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A Qualitative Investigation of German Manufacturing Enterprises' Efforts to Incorporate Sustainability Into Industrial Site Transformations

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ABSTRACT

Manufacturing enterprises aim to futureproof their sites through transformations towards sustainability. These are affected by an inherent competition for usable space, with each successive transformation changing the overall site composition. Despite finances having the highest priority for enterprises, land is nonetheless being allocated to socio-environmental measures. Using insights from a systematic literature review addressing integrated site planning and land use competition, an interview study with 19 experts was conducted. Experts represented the fields of site planning, facility management, and sustainability management. The study focused on plans for energy systems, including challenges faced during their planning and execution, supplemented by how land is used for socio-environmental sustainability measures. The interviews were coded and analyzed using Kuckartz' qualitative content analysis. The results show proactive engagement by enterprises to meet climate goals ahead of regional policies. Within this scope, the goal of ensuring economic competitiveness is pursued through a variety of different means, such as security of energy supply, self-sufficiency, adaptability to new technologies and regulations, and staff retention. Organizational challenges were found to outweigh financial ones. Socio-environmental site measures are considered important by site planners, but not necessarily decision-makers who approve investments. Land use competition is addressed implicitly, but not systematically, pointing towards a need for methodical approaches integrated site planning.

Keywords

Net-zero production;
Land use competition;
Industrial energy supply systems;
Multicriteria decision-making

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1. Introduction

The European Union (EU) has pledged to achieve climate neutrality by 2050 [1]. As the second largest global economy (measured by gross domestic product) in 2024, the EU aims to thus make significant contributions towards sustainable development [2]. The climate goals are further anchored in absolute sustainability, as reaching them would significantly reduce global anthropogenic emissions by shifting human activities towards the safe operating space (SOS) within the model of planetary boundaries [3].

Despite human activities typically being quantified through greenhouse gas emissions, manufacturing enterprises do not solely affect the planetary boundary for

climate change. Of the remaining eight boundaries, this work addresses land system change, which is defined as a change in natural landscapes affecting the current equilibrium state of the system Earth [3]. Urbanization, particularly the sealing of surfaces as an infrastructure measure, factors into this. By extension, industrial sites contribute to land system change during their initial construction and subsequent transformations.

Sites also continuously experience land use competition. As per Siemons et al., land use competition refers to competing types of usage for the same plot of land [4]. Since land is a finite resource, prioritization must be made between economic gains (e.g., through

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List of Abbreviations

IESS: Industrial energy supply system

construction of individual factories) and environmental considerations (e.g., greening, reforestation, unsealing surfaces). Sites further incorporate spaces used for social sustainability (e.g., break rooms, coffee/tea kitchens, canteens, recreational facilities), requiring financial investments by the enterprise without having directly measurable financial returns. Nevertheless, enterprises make investments into socio-environmental measures, with motivation ranging from workforce retention to regulatory requirements, such as the European Sustainability Reporting Standards.

Methods, frameworks, and tools for sustainable planning, particularly for energy systems, already exist, including multicriteria decision-making [5] and sustainable energy planning [6]. These can be combined with other methodologies, such as energy flow optimization and energy modeling (for system design) or Delphi communication techniques (for project management) [5], and can even be applied to sustainable energy management applications [7]. Despite these approaches existing for specialized fields of sustainable planning, ones that systematically consider integrated sites appear to be limited.

This prompted the authors of this work to conduct a systematic literature review to identify current investigations into integrated sustainability on a site level (see Section 2). The results showed a substantial gap between perceived industrial efforts and academic research, as publications either focus solely on energy systems, or lean into socio-environmental aspects with minimal consideration of how these affect manufacturing processes and overall site compositions. These insights led to the formulation of the following two research questions: How is integrated sustainability pursued by German manufacturing enterprises as part of their transformation strategy? How does land use competition manifest on sites? The questions were then addressed in an expert interview study (see Section 3).

In the context of this work, integrated sustainability considers all three pillars of sustainability (environmental, social, economic) [8]. It is sometimes referred to as holistic sustainability [9], with exemplary models that build on this concept including the wedding cake model [10, 11] and the Humanitarian Information, Logistics, Coordination, and Situation Awareness (HILCSA) framework [12].

This work focuses on German manufacturing enterprises and their efforts to incorporate sustainability into industrial site transformations. Transformations are investigated with regards to how industrial energy supply systems (IESS) are incorporated into sites and trends for futureproofing said systems, as well as with regards to socio-environmental site measures. The latter is highly relevant, as such examples of site usage reduce the available space for manufacturing, which results in a form of land use competition. Section 2 provides the procedure used to identify the research gap through the aforementioned systematic literature review. Section 3 gives an overview over the methods used in the qualitative study that was conducted to address the research gap identified during the review from Section 2. Planning methods and methodologies, as well as challenges and criteria for successful transformation, are also analyzed. Section 4 presents and discusses the results of the content analysis. Section 5 summarizes the findings and offers an outlook for this work.

2. Systematic Literature Review

To analyze existing research related to sustainability-focused industrial site transformation, a systematic literature review was conducted in accordance with David and Han [13]. Three search dimensions (System Boundary, Objective, and Approach) were defined to set the scope. Searches were carried out in English, with full search strings documented in Figure 1 along with the workflow in Figure 2. The databases ScienceDirect and Web of Science were used. Snowballing and gray literature were used to generate additional search results, along with searches in German. The results of the broad review were used to shape the fine review (Section 2.2) and qualitative study (Section 3.1), as per Figure 2. The full review was completed on February 1, 2025.

