secondary AES* depends on the amount of the *Primary AES*. For instance, if an approach optimizes the fulfillment of the primary AES demand (e.g., steam) through an CHP which can additionally provide electric power as a byproduct, then electric power is the *Secondary AES.*

The aggregated sub-categories for the *Secondary AES* are similar to the *Primary AES*: *Power, Heat* (with the AES: hot water, - air, and -steam), *Cold* (with cold water, and - air), *Pressure* (with steam, air, or oil), and additionally *Mechanical energy* (cf., e.g., Andiappan and Ng, 2016; Emadi and Mahmoudimehr, 2019; Keshavarzzadeh et al., 2020, Fig. 11).

Note, that the attributes of the category *AES types* are non-exclusive, because if an approach uses or compares several operational strategies (e.g., TLF and ELF cf., Ghadimi et al., 2014), more than one AES can be categorized as a *Primary AES* as well as a *Secondary AES.*

4.5. CU types

There exist several possibilities to classify CUs within an ECS design framework. As every CU converts one form of energy (e.g., chemical energy) into another form of energy (e.g., thermal energy) (cf., Shiun et al., 2012) and/or one energy sources (e.g., gas) to another energy sources (e.g., steam) (cf., Rager et al., 2015), these aspects could be the basis for the categorization. The first aspect of energy form conversion is not directly reflected by the ECSDF, because some CU integrate several conversion steps (e.g., internal combustion engines) and it is hardly possible nor helpful to dismantle CUs for identifying all energy form conversions. The second aspect of energy source conversion is also not unique for every CU as for example boilers can convert gas to steam or power to steam, depending on whether they are an electrical or a gas-fired boiler. Therefore, we follow the recommendations of several authors and use concrete manifestations of CUs as attributes for the category *CU types* (cf., Cho and Lee, 2014; Liu et al., 2014 and Sun and Liu, 2015; Al Moussawi et al., 2016).

The attributes are depicted in Fig. 11. Most of them are self-explanatory and not explained in more detail, but note that most of them aggregate concrete unit specifications. The attribute *Boiler* for instance unifies gas-fired and electrical boilers as well as all boilers which provide any pressure of steam or heat of water. The attribute *Chiller* unifies for instance absorption and compression chillers. The attribute *CHP unit*, describes an arrangement of CUs to a combined heat and power (CHP) unit that is not specified in more detail. *Energy storage units* unifies for instance batteries, compressed air storages or hydrogen storages. *Fuel cells* unifies for instance solid oxide (SOFC) or proton-exchange membrane fuel cells (PEMFC). Heat recovery units unifies for instance heat exchanger or heat recovery boiler. The attribute *Refrigerator* unifies absorption, electric, and compression refrigerators. The attribute *Solar thermal unit*, which defines units (e.g., power tower, solar panel, etc.) collecting solar energy and converting it into heat (in contrast to photovoltaic units which provide power). The attribute *Turbine* unifies for instance gas, steam, and micro turbines.

The additional attribute *Flexible* classifies approaches which are not specialized on any specific CU type, but can address different CU types.

