Decarbonization of industry: Implementation of energy performance indicators for successful energy management practices in kraft pulp mills

Elias Andersson a,∗, Henric Dernegård b, Magnus Wallén a, Patrik Thollander a

a Department of Management and Engineering, Division of Energy Systems, Linköping University, 581 83, Sweden
b HOLMEN Teknik, SE-114 84, Stockholm, Sweden

A R T I C L E   I N F O

Article history:
Received 5 September 2020
Received in revised form 11 February 2021
Accepted 14 March 2021
Available online xxxx

Keywords:
Energy management
Energy performance indicators
Key performance indicators
Energy management system
ISO 50001

Pulp and paper industry

A B S T R A C T

Energy management is the most prominent means of improving energy efficiency, and improved energy efficiency constitutes the cornerstone in decarbonization. For successful industrial energy management, defining accurate energy performance indicators (EnPIs) is essential. Energy-intensive industries have previously been found to have an improvement potential regarding the current monitoring of EnPIs, especially at process level. While general models for developing and implementing EnPIs exist, manufacturing industries are diverse in terms of their production processes, which is why industry-tailored models for EnPI development are needed. One major outcome of this paper is a unique model specifically tailored for kraft pulp mills. The model derives from a practice-based approach for EnPI development, building on real-life experiences from a Swedish group of companies. This paper's developed model, and the validation of the EnPIs, further increase the understanding of the kraft pulp industry’s processes and how to apply descriptive and explanatory indicators. The developed model can potentially be generalized to other sectors.

© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Improved industrial energy efficiency is necessary in order to achieve energy targets, and is recognized as being important by the IPCC (2014) and the EU (EEFIG, 2015). In the EU, the Energy Efficiency Directive (2012/27/EU) requires the member states to achieve an increase in energy efficiency of 20% (European Commission, 2012). This target has been updated to 32.5% by 2030 (European Commission, 2018). As part of fulfilling the requirements in Sweden, the Act on Energy Audits in Large Enterprises (EKL) entered into force in 2014 (SEA, 2019). According to EKL, large enterprises must carry out an energy audit every fourth year and this must be performed by a certified energy auditor. However, if a company has implemented an energy management system certified to ISO 50001, it is possible to conduct the energy audit in-house given that other requirements are met. Assuming a large international uptake of ISO 50001 in industrial organizations, considerable energy saving potentials and a reduction in CO2 emissions can be achieved (McKane et al., 2017).

Strategic and systematic management of energy in an organization is important in order to achieve a continuous reduction in energy use and energy costs (Schulze et al., 2016), in particular for energy-intensive industries such as the pulp and paper industry (Posch et al., 2015). Pulp and paper mills in Sweden are found to carry out well-established continuous energy management work (Lawrence et al., 2019). In addition, as a result of the Program for Improving Energy Efficiency in Energy Intensive Industries (PFE), many pulp and paper mills in Sweden have implemented a standardized energy management system (Thollander and Ottosson, 2010). One central energy management practice is to define and implement energy performance indicators (EnPIs) (Schulze et al., 2016; Trianni et al., 2019). Indeed, one of the requirements of ISO 50001 is that the organization shall develop and implement EnPIs for continuous monitoring (ISO, 2018). To help organizations meet this requirement, the ISO 50006 standard provides practical guidelines (ISO, 2017). Central reasons for developing and monitoring EnPIs include supporting the setting of energy targets and decision-making within a company (Benedetti et al., 2017). One of ten success factors for in-house energy management, as identified by Johansson and Thollander (2018), is having implemented clear EnPIs, which also facilitates setting targets for the long-term energy strategy.

Accurate EnPIs at a detailed level have for other industries shown valuable. For example, Johnson et al. (2019) used bottom-up energy data to identify processes with large energy efficiency potential in the Swedish wood industry. A construction equipment manufacturing company monitored the electricity idle load...
for multiple sites and reached large savings through management measures (Sannø et al., 2019). Kanchiralla et al. (2020) presented EnPIs on different hierarchical levels for a systematic analysis of the energy performance in the engineering industry. Furthermore, indicators at a detailed level have been deemed to be more relevant for energy benchmarking in small and medium-sized enterprises (SMEs) (Kimura et al., 2015). Andersson et al. (2018) exemplified this by carrying out energy benchmarking at a process level for sawmills using an energy efficiency index.

