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Authors		
Author(s) Name	Organisation	E-mail address
Jens Petter Johansen	NTNU SR	Jens.petter.johansen@samfunn.ntnu.no
Torgeir Haavik	NTNU SR	Torgeir.haavik@samfunn.ntnu.no

Abstract

While exchange of surplus energy between companies can be economic beneficial and environmentally friendly, such inter-organizational integration of industrial rhythms imposes dependencies and uncertainties for the companies involved. This paper expands on the structural focus of studies of resilience in industrial symbiosis by addressing the social and organizational aspects of adapting to variability. The study is based on case studies in three industry clusters in Norway where companies engage in collaboration concepts and exchange surplus energy streams such as heat, CO-rich off-gas and CO2. The paper shows how formal and informal aspects of the inter- organizational collaborations can add resilience to socio-technical-economic systems for energy exchange that face uncertainties to the flow of operations and the viability of the systems.

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J.P. Johansen

NTNU Social Research, Norway. E-mail: jens.petter.johansen@samfunn.ntnu.no

T.K. Haavik

NTNU Social Research, Norway. E-mail: torgeir.haavik@samfunn.ntnu.no

While exchange of surplus energy between companies can be economic beneficial and environmentally friendly, such inter-organizational integration of industrial rhythms imposes dependencies and uncertainties for the companies involved. This paper expands on the structural focus of studies of resilience in industrial symbiosis by addressing the social and organizational aspects of adapting to variability. The study is based on case studies in three industry clusters in Norway where companies engage in collaboration concepts and exchange surplus energy streams such as heat, CO-rich off-gas and CO_2. The paper shows how formal and informal aspects of the inter-organizational collaborations can add resilience to socio-technical-economic systems for energy exchange that face uncertainties to the flow of operations and the viability of the systems.

Keywords: energy exchange, industrial symbiosis, socio-technical-economic system, energy, resilience.

1. Introduction

Exchange of energy between companies with complementary energy- surplus and demand can be an efficient approach to reduce direct energy consumption in industries. Such collaboration concepts have most prominently been researched in industrial ecology as industrial symbiosis, which entails the inter-organizational efforts of utilizing industry surplus energy and material streams for value creation (Chertow 2000). While industrial symbiosis can be both economic beneficial and environmentally friendly, such integration of companies imposes dependencies and uncertainties for the companies involved. Increased attention has been directed toward the stability (robustness) of such systems and their ability to adapt (resilience) to variabilities and perturbations (Walls & Paquin 2015). While research on resilience in industrial symbiosis (and ecosystems) have been studied in terms of reliance on network nodes and degree of dependencies between companies, less attention has been given to the resilience of particular exchange structures, and how social and organizational factors contributes to the ability to adapt and respond change.

This study draws insight from three case studies of energy exchanges in the Norwegian industry. While the cases differ in types and diversity of industry, quantity of energy exchanged, number of companies involved, degree of dependency, forms of organization and regional frame conditions, we find that a main concern for stabilizing energy exchanges are to align the different industrial rhythms, also in the face of disruptions. While much of this alignment work have been delegated to technologies (energy management systems, redundant solutions), we find that organizational, cultural and social elements are important to co-produce stability and resilience in such exchanges. Similarly, uncertainties with the potential to cause more severe perturbations to the exchanges are also handled with different reliance on informal factors across the cases. In light of these findings we provide a discussion on how formal and informal aspects of such socio-technical systems produce resilience.

2. Resilience in industrial symbiosis for energy exchange

In the safety literature, the use of the term resilience reflects different academic traditions. These traditions may be divided into three strands, occurring within the fields of psychology, ecology and the social sciences respectively (De Bruijne, Boin, and Van Eeten 2010). Resilience Engineering (RE) (Hollnagel, Woods, and Leveson 2006) has in particular lent inspiration from the ecological tradition (Holling 1973), and paid particular attention to understanding the variability and adaptations associated with the well-functioning of socio-technical systems. The study of industrial symbiosis is an established sub-field of industrial ecology with a particular focus on the local evolutionary dynamics of inter-organizational energy and material flows (Chertow 2007). In a review paper tacking stock on research on resilience in the field of industrial ecology, Meerow and Newell (2015) conclude that while resilience research in industrial ecology have identified a large number of theorized characteristics of resilient systems, such as adaptability, diversity, efficiency, flexibility, learning, and redundancy, the phenomenon is still understudied. More specifically on industrial symbiosis, resilience has been studied in terms of