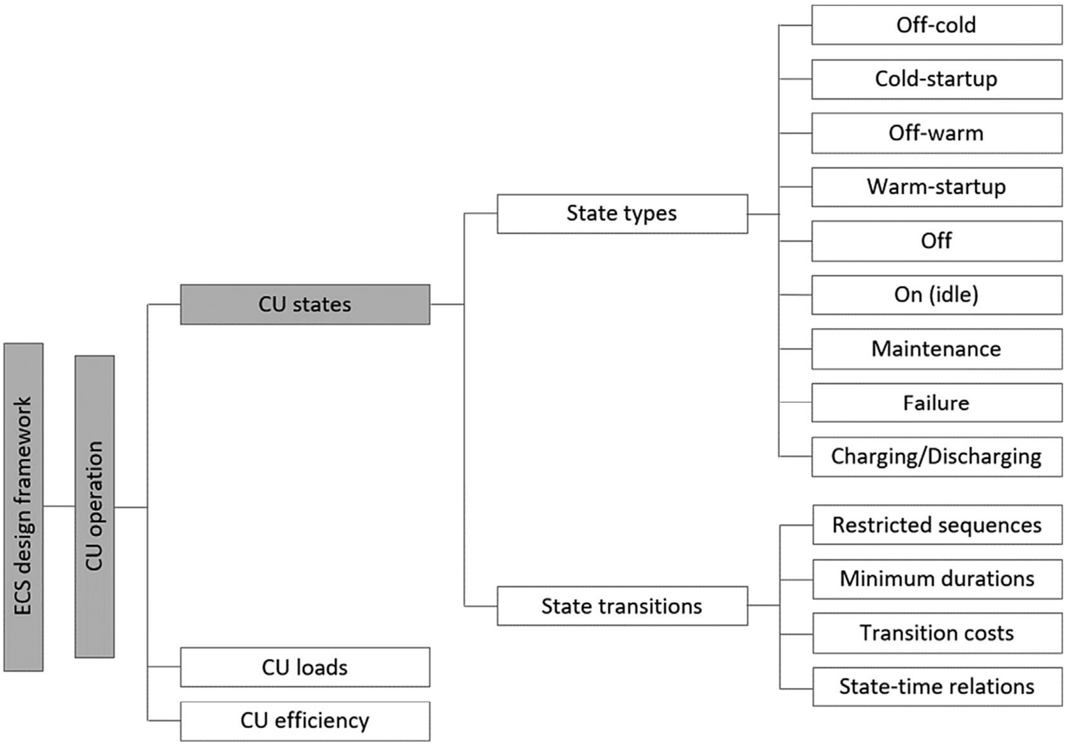

Fig. 12. Category CU operation.

All these attributes are non-exclusive because an ECS can consist of more than one CU. Note, that approaches are only classified by the attribute *Electrolyzer* when the electrolyzer does not serve as a production unit for commercial hydrogen production but to supply AES as part of the ECS and/or to convert surplus AES for energy storage.

During the literature analysis we observed that, in addition to these typical CUs, extra units like control units, pumps, AC/DC converter, DC/DC converter, inverter, compressors, or rectifier are installed. As these units are essential for ECSs but not a distinguishing feature they are not included into the ECSDF.

4.6. CU operation

Approaches considering the design and operation of an ECS may consider different operational characteristics of the individual CUs during the ECS design. These operational characteristics are represented in the category *CU operation* comprising of the sub-categories *CU states*, *CU loads*, and *CU efficiency* (cf., Fig. 12).

4.6.1. CU states

The sub-category *CU states* is about the different operational states a CU can operate at (e.g., *Off* and *On (idle)*) and the transition between these states. Thus, the *CU states* comprise the sub-categories *State types*, i.e., the operational states, and the *State transitions,* which represent the conditions of switching between two states (cf., Fig. 12).

4.6.1.1. State types. The *State type* considered by any approach that considers *CU states* at all is the operating state, i.e., the state in

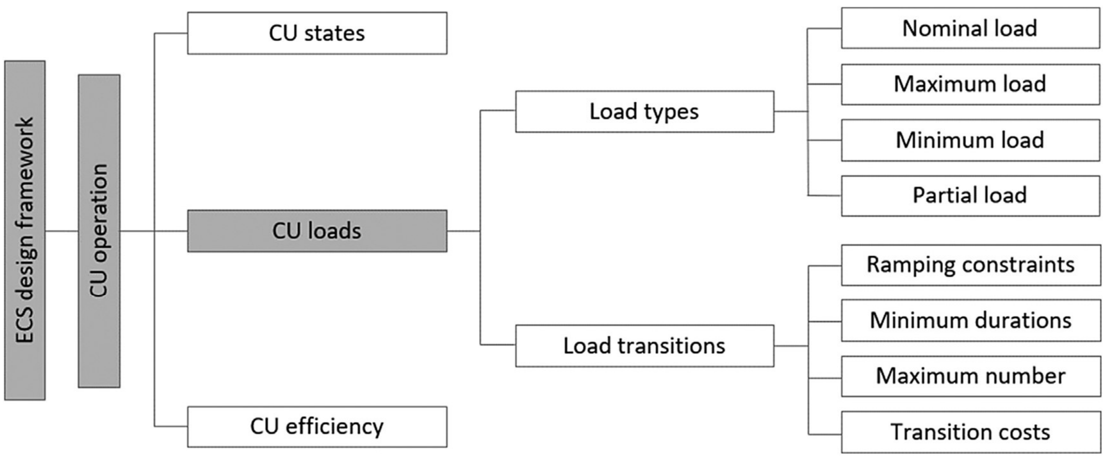

Fig. 13. Sub-category CU loads.