However, it has been revealed that energy-intensive industries in many times do not possess the necessary data or indicators on a sufficiently detailed level for effective decision support in in-house energy management (Sivill et al., 2013). The lack of relevant indicators at both process and plant levels has been identified as an industry knowledge gap (Busse et al., 2011). In light of this, general models for drawing up EnPIs for energy management have been developed (Benedetti et al., 2017; May et al., 2015). Sector-specific EnPIs for the pulp and paper industry have also been developed (Ammara et al., 2016; Mateos-Espejel et al., 2011). Still, Andersson and Thollander (2019) identified a substantial improvement potential in the pulp and paper industry regarding EnPI implementation and monitoring, while also arguing that energy managers at pulp and paper mills find it more valuable to develop EnPIs within the context of the company. Furthermore, Lawrence et al. (2019) found that two of the four highest ranked drivers for successful energy management in the Swedish pulp and paper industry were related to process knowledge, namely, access to internal competence with knowledge of the processes and knowledge of daily operations. Correctly designed EnPIs contribute exactly to that for company staff. This suggests that the process of developing company-specific EnPIs is itself important for acquiring deeper knowledge of the production processes. To the authors’ knowledge, no model for in-house development of EnPIs specifically for the pulp and paper industry exists in the literature to date (Fig. 1).

The aim of this paper is to present a model for the development and implementation of EnPIs for in-house energy management in a kraft pulp mill. The presented model is related to the standardized and general method for EnPI development and implementation within an energy management system according to ISO 50001 and ISO 50006. The contribution of this paper is unique, as it takes a practice-based and bottom-up approach of EnPI development for kraft pulp mills while simultaneously considering the requirements and principles of the ISO 50001 standard for energy management systems. The paper is structured as follows: First, a background on EnPIs in industrial management is presented, followed by a description of the methodology. In the results, first a harmonized categorization of energy end-use processes is provided. The ensuing sub-section describes the currently used EnPIs in the industry, followed by the main contributions of this paper, namely the importance of monitoring both explanatory and descriptive indicators as well as a new model for developing accurate EnPIs. After the results, a concluding discussion is given.

2. Energy management system and performance indicators

2.1. ISO 50001 and ISO 50006

In parallel with an increased uptake of ISO 50001 certifications, tools have been developed to assess the overall quality of energy management systems (cf. Antunes et al., 2014; Carbon Trust, 2011; Jovanović and Filipović, 2016). The effect of a standardized energy management system on energy efficiency improvement in the Swedish pulp and paper industry has been studied (Stenqvist et al., 2011). It is important to distinguish between energy management systems and energy management, with the former being a tool for implementing the practices of the latter (Thollander and Palm, 2013). One strength of implementing ISO 50001 is that it contributes to top management commitment in energy performance (Chan and Kantamaneni, 2015), but it risks competing with personnel’s main assignments (Păunescu and Bld, 2016). However, making use of the internal competence of cross-functional staff in energy efficiency improvement projects not only reduces the deterrent effect of a measure’s complexity, but also promotes organizational learning through an exchange of knowledge (Svensson and Paramonova, 2017), and encourages energy efficiency innovations (Solnordal and Thyholdt, 2019).

The ISO 50001 standard requires, among other things, that appropriate EnPIs are identified and monitored (ISO, 2018). The EnPIs are to be regularly reviewed and compared to an energy baseline. To facilitate this process for companies, ISO 50006 provides general principles and guidance (ISO, 2017). It should be noted that the standards address all organizations with an energy management system, i.e., a broad range of industries. It might therefore be necessary for companies in a specific industry to be provided with further assistance and guidance for the implementation of EnPIs.