Dimension 1 was set as the system boundary, focusing on the industrial sector. Due to manufacturing and production often being used interchangeably in this sector, both terms were used. Furthermore, industrial sites were considered to include sites, locations, bases, centers, and facilities. During the review, factories were

Dimension	Sub-Dimension	Search Strings
System Boundary		facility* ; produc* ; manufactur* ; site* ; location* ; base* ; cent?r* ; facility* ; factor*
Objective		sustainab* ; transform*
Approach	Processes	“energy efficien*” OR “production efficien*” ; “energy flexib*” ; “renewable energ*” ; energ* ; renewables ; therm* OR heat* or cool* ; electric* ; layout* ; structure*
	Socio-Environmental	green* ; “green space*” ; “wall-greenery” OR “wall greenery” ; “roof-greenery” OR “roof greenery” ; “blue space*” ; “bod* of water” ; river* OR lake* OR sea* OR ocean* ; biodiversity OR “bio-diversity” ; UHI OR “urban heat island” ; SDG OR (“social development goal” AND “social development goals”)

Figure 1: Full search strings grouped by dimension and sub-dimension.

identified as a focal point of transformation and were thus added to the search terms.

Dimension 2 was set as the objective, aiming to identify sustainability measures that are anchored in the physical level of sites and linking them to on-going or planned transformation projects. Enterprise transformations at the conceptual or strategic level were omitted from the review.

Dimension 3 was set as the approach, but due to the scope of integrated sustainability, this dimension was further split into two sub-dimensions. Processes refer to site measures that directly affect production, e.g., energy efficiency measures, renewables integrating into industrial energy supply systems (IESS), changing site layouts. Socio-Environmental refers to measures that are peripheral to production, e.g., biodiversity through greening, pursuing sustainable development goals, addressing air pollution, utilizing bodies of water.

2.1 Broad Review

A broad review was performed using the predefined dimensions. Figure 2 details the number of identified

results for System Boundary, and for combinations of System Boundary and Objective. Results for combinations of System Boundary and Objective and Approach can be found in in Table 1. The number of duplicates between databases was not investigated. The term variations was used to refer to repeated searches in Dimension 3 using similar terms, e.g., one search with green*, another with “green space”.

Each subsequent dimension successfully focused the scope. However, publications from unrelated fields (e.g., chemistry) could be found as early as in the first five search results. Thus, a fine review was conducted in accordance with David and Han to identify works with high relevance to sustainability in industrial site transformations [13].

2.2 Fine Review

Results from Table 1 were initially analyzed based on titles and keywords, followed by abstracts. Publications that could be accessed as full papers were then selected based on relevance and innovative perspectives.

Broad Review

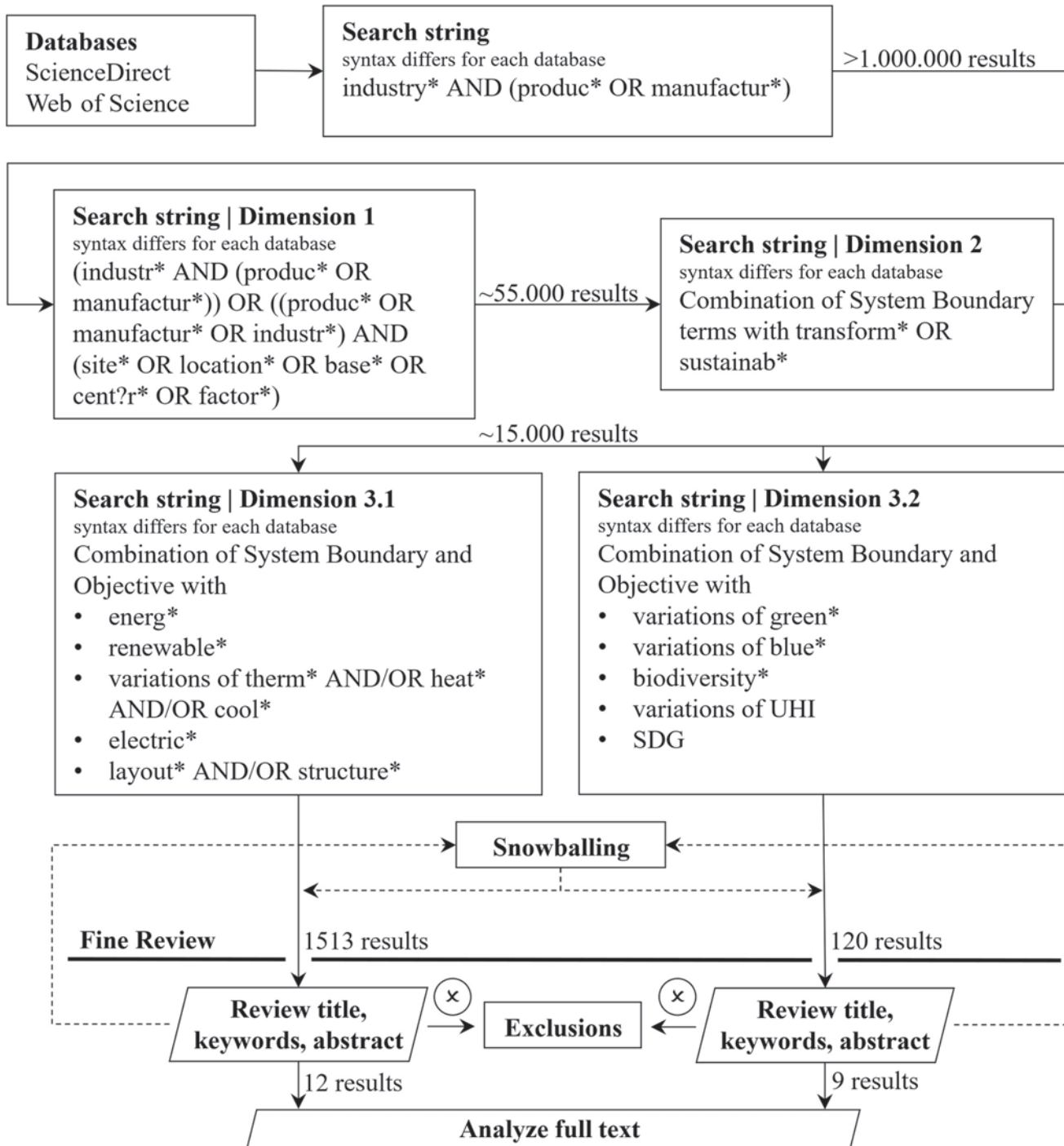


Figure 2: Workflow of the systematic literature review. Search strings shown in simplified form.