which a CU is converting FES into AES. As this state is represented in every approach, it is not included into the ECSDF as it does not provide any helpful information. Beside the operating state, further states are considered in literature (cf., e.g., Aguilar et al., 2008; Sun and Liu, 2015; Amusat et al., 2017): The state *Off-cold*, i.e., in which the CU is not converting and has spent a minimum amount of time off, making a specific (cold) startup process necessary to reach the operating state. The state *Cold-startup*, i.e., the explicit state in which the CU switches from *Off-cold* to operating. These startup states can take several hours and during startups FES is consumed but no AES is provided. The state *Off-warm*, i.e., the state in which the CU is not converting and has not yet spent a maximum amount of time *Off*, making a specific (warm) startup process necessary to reach operating state. The state *Warm-startup*, i.e., the explicit state in which the CU switches from *Off-warm* to operating. The state *Off*, i.e., in which the CU is turned off and is not converting and not consuming any FES. Here, a transition between the states *Operating* and *Off* is possible without a transition state in between. The state *On (idle)* (also called hot standby), i.e., the state in which the CU is not converting but consumes FES to preserve its state to reach its operating state immediately (without an explicit startup process). The state *Failure*, i.e., in which the CU has an error and cannot convert anymore, making a maintenance procedure or repairs necessary to operate again. The attribute *Failure* represents (stochastic) CU breakdowns and thus, the consideration of the state *Failure* should imply the consideration of the ECS's reliability. The state *Maintenance*, i.e., the explicit state in which the CU is not available as it receives repairs or maintenance. Furthermore, if a CU is an energy storage system, the state *Charging/Discharging* can be considered (because approaches always consider both states when considering the charging or discharging process, a differentiation is unnecessary).

4.6.1.2. State transitions. A state transition is the switching from one *State type* to another. Generally, state transitions are subject to certain physical rules, e.g., a CU cannot change from *Off-cold* to *Operating* state directly without a *Cold-startup* process in between or a CU cannot change its state from *Operating* to *Cold-startup* as it is not possible. To consider these physical rules during ECS design (and operation), an appropriate representation of state transition restrictions is necessary. This can be accomplished in several ways, e.g., by *Restricted sequences* specifying the order in which the CU state types can be run through (e.g., Sun and Liu, 2015), by *Minimum durations* specifying how long a CU must remain in a specific CU state at least before it can switch to another CU state (e.g., Aguilar et al., 2008), by *State-time relations* specifying the time needed to switch between two distinct CU states (transition times can vary depending on between which states the transition takes place), or by *Transition costs* (e.g., in form of additional FES requirements, losses of useful energy, or monetary values (e.g., Sun and Liu, 2015).

Note, that all attributes of the sub-category *CU states* are non-exclusive.

4.6.2. CU loads

In the operating state, a CU provides a specific amount of AES, named (operational) load. The sub-category *CU loads* specifies the different loads a CU can provide and the transition between these loads. Thus, the category *CU loads* comprises the two sub-categories *Load types*, i.e., the different operational loads, and *Load transitions,* which represent the conditions of switching between different loads (cf., Fig. 13).