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reliance on network nodes, diversity, lock-in consequences and degree of dependencies between companies (Chopra & Khanna 2014, Zhu & Ruth 2013). Such studies focus on the larger network- or system resilience of connected companies (i.e. Fracassia et al 2017) and investigate the consequences of perturbations (i.e. exit of a company) for the larger system. However, for the companies that are involved and committed to particular symbiotic structures, for example a specific relation of energy exchange, the larger system perspective is less relevant. This paper addresses this research gap by exploring how particular structures can adapt to perturbations. The importance of social ties has been widely recognized in studies of emergence and development of industrial symbiosis (Walls & Paquin 2015), drawing on sociological concepts of embeddedness and weak ties (Granovetter 1985). Aspects such as informal networks, trust, shared vision and culture are acknowledged as important elements in symbiosis formation (Domenech & Davies 2011, Johansen & Røyrvik 2014). However, less attention has been given to how informal aspects can contribute to the resilience of industrial symbiosis.

3. Methodology

This study is based on case studies of industrial symbiosis for energy exchange in the Norwegian industry. The methodology involved a triangulation of qualitative methods (Yin 2009) including interviews, document studies and field visits to achieve a thorough understanding of the cases. Interviews have been conducted with industries participating in the symbiosis as well as stakeholders including local energy companies (i.e. district heating), municipality or other mediator organization (i.e. development companies, county councils) when relevant. In total 15 interviews and one workshop has been conducted. Document studies include studies of regional energy plans, media events covering the cases and public documents of emission- or funding applications.

3.1 *Data collection and cases*

The selection of case studies was based on finding examples of inter-organizational energy exchange in the Norwegian industry. The cases include examples of external utilization of surplus heat (heated water) from industry processes which are utilized for thermal demand, and CO-rich off gas, a bi-product of manganese production, which are combusted to utilize the thermal energy instead of being flared. There are clearly differences between these types of energy, in terms of scale, infrastructures, technical components, and energy management systems where CO-gas infrastructure is far more complex and costly. There are also several other factors differentiating the case studies including i.e. number and type of industry, localization and regional factors, proximity to nearby town or DH infrastructure among others. Two of the case studies was conducted between 2017/2018 (IndNor and IndSouth). The IndWest case have been previously studied as a formation of an energy exchange (Johansen & Røyrvik 2014), where the data was re-analysed with focus on uncertainties and characteristics of resilience.

Table 1. Case studies

Case ID	Energy exchange	No. companies involved
IndWest	Surplus heat	3
	CO_2	3
	District heating	
IndNor	CO-rich off-gas	4
	Surplus heat	2
	District heating	
IndSouth	CO-rich off-gas	2

3.1.1 *IndWest*

The case of IndWest involves an industry park consisting of five industrial food companies. The energy exchanges involve surplus heat from dairy and a poultry processing plant to a nearby greenhouse. Also the CO_2 from the natural gas combustion from two of the companies is utilized in the photosynthesis in the greenhouse. Thus, the greenhouse is completely dependent on the symbiosis and do not have their own energy central.

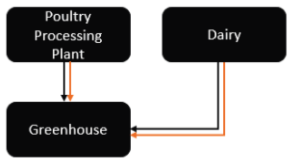

Fig. 1. IndWest, exchange of surplus heat and CO2

The exchanges are based on bi-lateral agreements and with no intermediary organization. The exchanges were established in 2010 and the cluster was connected to the regional DH network in 2018.

3.1.2 *IndNor*

IndNor is an industry park with over 100 companies. The history of the park goes back to the re-structuration and privatization of a public owned iron mill in the 1980s, resulting in a horizontal split of an existing value chain to a multitude of companies.

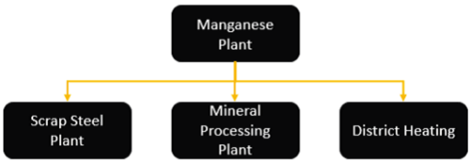

Fig. 2. IndNor, CO-rich of-gas exchange

In this paper we focus especially on the energy exchange of CO-rich off-gas from a manganese alloy plant which are sold and utilized by the nearby scrap metal steel plant (pre-heating of steel works in a rolling mill), a mineral processing plant (producing dolomite, quicklime, limestone) and as peak load capacity for the local DH provider.

3.1.3 *IndSouth*

In the case of IndSouth we focus on a particular bi-lateral energy exchange of CO-rich off-gas from a manganese alloy plant to a nearby ammonia plant.