Relevance was based on whether papers addressed sustainability and industrial site transformation. Innovation was based on consideration of integrated sustainability

or land use competition. Using this approach, the number of results obtained from the broad review was successfully reduced.

Table 1: System Boundary combined with Objective and sub-dimensions for Approach (Processes and Socio-Environment) – search string logic and total resulting number of identified papers.

Search String for Processes	Results
Combination of System Boundary and Objective with variations of energy*	855
Combination of System Boundary and Objective with renewable*	314
Combination of System Boundary and Objective with variations of therm* AND/OR heat* AND/OR cool*	119
Combination of System Boundary and Objective with electric*	164
Combination of System Boundary and Objective with layout* AND/OR structure*	61
Search String for Socio-Environmental	
Combination of System Boundary and Objective with variations of green*	58
Combination of System Boundary and Objective with variations of blue*	22
Combination of System Boundary and Objective with biodiversity*	22
Combination of System Boundary and Objective with variations of UHI	5
Combination of System Boundary and Objective with SDG	13

The sub-dimension Processes returned significantly more results than Socio-Environmental, particularly for energy-related measures. Generalized aspects of energy (e.g., renewables) were the most common. Electrical applications were discussed more than thermal ones. While the review was aimed at specific applications of research to industrial sites, most energy-related technological and operational findings could be transferred directly to site planning. The following paragraphs contain the findings identified as most relevant to Processes, clustered by content; for research that was not explicitly linked to site planning/transformation, it was selected due to being anchored in IESS.

The link between land system change and site transformation is addressed in two publications. For this work, transformation was defined as a process that begins with a current state, from which a fundamental change is initiated and executed with the aim of reaching a predefined target state [14]. For the review, it was taken to refer to enterprise activities that change aspects of an industrial site, e.g., technical changes to energy systems or construction around factory buildings.

Sredić proposes that transformable area systems can be introduced as technical systems to replace terrestrial areas [15]. Transformability of factories is investigated for factory planning and applied to automobile manufacturing plants [15]. Bigliardi et al. conduct a literature review of industrial additive manufacturing with regards to economic, environmental, and social sustainability [16]. Contrary to economic and environmental sustainability, social impacts remain largely unmeasured [16].

Planning approaches are addressed in four publications. Hassan et al. introduce a scenario-based framework for integrating energy storages for decarbonization [17]. Bang et al. propose a methodology for translating national energy scenarios into local ones, including ones for the industrial ones [18]. Their framework specifically addresses national goals for Denmark [18]. Kaucher et al. describe the need to futureproof industrial buildings in as early as their planning phase [19]. Through their planning method that identifies potential future changes to production, future building requirements can be identified in early planning phases [19]. Kapp et al. present a machine learning model based on energy audits from 45 manufacturing facilities, which predicts the energy consumption of buildings [20].

In terms of production and energy scheduling, three publications were identified. Jabeur et al. present a mathematical programming model for production scheduling that accounts for energy storage systems, renewable energies, and peak load shaving via demand-side management [21]. The model is tested in an industrial use-case involving a multi-product and multi-process manufacturing system [21]. Su et al. present a multi-objective optimization scheduling model for steel plants, which includes renewable energy sources and energy storage systems [22]. The integration allows for costs to be reduced by 68.5% (electricity and emission costs), and for grid-related emissions to be reduced by 83.5% [22]. Ibitoye et al. give an overview of integration of biochar production into iron and steel plants [23]. They assess the impact of such transformations on iron/steel industrial processes (i.e., heating values being comparable to coke

and higher than those of coal), as well as environmental impacts (32-58% reduction of CO₂ emissions) [23].

The largest number of publications addresses IESS. The following eight were identified as most relevant to site planning. Schulz et al. analyze potentials of German manufacturing enterprises' on-site power generation (thermal and electrical) [24]. Sustainability in this work refers to the energy policy trilemma: economic efficiency, supply security, environmental impacts [24]. They characterize industrial on-site consumers in electrical and thermal grids by dividing them into 48 type groups [24]. Schmid et al. use a German chemical site to investigate integration of renewable hydrogen into production sites, evaluated using a cost-optimization energy system model [25]. The need for policies to accelerate transformation is explicitly addressed [25]. Asplund and Nilsson consider industrial electrification and photovoltaic systems in Northern Scandinavia, the latter showing levelized costs of electricity to be at 51 EUR/MWh, expected to sink to below 35 EUR/MWh by 2030 [26]. Karthikeyan et al. analyze thermo-economic approaches to integrating cooling, power generation, and green hydrogen production in dairy plants [27]. This is investigated in conjunction with a solar-and-biomass supply system. As a result, environmental impacts can be lessened by a minimum of 43.6 kg CO₂/h in comparison to electricity-powered systems [27]. Despite peak energy efficiency of 19%, exergy efficiency of 11%, and economic efficiency of 34% of the system, the infrastructure and its operation raise total plant costs by 75% [27]. Ghionda et al. consider not only energy efficiency, but also energy flexibility for decarbonizing electrical and thermal supply systems in pharmaceutical applications [28]. Kohne presents a techno-economic optimization method for planning around the investment and deployment of connections between district heating and IESS [29]. Pastore et al. investigate levelized costs of hydrogen from solid oxide electrolysis cells when coupling industrial waste heat with on-site electrolysis [30]. The best result is achieved at 6.1 Euros/kgH₂ [30]. Mahamoud Abdi et al. analyze obstacles in the implementation of geothermal systems across Djibouti, Ethiopia, and Kenya [31]. They identify categories for trust issues relating to corporate organizations, governmental institutions, procedural systems, and technology [31].

As can be seen from the results for Processes, this dimension mainly investigates energy efficiency and scheduling measures. While these are linked to site planning, the link remains largely implicit. Instead, this

sub-dimension is focused on transformation. Integrated sustainability is only addressed by Bigliardi et al., leading to the conclusion that, unlike factory or energy system planning, site planning is underrepresented in academic publications.