Continuous monitoring of EnPIs and the improvement progress are excellent practices for process industries to respond to the requirements of continuous improvement (Beisheim et al., 2019). Developing EnPIs is a complex matter for manufacturing industries due to the interlinkages of processes (Cosgrove et al., 2018). This is one of the most commonly studied issues in relation to ISO 50001 implementation (Rampasso et al., 2019). As the performance of production processes varies with changing conditions, such as the feedstock quality, the influence of these conditions on the developed EnPIs has to be accounted for in the analysis of the energy performance (Beisheim et al., 2019). Previous research has successfully identified influencing factors and defined EnPIs using historical energy data, enhancing a continuous improvement of energy performance (Velázquez et al., 2013). Depending on the organization’s operations, the methods for defining EnPIs differ (Chiu et al., 2012). Sivill et al. (2009) also distinguish between the purpose of indicators as being either descriptive or explanatory. Key elements of EnPI development include the granularity of available data, establishing a baseline of normal operation based on historical best practice, and effective communication within the organization (Cosgrove et al., 2018).
2.2. Energy performance indicators in the pulp and paper industry

The body of literature shows that, for the pulp and paper industry, a commonly applied EnPI is specific energy use \(^1\) (SEC) expressed as e.g. kWh/ADt or GJ/ADt: At the industry level (Lawrence et al., 2018), mill level (Stenqvist et al., 2011), or process level, including the consideration of different pulping technologies and paper grades (Fleiter et al., 2012; Laurijssen et al., 2013; Rogers et al., 2018). The indicators are often divided into electricity use and heat use. SEC is sometimes weighed into an energy efficiency index to monitor the energy efficiency progress (European Commission, 2009). SEC of electricity and heat are commonly monitored indicators by the Swedish pulp and paper mills together with the uptime of the production, while energy cost indicators are less often monitored (Andersson and Thollander, 2019).

To accurately determine an industrial site’s aggregated performance, and to understand deviations in performance, influencing factors at the process level need to be identified to enable a root-cause analysis (Reischle et al., 2020). Ammara et al. (2016) present a number of important parameters for different departments of a kraft mill, such as enthalpy of steam and density of wood. For the pulp and paper industry in general, and for kraft mills in particular, exergy efficiency indicators could prove to be highly relevant as they cover both energy and material losses associated with the process. Various energy indices are used to reflect the economic efficiency of energy use in industry (Hernandez and Cullen, 2019). Mateos-Espejel et al. (2011) make an important contribution in this regard.

3. Methodology

The study was carried out as a multiple case study, as described by Yin (2014). Three kraft pulp mills constitute the studied cases. All mills belonged to the same group of companies. The cases studied serve as representative cases for the context in which they operate (the pulp industry) (cf. Bryman, 2008). The following steps were covered in order to address the aim:

1. Define a harmonized categorization of energy end-use processes.
2. Define the general EnPIs currently in use in the industry.
3. Relate the energy EnPIs to the relevant energy end-use processes.
4. Develop a model for defining and implementing EnPIs for in-house energy management.

Defining a harmonized categorization of energy end-use processes (step 1) was deemed relevant to mitigate the risk of using different terminology and system boundaries (cf. Andersson and Nehler, 2018). How energy managers in the pulp and paper industry perceive the benefits of a common categorization has not, to the authors’ knowledge, been outlined previously.

The abovementioned steps were covered during three workshops. The workshop sessions were held between September 2018 and January 2019. Representatives from the pulp mills in the group attended on all occasions. All the mills are classified as kraft mills, but differ in terms of their processes and end-products. Validations of the suggested EnPIs are provided, based on experiences and lessons learned at one of the company group mills, henceforth referred to as the reference mill.

Workshops have previously been used in research to develop a categorization framework (Lindkvist and Karlsson, 2018). They have also been used to understand complex conditions and flows (Ryblicka et al., 2015).

The developed model in this paper (i.e. step 4) is related to the ISO 50001 standard and the general guidance for developing EnPIs as presented in ISO 50006. To measure the energy performance of an organization, ISO 50001 presents five main steps: (1) deriving relevant energy performance information, (2) developing EnPIs, (3) establishing energy baselines, (4) applying EnPIs, and (5) maintaining and adjusting EnPIs and energy baselines. The model in this paper will facilitate the definition of EnPI boundaries in a kraft mill and identification of relevant variables that affect the energy performance.

4. Results and analysis

4.1. Categorization of energy end-use processes

The following benefits of a common categorization of processes were highlighted by the workshop participants: First, it enables a standardized way of working with data collection and data management. Second, when deviations in production are identified, this helps to locate the processes causing the deviation. Third, a common categorization also allows for comparisons, which, in the context of mills within the same group of companies, are less hindered by data confidentiality than when benchmarking mills from different groups. Last, using the same names for processes facilitates the discussion between participants from different mills.