4.6.2.1. Load types. The attributes of the sub-category *Load types* reflect the way the different amounts of AES provided by the ECS are considered by a design approach (cf., Fig. 13). The first three attributes address discrete load points. The first attribute, the *Nominal load,* classifies approaches which explicitly consider the nominal load (also called design point), i.e., the load at which the CU operates with maximum conversion efficiency. The second attribute is the *Maximum load*, i.e., the highest possible load and thus, a CU's maximum AES capacity. The third attribute is the *Minimum load*, i.e., the lowest possible load a CU can provide before it must be shut down due to technical reasons. Together the *Maximum load* and the *Minimum load* determine the operational range of a CU. The last attribute is called *Partial load*. In contrary to the first three attributes, this attribute does not only classify approaches considering discrete load points, but approaches considering any loads within a CU's operational range. Regarding partial loads, approaches can consider continuous partial loads (i.e., the CU can provide any partial load within its operational range (cf., Azit and Nor, 2009 or Morais et al., 2020) or a limited number of discrete partial loads (cf., Roy, 2001 or Gibson et al., 2013).

We would like to emphasize that even though every CU underlies physical restrictions in the maximum and minimum providable loads, it does not mean that every approach is classified into the corresponding attributes. The attributes *Maximum*, *Minimum*, *Nominal* and *Partial loads* are only classified for an approach, that explicitly defines or considers them. For instance Abdelkader et al. (2018) explicitly consider maximum and minimum operational loads in the constraints 19 to 22, and Yokoyama and Ito (2006) consider *Maximum loads*, *Minimum loads*, and continuous *Partial loads*. Strongly related to partial loads is the category CU efficiency discussed in section 4.6.3.

4.6.2.2. Load transitions. Load transitions (similar to *State transitions*) refer to the switching between different loads. Load transitions are subject to certain physical rules, e.g., a CU cannot change from the minimum load to the maximum load within an arbitrarily short time. To classify approaches according to the respected physical rules during ECS design and operation, the category *Load transitions* provides the following attributes: *Ramping constraints* (i.e., an approach considers the maximum height of a load change a CU can manage within a certain amount of time cf., Shamsi et al. (2019)), *Minimum durations* (i.e., an approach considers the minimum amount of time a CU must remain at one load at least, before it can switch to another load), *Maximum number (*i.e., consideration of a maximum amount of times a CU can perform load transitions within a specific time interval), and *Transition costs (*i.e., an approach considers additional energy requirements, loses of useful energy, efficiency losses, or monetary values for a load transition).

All attributes of the sub-category *CU loads* are non-exclusive.

4.6.3. CU efficiency

Each CU has its individual conversion efficiencies, which are generally listed in the CU's specifications (Azit and Nor, 2009). Most approaches consider load-dependent conversion efficiency characteristics, as the efficiency strongly depends on the CU's operational load (Ghadimi et al., 2014), or age- and size-dependent efficiency characteristics. The ECSDF considers these aspects in the category *CU efficiency* and differentiates between the attributes *Constant, Discrete*, *Linear*, *Piecewise-linear*, *Non-linear*, *Performance degradation*, and *Scale-effect* (cf., Fig. 14).

The attribute *Constant* classifies approaches considering one single conversion efficiency value for the CU's entire operational range (cf., Behzadi et al., 2019), or in rare cases for a CU with a single nominal load (cf., Cho and Lee, 2014). The attribute *Discrete* classifies approaches considering a few discrete efficiencies with corresponding discrete loads (e.g., for the minimum-, maximum-,

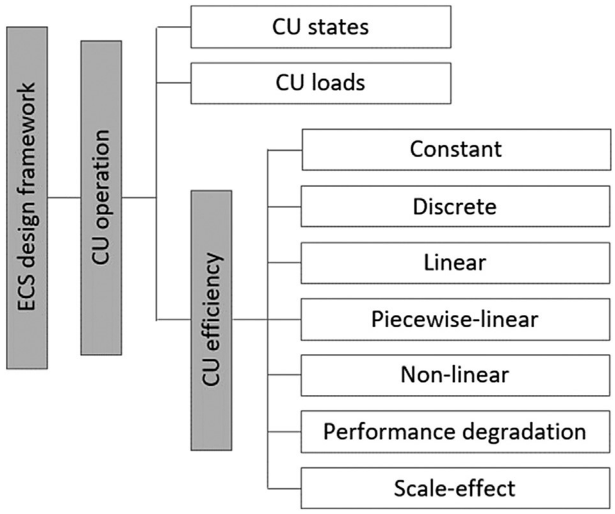

Fig. 14. Sub-category CU efficiency.