Fig. 3. IndSouth, CO-rich off-gas exchange

3.2 *Analytical model: Pentagon*

The investigation of variabilities and uncertainties are based on interview data and analysed across the cases. These include experienced as well as possible uncertainties identified by informants and are presented through examples and overviews. To analyse the organizational and social factors contributing to resilience in the energy exchanges we apply the Pentagon model as an analytical tool. The pentagon model systematises and operationalises the key variables that characterise an organisation: formal structure; technology and infrastructure; culture; interaction; social relations and network (Schiefloe, 2019). The model and its concepts can be used to analyse adverse events, planning and organisational development. The five dimensions of the model represent the formal and informal qualities of an organization, or in this case an industry symbiosis for energy exchange. While we also include the dimension of technology, infrastructure and equipment (1), we are especially addressing the formal structure and regulations (2) of the energy exchanges as well as the informal qualities connected to values, attitudes and competence (3), interaction and work processes (4) and social relations and networks (5). Thus, after identifying the characteristics which contributes to resilience in energy exchanges we are analysing them according to the dimensions in the Pentagon model.

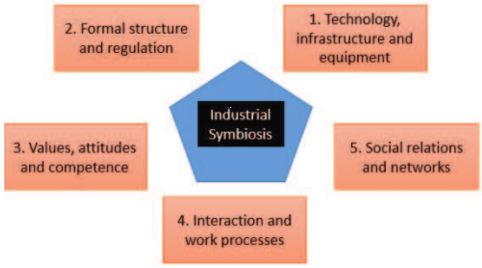

Fig. 4. Pentagon model adapted from Schiefloe (2019)

4. Analysis

The first part analyses aspects of variability through the concepts of industrial rhythms and disruptions affecting the stability, with that of more severe uncertainties in which perturbations can threaten the existence of these socio-technical systems. Further we investigate how formal and informal aspects of the inter-organizational network contribute to alignment work and resilience.

4.1 *Variability*

4.1.1 *Rhythms and disruptions*

From the production side the energy types investigated in this study, surplus heat, CO-rich off-gas and CO_2 are made as the result of the industry processes of which they occur. Consequently, the production of (waste) energy is inherently coupled with the industrial rhythms of dairy products, manganese alloys and other industry processes. Similarly, from the demand-side, energy consumption is inherently coupled with the industry processes they enable. While the production of some facilities must stay in constant operation due to technical constraints, for example the continuous production in manganese furnaces, the production sequences of other companies follow other rhythms such as regular work hours, vacation times, demand of products, seasonal variations and even biological rhythms of tomatoes in the case of the greenhouse. In IndNor, variability in delivery of CO-gas is connected to the industrial rhythms of its users. The mineral processing plant requires stable delivery of CO-gas where switching to alternate fuels requires sufficient time in order to avoid production disruptions. However, the largest user of the gas, the rolling mill connected to the scrap steel plant, varies and stops production according to vacation periods, regular maintenance, which significantly impact the level of gas delivery. Also the delivery of CO-gas as peak load capacity for the DH-network is dependent on seasonal demand of district heating. Another example of an inherent misalignment is found in IndSouth, where the ammonia plant utilizing the CO-gas, serve as a swing capacity in a larger corporation:

> "[…] actually that plant serves as a swing capacity and it's like, are they producing in Q4 or are they stopping?" IndSouth, Informant

In this case, the misalignment in supply and demand of CO-gas is due to reoccurring commercial rhythms causing uncertainties. Process variability is also a concern in the surplus heat exchange as one informant argues:

> [..] they have maintenance or production checks every week alternating between the two furnaces for two hours. Every other year they have a weekly revision on each furnace. That's the planned things, but a furnace is really a living organism, it has process variations, periods where it's not optimal, the load is low, the gas is cold, so we must peak load because of that. So it is variations in the process, but it is fairly continuous and stable source anyway.

Disruptions on both the supply or demand side in an energy exchange can affect the technical and economic efficiency of the systems. Some disruptions are as mentioned anticipated; regular maintenance causing stops in production, vacation times and work hours. For CO-gas factors such as quality of raw materials can affect the fuel-value and quantity of available gas, weather conditions affect available capacity in a gas buffer clock. Misalignment (or lack of optimizing) rhythms and disruptions in production may impact the efficiency of the energy exchange and potentially the production capacity of fully integrated firms.