The suggested categorization of processes consists of three system boundary levels, as shown in Table 1, where the most aggregated level is the entire mill. It is common to have energy targets as well as EnPIs for the entire mill. However, to allow for a more in-depth understanding of the energy performance of different processes, a more detailed level is necessary. Since a kraft mill has a number of flows of different elements, i.e. the fiber line, the flow of chemicals, and energy flows, which also intersect with each other, this specific industry poses difficulties when developing a categorization of processes. To address this, the second level of the suggested categorization accounts for the different systems and flows in a kraft mill. The third level of the categorization is the most detailed level, and refers to single production steps such as cooking.

The three selected boundary levels, as presented in Table 1, are in line with the boundary levels for defining EnPIs in ISO 50006 (in the standard denominated process, system, and organizational level). One energy end-use process can relate to more than one system of processes (level 2). In other words, each process has EnPIs related to one or more systems and flows at level 2. Table 2 presents each system and flow at level 2, and which underlying processes at level 3 are correlated to each of these.

4.2. Energy performance indicators for in-house energy management

Similar to the benefits of a common categorization, the most important aspects of the use of EnPIs for energy management were also covered during the workshops. Two mentioned areas of use are the ability to identify deviations in energy use and benchmarking (external and internal). EnPIs for monitoring energy performance were found to be a highly relevant part of energy management. Accurate EnPIs facilitate the standardization of energy management, directing the focus by sorting out the most important information, and enable preventive maintenance, which could avoid production stops, for example.

For internal monitoring of EnPIs using historical values (cf. Fantini et al., 2015; Peterson and Belt, 2009), it is suggested that SEC for both electricity and heat is monitored for the entire mill (Fig. 2). Only the energy end-use for the production of pulp is considered for these indicators, i.e., other by-products such as tall oil, methanol, district heat production, and electricity production are omitted. In order to describe the current state of energy consumption.
flows in the mill, the two more detailed levels of system boundaries are used. EnPIs for systems and flow level mainly serve to identify deviations from what is defined as a mill’s normal state of operation, i.e. the range of accepted values for the EnPIs monitored. The normal state corresponds to the “energy baseline” in the ISO 50001 and ISO 50006 standards, which provide a basis for comparing energy performance. Since the normal state of a mill will be unique, as it depends on factors such as technology used, chemicals used, type of end-product, raw material, etc., “the normal state” has to be defined individually for each mill. Given a deviation from the normal state, the EnPIs monitored at process level are used to analyze such an event. A list of general EnPIs monitored at process level in the studied cases is presented in Fig. 2, also showing the interrelation of the suggested EnPIs and how they relate to each system level.

In addition to the EnPIs in Fig. 2, the following EnPIs were also monitored within the company group: crude tall oil production [kg/ADt], waste water flow [m³/ADt], electricity production [kWh/ADt], methanol production [kg/ADt], energy use by amount of methanol produced [kWh/(t MeOH)], and amount of heat to district heating network [kWh/ADt].

As highlighted by, for example, Sivillet al. (2009), it is important to distinguish between descriptive indicators and explanatory indicators. Descriptive indicators provide the results of a metric, but do not indicate the underlying reasons for the outcome of the results. Common descriptive indicators are figures found in best available technologies (BAT), often presented as SEC. The EnPIs in Fig. 2, for example, are descriptive indicators. Explanatory indicators, on the other hand, are the root-cause parameters that help to understand the outcome of a descriptive indicator. For successful in-house energy management, it is necessary to include and act on explanatory indicators.

An illustrative case is the steam demand in the evaporation unit. Fig. 3 shows the connection between energy demand at the evaporator and tons of evaporated water per ton of pulp produced. The reference mill has a higher steam consumption than Mill 2 (a second mill of the company group) due to the need to evaporate a larger amount of water. Even at the best point of operation, i.e., lowest steam consumption for a period of time that is long enough to be considered steady-state, the steam consumption at the reference mill is still higher than the normal operation at Mill 2.