In addition, this sub-dimension shows that usage of the term "green" for sustainability-related terms is not subject to standardized definitions, as noted by Mueller et al. [32]. Motivation for investigating process-related measures is rooted in concepts ranging from sustainable development to absolute sustainability. Sustainable development takes place when the needs of the present generation are met without compromising future generations' ability to meet their respective needs [8]. While the definition for sustainable development implies limits, these limits are not absolute. Rather, they are imposed by the current technology and social organization on environmental resources, as well as the biosphere's ability to naturally balance out the effects of anthropogenic activities [8]. On the other hand, absolute sustainability places quantifiable limits on anthropogenic activities [33]. These limits are currently based on the SOS defined by the planetary boundaries model; for climate change (specifically atmospheric CO₂ concentration) the SOS is set at 350 ppm atmospheric CO₂ (compared to the average measured value of 423 ppm in 2025) [3]. Activities can only be called sustainable once they are within the allocated SOS. This offset for "green" leads to academic approaches aiming for states that can either relatively improve a current state (i.e., make it better than before) or result in quantifiable improvements that implicitly contribute reducing emissions to within the SOS. However, few publications explicitly aim for absolute sustainability.

For the sub-dimension Socio-Environmental, the review revealed that it had more publications related to site planning than Processes, albeit ones centered around ecological and geographical research. Industrial aspects were often mentioned, but rarely the focus. Thus, industrial integrated sustainability was even less prevalent. This was to be expected, as manufacturing sites typically prioritize economic sustainability during investment and transformation decisions. A selection of innovative takes on the socio-environmental sub-dimension is as follows.

Four publications address sustainability assessments for industrial sites. Bilyaminu et al. investigate the transformation of industrial parks using an integrated sustainability assessment [34]. They identify transformation

opportunities (e.g., renewable energy integration, upgrading existing infrastructure cross-sectoral resource sharing, education for employees) and apply them to an existing industrial park [34]. The findings are transferred to a nationwide level [34]. Fernando et al. investigate challenges of implementing green spaces into manufacturing environments using a textile factory [35]. They address different enterprise hierarchy perspectives as well as benefits of successful implementation [35]. Trubetskaya et al. investigate the relationship between industrial sites and their environmental footprint [36]. Interdependencies between energy use, water use, and carbon emissions are analyzed for the steel, healthcare, textile, and paper industries [36]. Banti et al. investigate the link between energy demand of industrial buildings and their environmental impacts (e.g., resulting urban heat islands) through the use of greenery systems (e.g., green facades) [37]. Their model shows potentials of up to 34% energy demand reduction during the summer period [37].

Three publications address site layouts. Liu et al. use an artificial neural network to simulate the effect of factory layouts on the environment [38]. An industrial site incorporating steel factories is used to generate the datasets, with which extreme urban heat islands are investigated [38]. Bücken et al. use a scenario-based analysis of logistics sites with regards to transformation and land use [39]. Transformation encompasses unsealing of surfaces and greening, and indirectly addresses land use competition [39]. Zhou analyzes ocean energy applications, including transmission and distribution [40]. While not directly linked to industrial sites, the application for seashore communities is analyzed and can thus offer planning insights for coastal manufacturing sites [40].

Land use competition is explicitly addressed in two publications. Bruns et al. offer a reflection on land use competition that focuses on the relationship between land and water [41]. Industrial uses for water (e.g., cooling energy) are indirectly addressed [41]. Niewöhner et al. present a high-level, integrated perspective (environmental, economic, and social) on land use competition [42]. Industrial applications are only inferred [42].

This section of the review highlights that Processes-related publications dominate the scientific manufacturing community. This is likely influenced by economic sustainability (i.e., aspects like efficiency) being the driving motivator for industrial applications and applied research. Environmental sustainability, too, is motivated

by costs (i.e., mitigated costs) and by policies/regulations. The socio-environmental sub-dimension largely focuses on non-industrial aspects, such as city planning and environmental preservation. Integrated approaches that link both sub-dimensions are rare, while land use competition in industrial settings is, at best, addressed peripherally. This led to the formulation of two research questions: How is integrated sustainability pursued by German manufacturing enterprises as part of their transformation strategy? How does land use competition manifest on sites?

3. Methodological Framework

This section describes the methods used to formulate a means of addressing the identified research gap through a qualitative study (Section 3.1) and analyzing the content from said study (Section 3.2).

3.1 Qualitative Study: Expert Interviews

Due to the open-ended nature of the research questions derived in Section 2.2, a qualitative study was developed to build on the literature review. It was designed in form of a series of expert interviews with German industry representatives working in site planning, facility management, and sustainability management. Each interview lasted about 60 minutes.

16 interviews were conducted to achieve sufficient saturation with a total of 19 interviewees. 16 representatives came from enterprises that either directly engage in manufacturing (12 interviewees) or work in the field of site planning (4 interviewees). 3 interviews took place as joint interviews with experts from two collaborating enterprises, business units, or departments. The remaining 3 interviewees represented research institutions and an administrative urban development office. The latter served to gain insights into city planning conditions that affect industrial sites, which will not be discussed in this work.

Participating enterprises belonged to the following industrial branches: chemicals/pharmaceuticals, electronics, mechanical engineering, metalworking, packaging and processing, and plastics. 10 interviewees represented small or medium enterprises, 5 a large enterprise, 1 a micro enterprise.

The interviews were drafted as semi-structured expert interview as per Helfferich [43], with the intent of allowing interviewees to give insights into aspects of sustainable site planning they believed to be most relevant to

their enterprise. To shape the semi-structured interviews, guiding questions were used, which are available on TUdatalib [44].

3.2 Qualitative Content Analysis

Qualitative data can be greater in diversity and complexity than quantitative data [45]. Particularly in interviews, interviewees can bring subjective perspectives to objective matters, which in turn is prone to further subjective interpretation by interviewers. The aim of a content analysis is thus to introduce a systematic approach with which to interpret qualitative results while simultaneously reducing biases.

