TOWARD SUSTAINABLE SEMICONDUCTOR MANUFACTURING: ENERGY EFFICIENCY, RESOURCE OPTIMIZATION, AND SOCIO-TECHNICAL DYNAMICS IN INDUSTRY 4.0

Themenbereich: ENERGIEEFFIZIENZ, DIGITALISIERUNG UND SMARTE ENERGIESYSTEME

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Motivation and Research Questions

The increasing pressures of climate change, rising energy demand and resource constraints have intensified the need for more sustainable and energy-efficient forms of manufacturing [1][2]. Within this context, the Industry 4.0 paradigm has gained widespread attention as a potential driver of sustainability, promising improvements through digitalization, automation and data-driven optimization of production processes [3][4][5]. Yet despite these expectations, the sustainability implications of Industry 4.0 remain insufficiently understood, particularly as the introduction of digital infrastructures may also increase electricity consumption and introduce new socio-technical challenges [5][6]. At the same time, human actors play a decisive role in shaping energy efficiency outcomes, from the adoption of new technologies to the management of organizational learning and cultural change [7]. However, their role is still underexamined in existing research [3][4]. Against this background, the present study employs a qualitative research design based on expert interviews and a focus group to investigate how issues of resource efficiency and environmentally responsible production are interpreted and addressed within Industry 4.0 settings in the semiconductor industry. The study seeks to identify the central organizational and human-centered conditions that hinder or facilitate more sustainable operational practices related to energy and resource efficiency in manufacturing environments.

Methods and Data

The study draws on a qualitative multi-stage research design combining expert interviews and an expert focus group. In an initial phase, the technological use case was defined in a series of requirements workshops, complemented by desk research to map the state of knowledge on non-technical, human-centered aspects of Industry 4.0 in relation to sustainability and energy/resource efficiency. A preliminary round of exploratory interviews served to refine the interview guide and to conduct a stakeholder-mapping exercise, through which additional relevant actors were identified. Building on this, five semi-structured expert interviews were conducted between March and June 2024, each lasting 45–70 minutes, to gather in-depth insights into organizational practices, resource-saving potentials, and procedural interfaces. All interviews were recorded, transcribed, and systematically coded using MAXQDA.

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The interview participants represented a cross-section of key operational areas, including facility management, line and production coordination, automation, logistics, and IT. To further elaborate process interdependencies and contextualize the role of human agency, a virtual focus group (lasting approximately 100 minutes) was held in June 2024 with five participants drawn from the firm-internal stakeholder network. Including specialists from operations management, project management, vacuum and abatement systems, facility management, and energy management ensured a broad and informed perspective on the use case. The discussion was transcribed and integrated into the analysis. The combined empirical material informed the development of a non-technical process map that synthesizes two strategic pathways for improving energy efficiency in the use case.

Results and Conclusion

The findings of the qualitative analysis indicate that vacuum pump systems constitute a major focus of energy and resource consumption in the context of the semiconductor production, with substantial efficiency potentials hindered by fragmented data use, legacy infrastructures and limited integration of digital tools such as predictive maintenance and monitoring systems. While technical solutions for improving energy efficiency exist, their implementation is constrained by organizational structures, unclear roles and weak coordination, particularly between production and facility management. Decisions are largely driven by quality, stability and cost considerations, with sustainability and resource conservation typically treated as secondary or incidental objectives. At the same time, human factors such as resistance to change, insufficient knowledge exchange and the lack of clear responsibilities emerge as central barriers to effective implementation. Overall, the findings highlight that resource efficiency in an Industry 4.0 context is not primarily a technical problem, but a socio-organizational challenge that requires cultural change, structured collaboration and systematic use of available data.

Literature

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