4.1.2 *Uncertainties and perturbations*

There are also internal and external uncertainties with the potential to disrupt the stability of energy exchanges. The most severe mentioned by the informants are incidents of companies closing down. As other industrial symbiosis researchers have noted (Walls & Paquin 2015), the resilience of a symbiosis in such situations depends on the resource dependency and diversity of the companies involved in the exchange. The case of IndNor provide one example, where one of the main consumers of CO-rich off-gas was shut down, immediately leading to a decrease in CO-gas that were sold, increased flaring as well as triggering price negotiations of the remaining companies in the exchange. The companies involved in the energy exchange for CO-gas were able to absorb this perturbation and eventually increase sale of gas to one of the remaining consumers. Novel concepts and innovations are also mentioned as uncertainties which can cause disruptions in energy exchanges. Even though the energy exchanges may still be beneficial in terms of environmental impact and total emissions novel business models or innovations for utilizing the resources can shift the profitability towards other use-cases. One example is innovations in use-cases of CO-gas. Novel concepts and innovations for utilizing CO-gas as a raw material (i.e. ethanol production) was mentioned as a potential factor which could threaten the energy exchange concepts. Other innovations that are mentioned are ongoing projects within carbon-capture and storage/usage (CCS/CCU) which potentially can disrupt the current CO-gas exchange concepts. Also for the case of utilizing surplus heat, energy efficiency or use of heat-pumps can in some cases decrease the need for external heat supply to the extent that it threatens surplus heat viability. Change of ownership of companies is mentioned as an uncertainty while it doesn't necessarily pose a direct threat to existing concepts. In the case of IndNor, the informants note that change of ownership can lead to price negotiations, especially in conjuncture with changes in prices for alternative energy sources for CO (i.e. propane, crude oil). Similarly, changes in collaboration concepts or cluster organization handling the exchange are mentioned as a source of uncertainty. Changes in ownership or personnel in cluster organizations can potentially lead to opposite agendas, price negotiations, renting price on infrastructure, or change of focus on existing operations vs development. Political frame conditions in flux is another form of uncertainty which potentially can impact the viability of the energy exchanges. This is especially important in the CO-rich off gas cases where prices on carbon credits (EU ETS) impact the local price dynamics:

> "If we get extreme increased in carbon credit prices it might trigger "solo-projects" around here and drastic changes for the concept we have in the park today. I think that in that respect there are also new technologies that can come in and suddenly change things around." IndNor, Informant

Changes in these regulations can impact the profitability of the CO-gas exchange concept and potentially favour alternative energy sources (leading to increased total emissions from a park as a whole). While the efficiency of energy exchanges is connected to how they align and optimize industrial rhythms and regular disruptions, adapting to uncertainties and more severe perturbations is essential for the longevity of the exchanges.

4.2 Formal and informal aspects of resilience

In the following, the Pentagon model (Schiefloe 2019) is used to analyse energy exchanges with respect to formal and informal aspects that contribute to aligning the material-energy arrangement to temporal rhythms and adapt to disruptions and uncertainties. The cases show how responses to rhythms, disruptions and uncertainties are both delegated to technologies and grounded in the informal qualities of the inter-organizational networks.

4.2.1 *Technology, infrastructure and equipment*
In the cases studied, redundancies, buffer capacities as well as variation responses have partly been delegated to technological systems. One example from IndNor is a gas buffer clock for CO-rich off-gas which can contain enough quantities for a six-hour shift at the nearby mineral processing plant. Thus, minor variations in supply and demand of off-gas can be handled. Also, the CO-gas users have redundancy options to switch to alternate fuels such as propane or crude oil although with economic and emissions related consequences. For IndWest the greenhouse has two sources of surplus heat and CO_2 from the natural gas induced production of the dairy and poultry processing plant. In cases of misalignment in productions at these sites, the boilers can still produce heat and CO_2 to maintain the greenhouse production, although without the benefits of using "surplus" energy.

4.2.2 *Formal structure and regulation*
The reliance on formal structures, such as governing procedures, regulations and working requirements, of the energy exchanges vary between the cases. IndNor have a dedicated company in the industry park responsible for the park infrastructure including the CO-gas network, although the prices on the gas are handled by bi-lateral agreements between the companies. A priority mechanism has been included in the contract ensuring that the mineral processing plant, which is most dependent on continuous supply of gas, has first priority in case of disruptions. This is one example of how disruptions are handled through formal procedures. Also re-negotiation options of contracts can be seen as alignment to the outside environment (energy prices for competing energy sources).