The qualitative content analysis as per Kuckartz was conducted using the software MAXQDA [46]. Six main categories were deductively identified prior to the first interview in a concept-driven approach, based on the systematic literature review from Section 2, the authors' existing knowledge, and the guiding questions. These can be found in Figure 3.

Transcripts were generated for each of the interviews, which were proof-read and manually revised as needed. All information regarding the enterprises was anonymized.

Sub-categories were derived inductively in an iterative, data-driven approach during the coding process, resulting in a mixed coding approach. Main categories were reworked in the same manner. Added categories can be found in Figure 3. The number of codes in Figure 3 denotes how often categories were mentioned in total, not how many unique perspectives were offered by the interviewees. Results from this section (included ones omitted from discussion for this work) can be found in anonymized and summarized form in TUdatalib [44].

4. Results and Discussion

This section presents the interview results, grouped by main categories. Results show identified trends in German manufacturing companies, along with insights into plans for transforming industrial sites. Only information gained directly from codes of the content analysis is discussed in this section, attempting to limit the authors' subjective interpretations, which is reserved for Section 4.6. The total number of mentions in each category are given in parentheses.

4.1 Industrial Energy Supply Systems

Space and process heating are addressed by all enterprises; cooling (outside of heat pump applications) only

by 5. Unidirectional district heating connections are used by 6 enterprises (1 connected directly to an indoor pool, 1 to a waste-to-energy plant). District cooling is used by 2, with a further 3 using central cooling systems on their sites. Bidirectional district heating connections were investigated in 1 case but were found unprofitable. For heating systems, 7 enterprises rely on natural gas, 3 of which use combined heat and power (CHP) plants, 1 of which is intended to be phased out soon. Heat pumps are used by 8 enterprises.

Electrical applications focus on lighting (15), heat pump operations (14), ventilation systems (12), air compressors (10), and electricity-intensive machinery (6 specific, 11 general mentions).

Renewable energy technologies focus largely on photovoltaic (PV) and geothermal energy. 12 separate instances of PV module installation were discussed: 7 roof-based (1 of which is specifically for circumventing fossil fuels), 1 placement of modules on unused land, 1 combined usage with electrolysis). For geothermal energy, 8 separate instances discussed: geothermal loop fields used for space heating and cooling (SHC) combined with process heating and cooling (PHC) (1 at depths over 150 m, was laid out to cover peak loads), plus loop fields for SHC (1 at 300 m, 1 at over 700 m, 2 at unspecified depths). 1 geothermal well system for SHC and PHC. 3 mentions of current usage times of geothermal systems: 1 year for 150 m, 9 years for 300 m, 15 years for unspecified depth. Air source heat pumps are used by 4 enterprises, 2 of which are substitutes for geothermal systems that were not feasible due to hydrogeological and spatial limitations. Hydrogen is used in 3 further cases (1 H₂-ready boiler, 1 H₂-ready CHP plant, 1 general preparation of energy infrastructure for hydrogen). Water-related applications included analyses of nearby river usage for cooling (2) and heating (1), though "investment costs were too high to be implemented" [44]. 2 planned uses for heating/cooling using river heat pumps, although these likewise are "subject to economic feasibility analyses" [44]. 1 potential use of hydropower for electricity. On-site wind energy exists for 2 enterprises, 1 of which uses rooftop wind turbines, albeit with "far lower yields than initially expected due to design limitation of such systems" [44].

16 types of storage systems are being used, including thermal buffer (2), hydrogen (1), ice (1), electrical battery (3), and compressed air storages (1). There were 2 mentions of storages being "unfeasible due to combined spatial and financial limitations" [44].

Main Categories	Sub-Categories	Sub-Sub-Categories
Industrial Energy Supply Systems (280)	Parameters (22)	
	Electrical (57)	
	Contracting (14)	
	Fuels, non-thermal (3)	
	Storages (16)	
	Thermal (9)	Heating (65)
	Renewables (2)	Cooling (17)
		Water (6)
		Wind (9)
		Heat Pumps, air (6)
PV (22)		
Hydrogen (7)		
	Geothermal (25)	
Environmental Site Measures (75)	Buildings (17)	
	Greenery (24)	
	Biodiversity (5)	
	Unsealed Surfaces (8)	
	Water (19)	
	Other (2)	
Social Site Measures (92)	Mobility (24)	
	Workspace (22)	
	Recreational Space (27)	
	Other Space (19)	
Industrial Site Planning (415)	Sustainability (49)	Reporting (16)
	Unsystematic Approaches (172)	
	Systematic Approaches (19)	
	Actors/Stakeholders (67)	
	Feedback for Policies (60)	
	Lessons Learned (32)	
Evaluating Transformation (247)	Obstacles (-)	Technical (21)
		Organizational (53)
		Regulatory (23)
		Financial (45)
	Criteria for Success (92)	
Certifications (13)		
Land Use Competition (52)		

Figure 3: Categories of the qualitative study with corresponding coded segments in parentheses.

Energy efficiency measures are pursued for both thermal and electrical applications. For thermal, waste heat recuperation for internal usage was prioritized, e.g., from air compressors (7), ventilation (6), and machinery (5). Electrical efficiency mainly included switching to more efficient technologies. Electrical recuperation was discussed in 1 case.

Parameters and target states were addressed 22 times. Self-sufficiency was mentioned for 12 enterprises (1 case as a means of responding to energy crises, 2 for achieving price and market independence; 6 cases of trying to reach climate targets earlier than 2050). Decentralized energy supply was addressed for 2 enterprises. There were 2 mentions of aiming for independence from fossil fuels. Peak load shaving (e.g., 1 use-case via bidirectional charging stations for enterprise vehicles) is attempted along with participation in energy markets (3).

For energy contracting, 14 enterprises have external sourcing of electricity, 3 of which use green electricity contracts. Power purchase agreements (PPA) exist for 7 enterprises (4 for wind energy, 1 for thermal energy) with a further 1 in planning for electricity.