If one were to improve the energy efficiency of evaporation by comparing with the BAT reference, the suggested solution would be to invest in additional evaporation stages. However, a more energy efficient solution to reduce the steam demand of evaporation is to improve pulp washing and use less washing water, while still maintaining the desired pulp quality. The theoretical dryness of the black liquor to the evaporation is about 25% (Lindau, 2008). As seen in Table 3, increasing the dry content of the weak black liquor from 15% to 25% for a six-stage evaporator reduces the steam demand by 0.52 kg steam per kg dry solids. By comparison, investing in a new evaporation stage while not improving the pulp washing and having a dry content of weak black liquor of 15% only reduces the steam demand by 0.17 kg steam per kg dry solids. One possible way of using less water in the evaporation is to utilize the pulp washing by adding a washing stage. Another possible way could be to dilute the pulp suspension by increasing the internal circulation of water in a washing stage. Both of these options show that the ways to increase energy efficiency in one unit operation is realized in another unit operation.

In the above case, the steam demand per amount of black liquor dry solids is considered the descriptive indicator, and the
dry content of black liquor is an explanatory indicator. Notably, the explanatory indicator is not tied to the process of which the descriptive indicators are analyzed. Instead, the explanatory indicator is derived from washing of pulp. In other words, for completeness of EnPI implementation and successful in-house energy management, it is essential that explanatory indicators and their interlinkages are defined. At the reference mill a number of explanatory indicators that affect the descriptive indicators of the chemical recovery system (i.e., the EnPIs with purple background color in Fig. 2) have been defined (Fig. 4). In Fig. 4, it is possible to see how the dryness of weak black liquor is affected by the efficiency of pulp washing and affects the energy demand in evaporation (marked with dashed rectangles in blue).

A case where the energy efficiency is affected across different processes regards the optimal level of sulfidity\(^2\) (marked with dashed rectangles in red in Fig. 4). In the cooking process, white liquor containing hydroxide ions (OH\(^-\)) and hydrosulfide ions (HS\(^-\)) is added to the pre-steamed wood chips. Both the hydrosulfide ions and around a quarter of the hydroxide ions are obtained when sodium sulfide in the green liquor is dissolved in water. The remaining three-quarters of the hydroxide ions are obtained when causticizing the dissolved carbonate ions in the green liquor with the solid calcium hydroxide that originates from the burned lime that has been slaked in water (Fig. 5).

\(^2\) Sulfidity is the share of sodium sulfide (Na\(_2\)S) in relation to the amount of active alkali (sodium hydroxide (NaOH) + sodium sulfide).
In the reference mill, a sulfidity of over 35% is maintained. This results in an excess of sulfate ions that do not react in the cooking and are therefore an unnecessary load. On the one hand, this excess load leads to increased heat demand in cooking and evaporation. On the other hand, the overuse of sodium sulfate allows for less use of sodium hydroxide, which in turn reduces the amount of calcium carbonates circulating in the system. This reduces the amount of calcium carbonate that has to be treated in the lime kiln, decreasing the kiln’s fuel consumption. Thus, to avoid sub-optimization of energy efficiency, a mill needs to find the optimal level of operation for these parameters.

Table 3

<table>
<thead>
<tr>
<th>Dry content of weak black liquor</th>
<th>Theoretical</th>
<th>Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>15%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

kg evaporated water/kg DS

kg steam/kg DS for six-stage evaporator

kg steam/kg DS for seven-stage evaporator

Steam consumption (GJ/ADt)

---

Fig. 3. The steam consumption of the evaporation process at the reference mill and at a second mill within the company group (Mill 2). The consumption of the reference mill is slightly higher than calculated since some hot water is extracted in the middle of the evaporator train. Normal operation refers to the most likely point of operation. Best operation refers to an optimal state of operation that is considered long enough to be steady-state. FRAM (Berglin et al., 2011) and Kangas et al. (2014) refer to theoretical calculations.

Fig. 4. Defined indicators and targets for the chemical recovery system at the reference mill. NPE = Non-process elements, ESP = electrostatic precipitator, RB = Recovery boiler.

Fig. 5. Schematic depiction of chemical recovery cycle.
The normal state of the mill, and its processes, is used as the energy baseline for comparing energy performance (Step 4). EnPIs are monitored at all three levels. In the event of deviation from the normal state of operation, descriptive indicators together with explanatory indicators support an analysis to identify the reasons for the deviation. This refers to the “predetermined method” for benchmarking against the energy baseline as outlined in ISO 50001. The frequency of data collection for EnPIs, which also applies to this step, has to be decided based on what is practically possible. Preferably, it should be on an hourly basis, as changes in production are sometimes short (i.e. daily energy data will sometimes not be sufficient). Different grades of pulp might be produced during different shifts in the day. Nevertheless, the normal state of operation – i.e. the baseline periods – should be connected to a certain setup of producing a certain grade of pulp. This means that the mill defines multiple normal states of operation for every type of pulp quality produced, raw material used, etc.