> "I think that sine there are a few options a three-year horizon is good. So if there are drastic changes in subsidies from the government, CO_2 compensation or anything, or the carbon credit prices should change drastically it could be attractive to do something else." IndNor, Informant

In the case of IndNor one of the major consumers of CO-rich gas was shut down and left the cluster. This also led to changes in available volume for other consumers, priority agreements as well as price negotiations for the involved parties (changing both technical and formal structure of the symbiosis). These processes are also a form of "repairing" the formal structures of the system when there are external perturbations in energy prices.

In terms of cluster organization, IndWest and IndSouth have conversely organized the governance structures of the exchanges solely on bi-lateral agreements between the companies, involving distributed ownership and responsibility for the infrastructure. Thus the infrastructure (pipelines, heat exchangers, energy centrals) are separated by technical and organizational boundaries and responsibility delegated to the distributed organizations.

4.2.3 *Values, attitudes and competence*
We also find expressions of how inter-organizational culture and shared visions between participants can contribute to resilience. One example of how aligned visions are important is in IndWest, where the participants highlight a "win-win" mentality as a clear success factor for the connection between the companies:

> "..it is exactly like he says all the time, no one can «insert the straw», it has to be «win-win»" – IndWest, Informant

In the case of IndWest the energy exchanges are especially grounded in informal organizational aspects and informal agreements have partly been used to organize particular exchange structures. While variation responses are also here handled by formal structures, they rely more heavily on informal aspects of the inter-organizational collaboration. In this case, the informants argue that an explicit grounding of a "win-win" mentality as well as "green profile" are important to maintain the energy exchange. Also, in the IndNor case, these aspects are highlighted as a stabilizing factor, although there is more focus on commercial business case of the concept:

> "At the same time it is important to say that it should be a win-win situation with this type of cluster concept. That means it should be a benefit for [them] to sell, make money and reduce their emissions, and for the local users I will say that price and economy is also important. Yes, we do want a "green" profile in the park, but at the same time it is odd if we would have to pay more for the CO-gas than for alternate energy sources". IndNor, Informant.

A similar trait between these cases is the decision to make equal and open pricing models for the surplus energy users in the energy exchange. This could potentially be constructed differently, but are argued in both cases due to "fairness" and transparency between neighbouring companies. This is regarded as especially important to adjust to price changes for alternative energy sources.

4.2.4 *Interaction and work processes*

Interaction is a precondition for developing and maintaining social relations and networks, and is also a foundation for organizational culture, experience transfer and learning (Schiefloe 2019:44). While the cases rely on different divisions of responsibilities and work, the importance of developing processes of information- and competence sharing over time is a common for the ability to align industrial rhythms and adapt the energy exchanges to disruptions and perturbations. One example is how information flow regarding production stops and disruptions in the CO-gas exchange in IndNor have been continuously improved:

> "If there is shorter than a few days we choose to do our own maintenance. We have developed a good collaboration over time. When they have disruptions they are very good to send out information "now have this happened and we will have a stop for three days" IndNor, Informant

The companies utilizing CO-gas have developed responses to disruptions in gas supply, which are strengthened by information exchange between the companies. Alignment of maintenance periods with planned downtime between the companies is also an example of such a response to different industrial rhythms and disruptions which minimize the impact of halt in supply of gas. The informants report that over time the information flow between the CO-producer and recipients have improved with regular email transaction of the quality and quantity of gas and possible disruptions. In addition to improved interaction between the companies, the informants stress the importance of specialized competence on the gas infrastructure from the dedicated cluster company. Alignment to rhythms and disruptions are also formed within the informal qualities of the system such as improved information and knowledge sharing and alignment of maintenance periods with production deviants.

Similarly, in the IndWest case, alignment of work processes and interaction between the companies are highlighted by the informants. The need for aligning the processes of the dairy and the greenhouse required continuous interaction between the two companies:

> "I have learned so much from him and he has learned a lot about greenhouses too. Actually he has full access to our energy control system from his computer, and he also has the access codes to get in here. So in some ways he has become a gardener." IndWest, Informant

While such integration between personnel in the companies is imperative for the alignment of the energy exchange, it also indicates the importance of trust in order to enable such interactions.