4.2 Environmental and Social Site Measures

Environmental measures focus on greenery on roofs (10) and ground-level (8). Building materials are also investigated: 3 cases of hybrid wood designs, 1 glass, 5

recycled building materials. Energetic structural restoration of existing buildings was mentioned by 4 enterprises. 3 mentions of unsealing surfaces for parking space (1), roads (1), unused land (1), along with 1 mention of planning new sites with minimal sealed surfaces and 1 mention of first replanning site layouts before sealing further surfaces.

Social measures are distributed evenly across four sub-categories. Recreational on-site spaces include break rooms (15 enterprises), canteens (4), and coffee/tea kitchens (4). For workspace, the focus lies on office designs (10 separate mentions). Mobility offers focus on enabling public transport connections (5) and subsidizing public transport/e-bike usage (5), and installing on-site charging stations for vehicles and bicycles (4). Other social spaces discussed included childcare facilities (3), fitness centers (2), medical facilities (2), and multipurpose rooms (2).

4.3 Industrial Site Planning

Sustainability in site planning shows a wide range of applications, including reduction of greenhouse gases (7), net-zero states (6), constructing green buildings (6), and using integrated sustainability (5). Other mentions include circular economy (6) and increasing employee satisfaction (4).

Systematic approaches for site planning include using established planning frameworks, like the VDI 5200 (5),

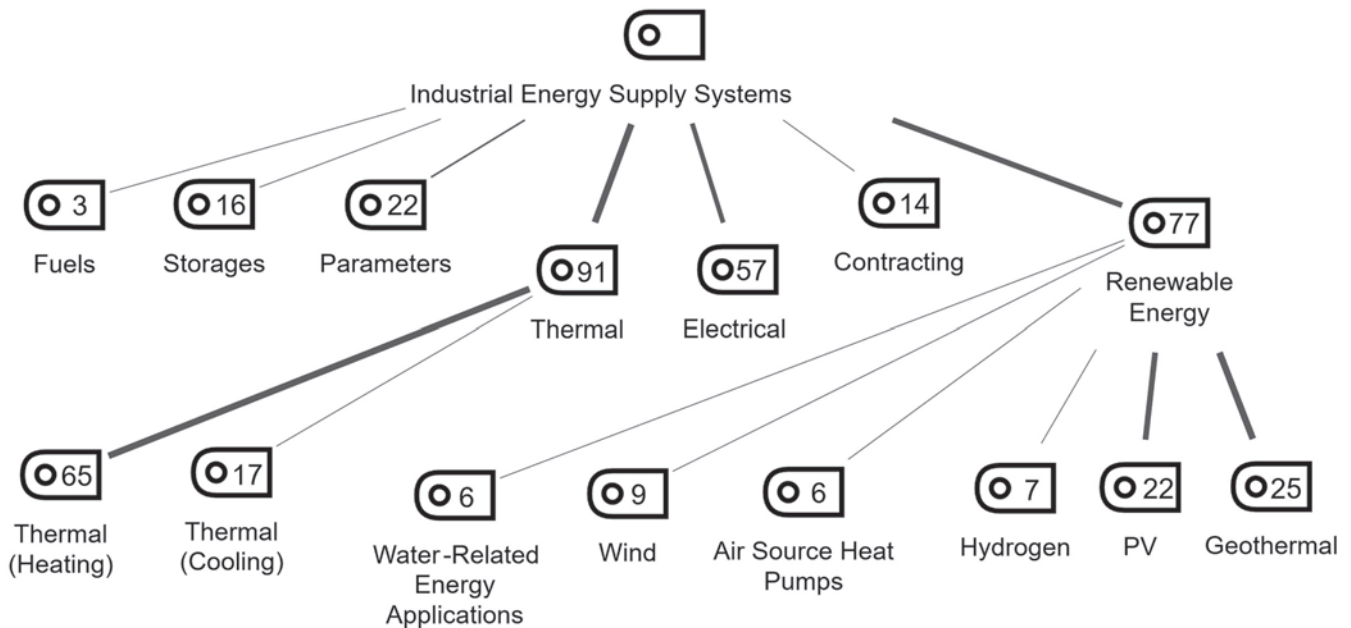


Figure 4: Visualization of code frequency for IESS; number of mentions on each label.

creating master and step plans in the early planning phases (4), top-down energy analyses (8), and systematic identification of efficiency/flexibility potentials (3). In addition, 5 enterprises “look to other sites” (and countries) when searching for solutions to specific problems [44]. 2 are eliminating technologies that are no longer compliant with European goals for 2050.

Unsystematic approaches are primarily based on involved actors’ knowledge and experience, including both one-off implementations and try-and-see approaches. The former includes:

- building modular factories and production systems (5) and vertical factories (4)
- laying empty ducts for future developments of thermal and electrical systems (2)
- leaving space for potential future development projects (4)
- “planning thermal pipelines to have currently larger-than-necessary diameters, in preparation for next-generational supply systems operating at lower temperatures” (1) [44]
- planning new buildings with access to geothermal systems through the basement (1)
- “adjusting ventilation rates based on actual particle concentrations in rooms” to save energy (1) [44]
- “isolating sub-optimal, yet critical processes, and providing them with individual solutions” rather than optimizing the entire IESS (1) [44]
- incorporating backup strategies (e.g., generators) to reduce risks of innovative systems (2)
- regional sourcing of materials and fuels (5)
- creating “company-internal standards for sustainable site planning”, which are “updated with each realized or failed project” (1) [44]
- using carbon capture and storage/utilization to offset remaining (not necessarily unavoidable) carbon emissions (1).

Positive feedback for policy makers includes energy regulations expediting the establishment of sustainability departments in enterprises (2), due diligence requirements opening “work relations with enterprises that share similar sustainability values” (1), and geothermal energy being simpler to integrate due to fewer regulatory requirements (1) [44]. Negative feedback mainly addresses the high degree of bureaucratization and regulatory requirements (8), political prioritization of renewable expansion over investments into storage systems

(2), “unreliable political support across longer time periods” (3), and local authorities’ efforts “slowing down company efforts rather than supporting them” (2) [44].

4.4 Evaluating Transformation

Criteria for successful site transformation were stated to include top-management commitment to sustainability (7), company-wide communication and knowledge-sharing (7), allowing for long-term breakeven periods for investments (5), working with interdisciplinary teams (5), and making profits through sustainability transformation (10).