nominal, or a discrete partial load, cf., Roy, 2001). When approaches consider different continuous efficiencies, they determine the efficiencies via a function based on the load. Thus, the attributes *Linear*, *Piecewise-linear*, and *Non-linear* classify approaches according to their considered efficiency functions (cf., e.g., Tichi et al., 2010; Voll et al., 2013). The attribute *Performance degradation* classifies approaches which consider a degradation of efficiency over the CU lifetime, for instance due to CU ageing (cf., e.g., Guinot et al., 2015). The attribute *Scale-effect* classifies approaches which consider CU efficiencies depending on the CU size. Hereby, the *Scale-effect* determines the proportionality between the increase in size and the thereof resulting increase of the (nominal) efficiency of a CU (cf., Gibson et al., 2013).

Note, that these attributes are non-exclusive. This is for example the case, if an ECS design approach considers more than one CU and assumes different efficiency characteristics for each CU (cf., Tichi et al., 2010).

4.7. *AES demand/FES supply*

Because the (strongly) varying AES demands of the production system severely impact the efficiency of the ECS (cf., Yokoyama and Ito, 2002; Ashok and Banerjee, 2003; Ghadimi et al., 2013, 2014), the consideration of historical and/or future (estimated) AES demands is mandatory to design an appropriate on-site ECS for manufacturing companies. But not only the characteristics of the AES demand influence the ECS design but also an accurate consideration of the prospective FES supply is needed for designing appropriate ECSs (Khatib et al., 2016).

As the characteristics of AES demand and FES supply are (almost) identical, they are both represented by the main category *AES demand/FES supply* which classifies design approaches accordingly. To indicate which case is characterized by the attributes of this main category, we use the "auxiliary" attributes *FES & AES related* and *Only FES related* and define the following conventions: If only AES demands are characterized, no auxiliary attribute is selected (cf., Maia and Qassim, 1997; Spyrou and Anagnostopoulos, 2010; Emadi and Mahmoudimehr, 2019); If the AES demand and FES supply are characterized, the auxiliary attribute *FES & AES related* is selected (cf., Won et al., 2017; Abbasi and Pourrahmani, 2020); And if only the FES supply is characterized, the attribute *Only FES related* is selected (cf., Kamel, 1995; Khalilnejad and Riahy, 2014; Tebibel and Labed, 2014; Waseem et al., 2020).

The actual classification is then based on the attributes *Stochastic* (cf., O'Brien and Bansal, 2000; Yokoyama et al., 2014) and the sub-categories *Time dependency, Aggregation level, Aggregation method*, and *Data basis* (cf., Fig. 15).

The attribute *Stochastic*, classifies design approaches which consider uncertain AES demand/FES supply to determine robust ECS designs (Yokoyama et al., 2014). Hereby, a scenario or sensitivity analysis or the modelling of AES demand/FES supply variations by probabilistic distributions imply a classification by the attribute *Stochastic* (e.g., Andiappan et al., 2015; Amusat et al., 2017).

4.7.1. *Time dependency*

Depending on the behavior over time, the sub-category *Time dependency* classifies AES demand/FES supply by the attributes *Static* and *Dynamic* (cf., O'Brien and Bansal, 2000). Hereby, the attribute *Static* classifies design approaches which consider only a single *Static* AES demand/FES supply (e.g., Marechal and Kalitventzeff, 1998; Keshavarzzadeh et al., 2020), whereas *Dynamic* classifies design approaches considering dynamic AES demand/FES supply which vary over time (e.g., Campana et al., 2019; Shamsi et al., 2019).

4.7.2. *Aggregation level and aggregation method*

Regarding the AES demand/FES supply at all, the considered amount of data and the way the AES demand/FES supply is modelled has a large influence on the accuracy of the design. For instance, Kavvadias and Maroulis (2010) recommend to take at least one year of historical data (e.g., in form of load duration curves) into consideration for designing a trigeneration plant and Azit and Nor (2009) state that the modelling must be as detailed as possible but also as aggregated as necessary. To these aspects, the sub-categories *Aggregation level* and *Aggregation method* are introduced (cf., Fig. 15). These terms are used because AES demand/FES supply are always modelled in an aggregated manner and the sub-categories classify the characteristics of the aggregation, which provides the appropriate level of detail.