4.2.5 *Social relations and networks*

Informal relations and trust connecting people between the organizations are important aspects of the energy exchanges which contribute to handling disruptions and even more severe perturbations. The case of IndWest provides an interesting example of how informal networks and trust can contribute to resilience by adapting to perturbations. During the establishment of the dairy and the greenhouse, the construction of the dairy was delayed due to unforeseen events. The greenhouse does not have their own energy central and was completely dependent on external heat supply. An informal agreement for supply was made with the nearby industrial poultry plant to supply surplus heat (and another symbiosis was made). The informants at the companies argue that the informal networks and trust were key factors in order to form an informal agreement at such short notice. The trust relations and shared vision in the network was here essential as the manager of the poultry processing plant argues:

> "We have had a fundamental idea that as long as we have a calculation with black numbers, consequently that it is not a net cost, then it is good, we are in" IndWest, Informant

These trust relations are essential parts of the system from the beginning contributing to its stability, exemplified through sharing of access to energy systems as well as explicit claims as one of the informants argues:

> "It has to be an open and transparent system where both they can trust what we are saying, and we can trust them, and it has been just like that. Everyone have to benefit" – IndWest, informant.

While social networks and trust are aspects contributing to resilience, they are in the case of IndWest also integral parts of how the socio-technical system is formed.

5. Discussion

The consequences of disruptions range from threats to daily production to economic viability and efficiency. For the surplus energy producers, disruptions in exchange of CO-gas implies less appropriation, profits for sale but also increased costs due to the connection with the EU ETS framework, where additional flared CO-gas affects the emission calculations of the plants. In the case of IndWest the greenhouse is completely dependent on stable delivery of heat and CO_2 from the dairy or poultry processing plant. Disruptions will here be severe and lead to halt in production. Thus, the degree of dependencies between the firms as well as consequences of disruptions or misalignment of industrial rhythms varies across the cases. The types of disruptions also connect across scales, as severe perturbations in the energy exchanges may require extensive work to align the new constellation of industries, energy flows and industrial rhythms. This is especially highlighted in cases a surplus energy user leaves a symbiosis, triggering changes in the formal structures of the energy exchange (price models, contracts), in addition to optimizing the peak / low alignment of the energy deliverance.

Aligning the energy exchanges with the industrial rhythms of the participating companies as well as regularly disruptions is a main concern for the participants. While much of this alignment work can been delegated to technologies (i.e. energy management systems, technical redundancy) we find that organizational and social aspects[a] can also serve as important elements in this task. However, this also implies that other uncertainties are foregrounded. While strong formalization of the exchange and delegation of variation responses to the formal structure can make symbiosis adaptive to changes in energy prices, this can come at the costs of weaker informal ties and community values such as a win-win system. On the other hand, while strong reliance on informal qualities such as social networks and personal trust can provide resilience, it is vulnerable if key persons leave the companies. Thus, managing unforeseen variations, absorbing minor shocks and preventing system breakdowns – in short, ensuring resilience – requires all organisational dimensions to be well developed.

While the cases rely differently on formalized structures, they do not represent "ideal types" of formalization. The numerous formal and informal qualities and aspects that we find to be associated with resilience in industrial symbiosis could be understood in terms of requisite variety[b]; for a system to be stable, it must be managed by measures that make it possible to match the number of possible states of the system (Ashby 1981). We hence do not suggest that there exists any formula combining every formal and informal aspects into a perfect combination, but that uncertainties and variability of internal and external environments requires a certain variety to maintain resilience; whereas formal structures and technological solutions may respond well to some challenges, social relations and informal networks may be suitable for others. We may find support for this in the organizational contingency literature (Donaldson 2001); there is no one size that fits all, which is probably the reason why particular recommendations for how to construct a resilient industrial symbiosis are so hard to formulate. Another reason could be that responding to fluctuations in the external context (e.g. regulations, technologies, demands) requires continuous adaptations; to counter brittleness[c], a resilient configuration tomorrow may differ from a resilient configuration today.

6. Conclusions

In this paper we have explored characteristics with energy exchanges contributing to its adaptive capabilities. While we make no claim that the energy exchanges under scrutiny *are* resilient, we argue that the dimensions analysed are important in understanding how resilience is produced in such settings. By focusing on organizational and social aspects we address a clear knowledge gap in the research on industrial symbiosis. Such

[a] The variety of these may be considered together as *organisational redundancy* (Rosness et al. 2000).

[b] The reference to requisite variety occurs many places in the safety literature, e.g. (Schulman 1993, Hollnagel 2011).

[c] "[R]apid fall off or collapse of performance that occurs when events push a system beyond its boundaries for handling changing disturbances and variations" (Woods 2016, 258).

insights may also have relevance for practitioners where particular structures of an energy exchange are more important than the survivability of a larger symbiotic system. For example, foregrounding how maintaining and repairing the cultural and social ties of these systems can be just as important as repairing the material ones.

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