Obstacles were grouped into four sub-sub-categories. Technical (21) and regulatory obstacles (23) were mentioned about half as often financial (45) and organizational (53) ones, as visualized in Figure 5. These partially address similar issues as the ones identified by Mahamoud Abdi et al. [31]. Technical obstacles address compatibility of systems with existing infrastructure (3), energy conversion efficiencies (4) and site-specific geological conditions (3). Regulatory obstacles mirror feedback for policy makers (see Section 4.3). Financial obstacles mainly address the need to have a business case for transformation. Organizational obstacles are mostly anchored within the enterprise’s structure (e.g., conflicts arising from either past decisions (5), decision-making processes (8), or available competences and resources (8)) though some addressed issues on the market-side of technologies, mainly the availability of specific technologies (4), e.g., H₂-ready CHP plants.

4.5 Land Use Competition

Competition between productive and non-productive spaces is implicitly considered by site planners, but seldom addressed systematically. Multiple mentions address rooftop competition between ventilation, PV, safety equipment, greenery, and windows (10). 2 mentions address other European countries being much further than Germany with regards to site densification. Additionally, competition is explicitly stated to arise from limited property spaces (7) and high costs for land (5).

1 enterprise introduced green space ratios at a company level, as otherwise productive spaces would always get prioritized by decision-makers. 1 interviewee mentioned that “Separating energy supply systems and production systems from social and environmental spaces in site planning leads to unnecessary complications in

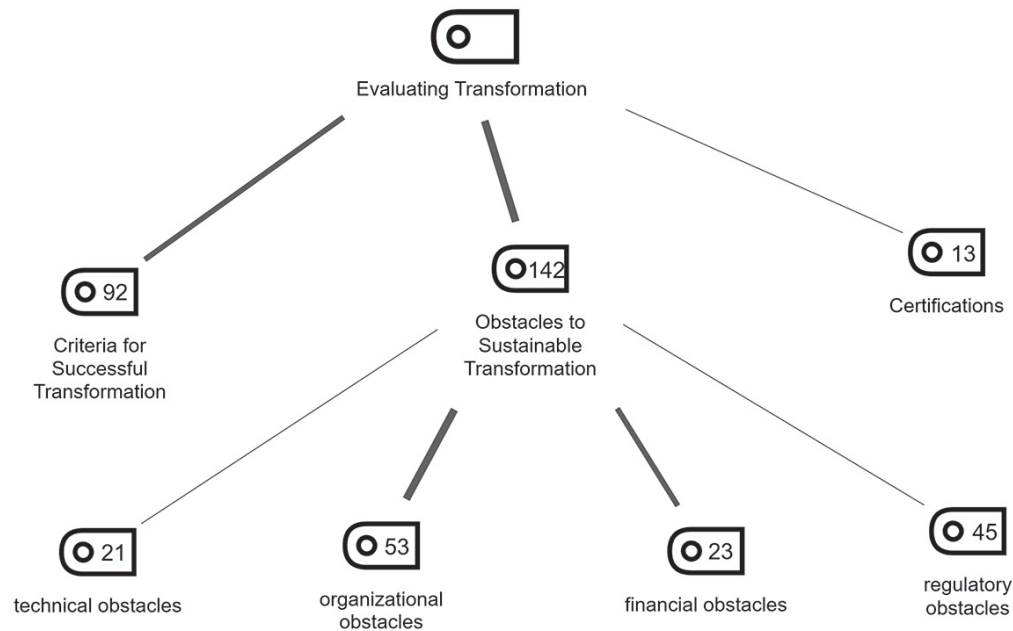


Figure 5: Visualization of code frequency for Evaluation; number of mentions on each label.

the long run. It also increases costs, as many issues can only be tackled holistically by taking an interdisciplinary approach and by conducting variant tests and utility analyses of different options” [44]. This sentiment was mirrored by 7 interviewees, with 5 of them stating that an analysis tool for land usage would greatly help incorporate integrative sustainability into their sites. In this regard, a quantification for social spaces that is on par with productive spaces was desired by 2 interviewees, with 1 other mentioning that “Maximizing productive spaces leads to social and environmental spaces being removed, as their contribution to productivity cannot yet be measured in, e.g., Euros. In that sense, the term productive space may need to be expanded to include manufacturing peripherals, like roads and canteens” [44].

5 interviewees believe that densification and land sufficiency are cornerstones of modern site planning that, due to being very complex and interdisciplinary, are not yet considered enough during investment decisions. 1 of them further stated that attempts at densification can realistically only be undertaken in economically stable periods.

Solutions to land use competition include joint PV ventures with other enterprises, e.g., agricultural space, for shared land use (2), expanding property (4), site densification (6), and using unutilized land for integrated site transformations (3).

4.6 Discussion of Results

Due to the semi-structured nature of the interviews, a highly varied and case-specific profile of approaches to integrated sustainability-focused transformation is presented by the experts. This limits statistical evaluation across the study. Furthermore, while sufficient saturation was deemed to have been reached, the scope of the study should still be considered limited. By interviewing more experts, a generalized overview could be derived for the German industry. Nonetheless, overlapping industrial trends were successfully identified.

Like the academic approaches identified through the literature review, German manufacturing companies seldom aim for absolute sustainability. Instead, they strive for transformations that improve the current state (relative sustainability), albeit with climate targets in mind. Additionally, energy systems are given much greater focus than integrated sustainability and integrated planning. The latter are seen as very important by site planners and architects, but proposed concepts are often dismissed, as company investments are driven primarily by immediate costs and financial returns. As such, socio-environmental decisions are generally only undertaken in times of economic growth.

For IESS, thermal applications were discussed in greater detail than electrical ones (91 vs 57 total mentions) across all interviews, as can be seen in Figure 4.