The sub-category *Aggregation level* classifies approaches according to the smallest time interval for which the AES demand/FES supply is considered. To that, it differentiates between the attributes *Seconds* (which considers intervals within the range of 1 s up to 59 s; cf., e.g., Saha and Kastha, 2010 or Jallouli and Krichen, 2012), *Minutes* (i.e., 1 min up to 59 min; e.g., Ghadimi et al., 2014), *Hours* (i.e., 1 h up to 23 h; e.g., Amusat et al., 2017), *Days* (i.e., one day up to 6 days), *Weeks* (i.e., one week up to 4 weeks), *months or longer* (e.g., Sun and Liu, 2015), and *Flexible*. *Flexible* classifies approaches which give instructions on how to adapt their approach to any appropriate aggregation level.

For every aggregation level, the AES demand/FES supply has to be determined. The sub-category *Aggregation method* classifies approaches depending on the applied technique to determine the AES demand/FES supply for each aggregation level. To that, the sub-category differentiates the attributes *Mean, Maximum, Minimum,* and *Sum*. The aggregation method *Mean* (*Maximum/Minimum/Sum*), calculates the mean (maximum/minimum/sum) of all available AES demand/FES supply values within the time interval specified by the aggregation level (e.g., Tebibel and Labed, 2014; Bhattacharyya et al., 2017; Alirahmi et al., 2020b).

Note, that the attributes within each sub-category are mutually exclusive, unless a comparison between different considerations of AES demand/FES supply is made.

4.7.3. *Data basis*

Furthermore, we found a broad difference in the considered

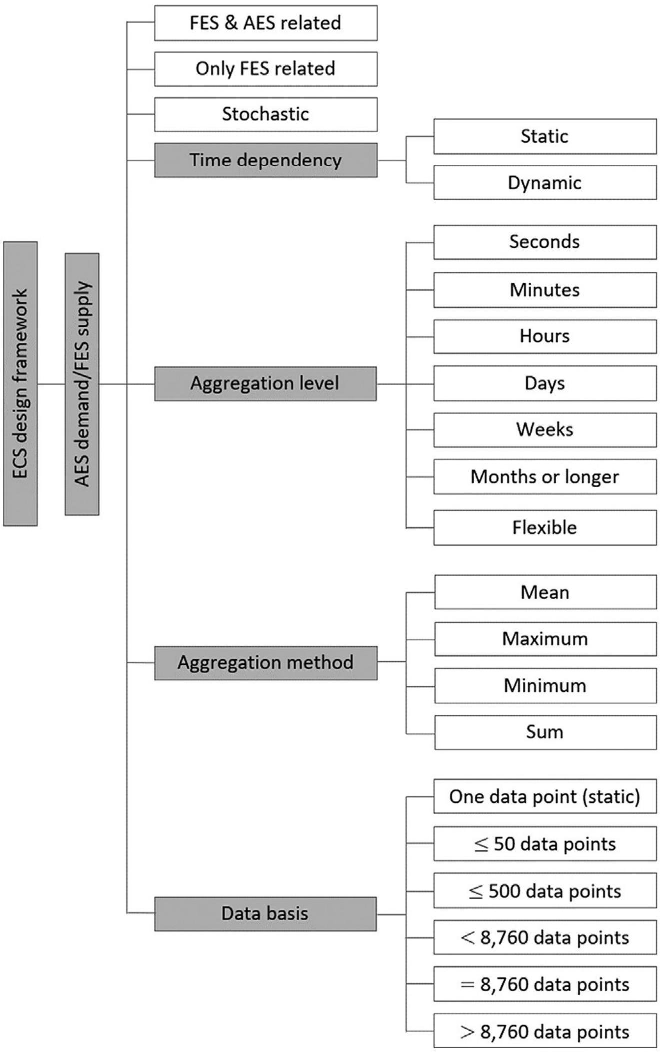

Fig. 15. Category AES demand/FES supply.