5. Concluding discussion

Energy management systems have emerged as an important tool for reaching energy efficiency targets, and in recent years the number of manufacturing companies with a certified energy management system according to ISO 50001 has increased. While systematic energy efficiency improvement work is important per se, an additional use is found in the context of kraft mills: Monitoring energy use in a kraft mill is an excellent way to acquire a deeper understanding of the processes involved. Unlike other inputs, such as chemicals, energy use is unique in that it connects all processes in a chemical pulp mill. To understand and interpret the entire pulping process, relevant EnPIs, including both descriptive indicators and explanatory indicators, are needed to increase the internal knowledge of the processes, which has been shown to be beneficial for energy efficiency innovations (Solnørdal and Thyholdt, 2019).

In this paper, a novel model for developing energy key performance indicators (EnPIs) for use in a kraft pulp mill’s energy management is presented. The outcome of this paper supplements previous general models for EnPI development for industrial energy management (Benedetti et al., 2017; May et al., 2015). The model in this paper was developed in collaboration with industrial actors, thus making use of their experience to increase its relevance. A distinction is made between descriptive and explanatory indicators (cf. Sivill et al., 2013, 2009), which includes the definition of parameters that influence the energy efficiency of processes. Awareness of factors that influence processes are vital for understanding and explaining deviations in energy performance (Beisheim et al., 2019).

Two main factors have been identified in terms of how the model developed in this paper contributes to improved industrial energy management. The first relates to the educational aspect. The development of EnPIs helps energy managers and other personnel involved in in-house energy management to better understand energy use patterns. This constitutes a critical knowledge progression that might help overcome knowledge-related barriers that have been shown to be eminent in the pulp and paper industry (Lawrence et al., 2019). Knowledge exchanges between employees also allow for the knowledge of processes to stay within the company (Svensson and Paramonova, 2017). Training as an energy management practice has been previously seen to be underprioritized in pulp and paper mills (Stenvist et al., 2011).

The second main factor in terms of how the developed model contributes to improved industrial energy management is the way in which energy monitoring can detect process variations...
and potential for process optimization. For instance, energy monitoring has been used successfully at the reference mill to identify insufficient agitation in a pulp mixer tank and insufficient utilization of cooking chemicals in the digester. Both these examples are associated with higher energy use when running at the desired point of operation but at the same time improve the productivity.

To conclude, the developed model provides a practical tool for implementing the guidelines and meeting the requirements of the energy management standard (ISO 50001) and the standard on EnPI development (ISO 50006) in kraft pulp mills. Given the specific challenges and complexities of kraft mills, this model is deemed to contribute to improved in-house energy management practices in the pulp and paper industry, and in particular to the development and implementation of relevant EnPIs. Even though Sweden is the context of the case study in this paper, the findings should be relevant to kraft mills across the EU as well as globally. The main general contributions of this paper are:

- A novel method for constructing a model for EnPI development, which could be of use, and generalized, in different types of industries.
- A novel model for EnPI development which can be used by kraft mills globally to comply with the requirements of an energy management system certification.

Further research is suggested, preferably in the form of case studies, where the methodology is implemented and further validated.

CRediT authorship contribution statement

Elias Andersson: Conceptualization, Methodology, Validation, Investigation, Writing - original draft, Visualization.
Henric Dernegård: Methodology, Validation, Formal analysis, Writing - review & editing, Visualization.
Magnus Wallén: Conceptualization, Methodology, Investigation, Writing - review & editing, Supervision, Project administration, Funding acquisition.
Patrik Thollander: Conceptualization, Validation, Investigation, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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.

Acknowledgments

The authors would like to thank all the participants at the workshops for their valuable insights. This study was funded by the Swedish Environmental Protection Agency and the Swedish Agency for Marine and Water Management, research project Carbonstruct, project no. 802-0082-17. We also thank the anonymous reviewers for the valuable comments and feedback on the paper.