This is mirrored for renewables, where mentions of geothermal, hydrothermal and environmental heating/cooling applications outweighed PV and wind applications. The reason likely stems from the fact that thermal applications display greater unused potentials (e.g., waste heat reduction and utilization), as electrical applications have a larger share of current implementation. The latter trend mirrors the literature review. It is also mirrored for renewables; PV currently has more usage on sites, but geothermal energy potentials were discussed in greater detail. This is likely due to PV being more established as a technology and thus acting as a low-hanging fruit. On the other hand, geothermal energy still is met with reservations, partially driven by a negative image resulting from failed cases across the country. As such, it requires either cost-intensive planning or top-level commitment for industrial settings. Nonetheless, the open-mindedness of enterprises to consider geothermal applications displays a promising development towards decarbonizing the operation of thermal energy systems.

An important topic is the compatibility of new technologies with existing IESS infrastructure. By proactively designing sites to be sustainably integrated and adaptable, enterprises can futureproof their industrial sites. This can be achieved by laying out systems with climate targets (enterprise-internal as well as on a national/EU-level) in mind, reducing future investments into infrastructure transformation that may otherwise become necessary because of regulations. Examples include expansion of greenery or water to counteract industrial heat islands or constructing energy infrastructure that is compliant with future generations of systems. In addition, sites need to be densified to reduce land use and enable further land usage for socio-environmental aspects, while simultaneously expanding value-adding spaces. For this type of adaptability, available land remains the key enabler. Vertical factories, despite having high capital (constructional) and operational (logistical) expenditures, can thus be pursued to counteract spatial limitations.

Across all interviews, unsystematic planning approaches were found to outweigh systematic ones, which is likely due to site transformation being an interdisciplinary undertaking that lacks standards covering all involved areas of expertise. Preexisting methods as per Terrados et al. were not discussed beyond multicriteria decision making [5]. One interviewee mentioned that scientific research needs to be shared more effectively

with the industry and public, which would expedite methodical transformations. On this note, the lack of integrated site planning in the literature review was mirrored throughout the interviews.

Economic potential remains the driving factor behind transformation decisions. Socio-environmental investments are driven by regulatory requirements and the strategic aim to increase staff and know-how retention. Top-level commitment remains important, though individual profiles of decision-makers nonetheless continue influencing sustainability investments: “Company structures are certainly critical regarding investment decisions. As soon as a company grows and has complex structures in different business areas, many people want to have their say, and a decision made by top-management in the group does not automatically mean that it will be implemented in the subsidiaries” [44]. As mentioned by a site-planner, avoided costs are not universally used as evaluation criteria during project authorization; however, doing so may shift the economic benefit towards integrated sustainability project [44]. In addition, socio-environmental site measures can directly boost productivity: subsidizing public transportation can reduce site-wide traffic, allowing for optimized logistical streams. Childcare facilities can expand the portfolio of potential employees and furthermore reduce productive downtime for parents. As stated by an interviewee, “Productive, social, and environmental spaces are often weighed against each other, but this should not be the case. Particularly in the case of social against environmental, the benefits are often mutual” [44].

Land use competition is seen as an important topic but is not addressed systematically. Like socio-environmental investments, it depends largely on subjective tendencies and past experiences of decision makers and site planners. This is further affected by a lack of transparency regarding integrated sustainability in land use. The term sustainability itself is not used uniformly, reflecting usage of the term “green” [32]. Nonetheless, systematic ways of addressing land use competition are desirable for communication with decision-makers, who rarely have knowledge about such issues.

Self-sufficiency and supply chain independence drives industrial transformation, albeit in conjunction with PPAs for green energy where necessary. This extends to independence from regional developments, e.g., of utilities companies, as represented by the 6 enterprises aiming to reach net-zero ahead of the EU and national targets. This was mentioned to be based on the

belief that local entities and regulations are too slow. At the same time, unreliability of politics (i.e., regulatory changes coinciding with regime changes) was cited as being a disincentive to sustainability transformations; one interviewee mentioned that “Ten years ago, the first site/factory projects with a vision for 2030 were started. Today, new projects are still targeting 2030. This new horizon is, in part, due to rising regulatory and technological uncertainties for the period past 2030” [44]. The focus on self-sufficiency lends itself to decarbonizing IESS, as this transformation for industrial sites can be attempted with minimal external influences outside of availability and market-readiness of net-zero systems.

Further critique of regulations mainly addressed the degree of regulatory requirements. For enterprises that did not set their own climate targets, they appeared to be driven by these perceived regulatory burdens. This sentiment was reflected by one interviewee stating that “SMEs should be given more responsibility (which does not correlate to more freedom) for safety compliance rather than more regulatory measures” [44]. As such, the industry may benefit from policy makers lessening bureaucratic requirements.

5. Conclusion and Outlook

To meet climate targets, German industrial enterprises must undergo site transformations. The long horizon for usage of IESS, along with regulatory uncertainties for the future, either pushes enterprises towards proactive investments into IESS or results in them waiting indefinitely before taking action. On the other hand, staff retention and regulatory requirements related to climate targets incentivize an integrated site-planning approach, which benefits from socio-environmental measures being considered alongside economic benefits. Through a systematic literature review and subsequent semi-structured expert interviews, such transformation approaches were investigated. In addition, the review and study considered integrated sustainability on a site level, along with resulting land use competition and approaches to address and circumvent it.

While a statistical evaluation of the study is not possible, a trend towards self-sufficiency and better utilization of thermal systems was identified, extending to both fossil and renewable systems. For site-planning, a trend towards densification was identified, indirectly addressing land use competition.

Two topics were identified by the authors as highly relevant for following up on the study. The first involves

a system of incorporating avoided environmental costs into cost analyses for investments into decarbonizing energy systems. Ideally, this would need to be developed to consider energy scheduling as well as production planning, due to the interdependency between both aspects resulting in requirements of key production processes affecting energy system transformations. The second involves a tool for enabling systematic analyses of integrated sustainability based on land usage, primarily targeted at enterprise departments with limited access to building information models; as per the study, such quantification would allow for better comparison between sustainability targets for different site investments, thus enabling informed decision-making for industrial site transformations. This quantification could further represent a step towards absolute evaluation of transformation by creating a bridge between absolute and integrated sustainability.

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