data basis within the analyzed approaches. The considered data basis vary from one considered data point to more than 8760 data points (e.g., representing 365 days with 24 h). The considered data basis has a huge influence on the reliability of the prospective ECS and the computational efforts of the solution methods applied to solve the ECS design problem. For this reason, and to make approaches comparable, the sub-category *data basis* with its attributes *One data point (static)*, $\leq$ *50 data points*, $\leq$ *500 data points*, $<$ *8670 data points*, $=$ *8670 data points*, and $>$ *8670 data points* is introduced (cf., Fig. 15). Each attribute describes an upper limit on the considered data points of an approach and classifies them accordingly. Hereby, a data point can represent any time unit which is defined by the *Aggregation level* (e.g., minutes or hours).

4.8. Relations to other systems

ECS design approaches may consider the relationship between the ECS and other systems (cf., Fig. 2). Thus, the main category *Relations to other systems* classifies ECSs according to their interaction and relationship with other systems and differentiates between the sub-categories *External grid* and *Energy market*, representing some of these systems and their attributes (cf., Fig. 16).

In general, connections to an *External grid* allow the import of AES from and/or the export to the grid. Since on-site ECSs are expected to be self-sufficient, they should be able to fulfill the base AES demand without exchanges with the external grid (Aguilar et al., 2008). Therefore, many approaches do not permit any AES exchange with the external grid during the design. In contrast, other design approaches explicitly allow the exchange of AES with the external grid in order to maximize the overall benefit (cf., e.g., Azit and Nor, 2009) or to minimize the overall costs (cf., e.g., Gamou et al., 2002). These aspects are considered in the ECSDF by the two attributes *Export*, i.e., the allowance to sell converted AES to the grid; and *Import*, i.e., the allowance to buy “missing” AES from the grid (note, that not the import of FES is reflected by this attribute). These attributes are non-exclusive, as an *Import* as wells as an *Export* can be considered by an approach.

Furthermore, an interaction with the *Energy market* could be considered. This sub-category differentiates between attributes to classify approaches that design an ECS with regard to external energy market influences like *Uncertain prices* or demand side management (demand response) mechanisms like *Time-of-use tariffs*, *Critical peak pricing*, or *Power purchase agreements* (cf., e.g., Kavvadias and Maroulis, 2010; Gibson et al., 2013; Cho and Lee, 2014). These attributes also are non-exclusive.

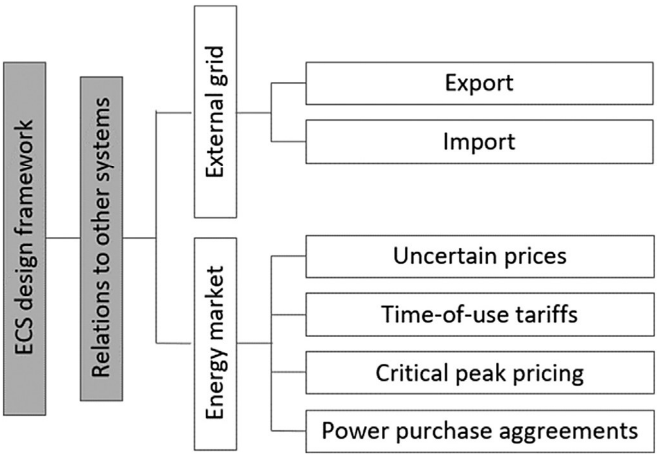

Fig. 16. Category Relations to other systems.

5. Conclusion

Rising energy demands, scarce resources, and continuously increasing resource costs require a more efficient use of energy in the industrial sector — from an ecological and an economical perspective. To use and acquire energy as efficiently as possible, on-site ECSs have been identified as one of the main solutions. To fully benefit from the efficiency potentials of on-site ECSs, the ECSs have to be designed accurately under the consideration of the relevant design aspects. This accurate design is especially relevant when designing an ECS for manufacturing companies, as their varying energy demands strongly decrease an inaccurately designed ECS's efficiency. Hereby, the many aspects that are crucial for an ECS's adequate design and the design's high complexity force researchers to focus on different design aspects for individual planning problems. This has led to a huge number of problem-specific approaches. Although this increasing number of approaches is very appreciated, it complicates the search for most related ECS design approaches for a specific design problem and the structuring and analysis of the research area. In Consequence, an appropriately comprehensive concept-centric framework with unambiguous and unified definitions is desperately needed.

Therefore, we developed the ECSDF. It is developed from an initial scope of more than 44 carefully selected publications and 32 preceding reviews and is composed of eight main categories, 27 sub-categories and 126 attributes representing aspects which are essential for a high quality ECS design for manufacturing companies. Of course, the current state of the framework is not final but future literature analysis will lead to continuous adaptations like performed in the iterative development process.

Next step to fully exploit the benefits of the developed ECSDF is the analysis of the classified articles by an extensive literature review (the classification of ECS design approaches used for the ECSDF development can be found in the supplementary material). Unfortunately, there is no space in this paper to perform such an analysis adequately.

In summary the concept-centric ECS design framework's main contributions are to provide a knowledge base for decision makers for identifying relevant design approaches, to facilitate the search within the existing literature, to unify the understanding of the crucial design aspects, to support the analysis and structuring of individual planning problems, and to provide the base for an empirical literature analyses to disclose research gaps and provide insights for future research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127258.

Appendix

A-1 Search string

TI = (conversion OR planning OR generation).

AND TI = (model* OR optim* OR dimensioning OR design*)

AND TS = (combined heat and power OR chp OR cogeneration OR cchp OR combined cool* heat* power OR trigeneration OR photovoltaic* OR pv OR Solar* OR turbine OR hydro power OR fuel cell* OR biogas* OR biomass OR boiler* OR combustion engin* OR heat pump* OR stand alone OR energy system* OR power system* OR wind power).

AND TS = (size* OR scale* OR dimensioning* OR design*)

AND TS = (plant* OR industr* OR produc* OR compan* OR firm* OR enterprise* OR corporation* OR concern* OR manufactur*)

NOT TS = (hospital OR building OR grid OR household OR store* OR schedule* OR commercial energy OR region* OR area* OR district* OR market).

AND SO = (Applied Energy OR Applied Thermal Engineering OR "Computers & Industrial Engineering"OR Electric Power Systems Research OR Energy OR Energy & Environmental Science OR "Energy Conversion and Management" OR Energy Economics OR Energy for Sustainable Development OR Energy Journal OR Environmental Research Letters OR "Experimental Thermal and Fluid Science" OR "IEEE Journal of Emerging and Selected Topics in Power Electronics" OR IEEE Journal of Photovoltaics OR IEEE Power & Energy Magazine OR IEEE Transactions on Energy Conversion OR IEEE Transactions on Industrial Electronics OR IEEE Transactions on Industry Applications OR IEEE Transactions on Power Delivery OR IEEE Transactions on Power Electronics OR IEEE Transactions on Power Systems OR IEEE Transactions on Sustainable Energy OR IET Generation Transmission & Distribution OR IET Power Electronics OR IISE Transactions OR International Journal of Electrical Power & Energy Systems OR International Journal of Engineering Science OR "International Journal of Heat and Mass Transfer" OR International Journal of Hydrogen Energy OR International Journal of Production Economics OR International Journal of Production Research OR International Journal of Thermal Sciences OR JOM OR Journal of Cleaner Production OR "Journal of Modern Power Systems and Clean Energy" OR Journal of Operations Management OR Nano Energy OR Nonlinear Analysis: Real World Applications OR "Production and Operations Management" OR Production Planning & Control OR "Progress in Energy and Combustion Science" OR Progress in Photovoltaics OR Renewable & Sustainable Energy Reviews OR Renewable Energy OR Solar Energy OR "Solar Energy Materials and Solar Cells" OR "Sustainable Energy Technologies and Assessments" OR Journal of the Energy Institute).

The abbreviations of the search string mean the following:

- TI = title
- TS = title, abstract, and key words
- SO = journal name

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