Electric Motor Systems
Platform EMSA

Digitalisation in electric motor systems – Part IV

Energy consumption due to the digitalisation of electric motor systems

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This is the fourth in the series of four reports published in 2024 on the digitalisation of electric motor systems, elaborated by EMSA. The four publications:

- Digitalisation in electric motor systems – Part I: Findings for policy makers
- Digitalisation in electric motor systems – Part II: Technical recommendations for industrial end-users
- Digitalisation in electric motor systems - Part III: Catalogue of case studies
- Digitalisation in electric motor systems – Part IV: Energy consumption due to the digitalisation of electric motor systems

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Abstract

By analysing current research and real-life cases in industry, this study aims to contribute to a better understanding of the impact of energy consumption due to the digitalisation of electric motor systems. In the cases studied, the energy expenditure to facilitate digitalisation never exceeded 1% but was rather insignificant. Consequently, on an overall level, the energy savings achieved through the digitalisation of motor systems far outweigh the additional energy consumption resulting from the digitalisation process. In the cases studied, what is decisive for the savings potential is to what extent systems were already optimised before the measures and to what extent measures can contribute to an optimised system operation.

About the 4E TCP Electric Motor Systems Platform (EMSA):

The goal of the Electric Motor Systems Platform EMSA is to increase energy efficiency and reduce greenhouse gas emissions worldwide by promoting highly efficient electric motor systems in the EMSA member countries, industrialised countries, emerging economies and developing countries. Electric motor systems consume about 10 700 TWh annually worldwide and were responsible for 53% of the global electric energy consumption in 2016. [1] This corresponds approximately to the combined electricity consumption of China, the European Union (28 countries) and the USA.

Further information on EMSA is available at: www.iea-4e.org/emsa

About the Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP):

The Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP), has been supporting governments to coordinate effective energy efficiency policies since 2008. Fourteen countries and one region have joined together under the 4E TCP platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However, the 4E TCP is more than a forum for sharing information: it pools resources and expertise on a wide range of projects designed to meet the policy needs of participating governments. Members of 4E find this an efficient use of scarce funds which results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions. The 4E TCP is established under the auspices of the International Energy Agency (IEA) as a functionally and legally autonomous body.

Current members of 4E TCP are: Australia, Austria, Canada, China, Denmark, European Commission, France, Japan, Korea, Netherlands, New Zealand, Switzerland, Sweden, UK and USA.

The main collaborative research and development activities under 4E include the

- Electric Motor Systems Platform (EMSA)
- Efficient, Demand Flexible Networked Appliances (EDNA) Platform
- Smart Sustainability in Lighting and Controls (SSLC) Platform
- Power Electronic Conversion Technology Platform (PECTA)

Further information on the 4E TCP is available from: www.iea-4e.org

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Abbreviations

4E	Energy Efficient End-use Equipment
a	annum
EDNA	Efficient, Demand Flexible Networked Appliances Platform
EMSA	Electric Motor Systems Platform
LCA	Life Cycle Assessment
IEA	International Energy Agency
IoT	Internet of Things
PECTA	Power Electronic Conversion Technology Platform
SSLC	Smart Sustainability in Lighting and Controls Platform
TCP	Technology Collaboration Programme
VSD	Variable Speed Drive

Executive summary

The introduction and rise of digitalisation in industrial electric motor systems (motor systems) is expected to enable a more energy efficient operation of motor systems. However, digital technologies also consume energy. This report focuses on motor systems in the industrial sector and addresses the following questions:

- How large is the energy consumption associated with the digitalisation of electric motor systems?
- What are the benefits and downsides of using digital technologies?
- Do the benefits outweigh the downsides?

The study employs the following methodology:

- Literature research
- Structure and types of digital benefits
- General analysis and decomposition of digital consumers
- Analysis of real cases
- Evaluation and key findings
- Discussion and recommendations for future research.

The rapid rise of digitalisation has been affecting various areas in the economy. Considering the substantial increase in data stream that inherently comes along with digitalisation, research interest regarding the impact on the energy effect has been growing. As for motor systems, the research on energy impact currently appears to be sparse. A comprehensive understanding related to the energy benefits and drawbacks of digitalisation in motor systems is still lacking. A crucial initial stride towards gaining a deeper understanding of this matter involves the classification of digital motor systems. [13] By analysing current research and real-life cases in industry, this study aims to contribute fragments to a better understanding of the impact of digital motor systems on energy consumption.

As for the main motives leading industrial users to the adoption of digitalised systems, energy related benefits (increase system efficiency, monitor energy consumption, avoid parasitic energy consumption) and non-energy related benefits (avoid down time, increase production efficiency, cost-effective maintenance, etc.) can be separated. While energy related benefits may reduce operational cost significantly, the primary motive for digitalisation is not per se related to saving energy but can be attributed to non-energy benefits.

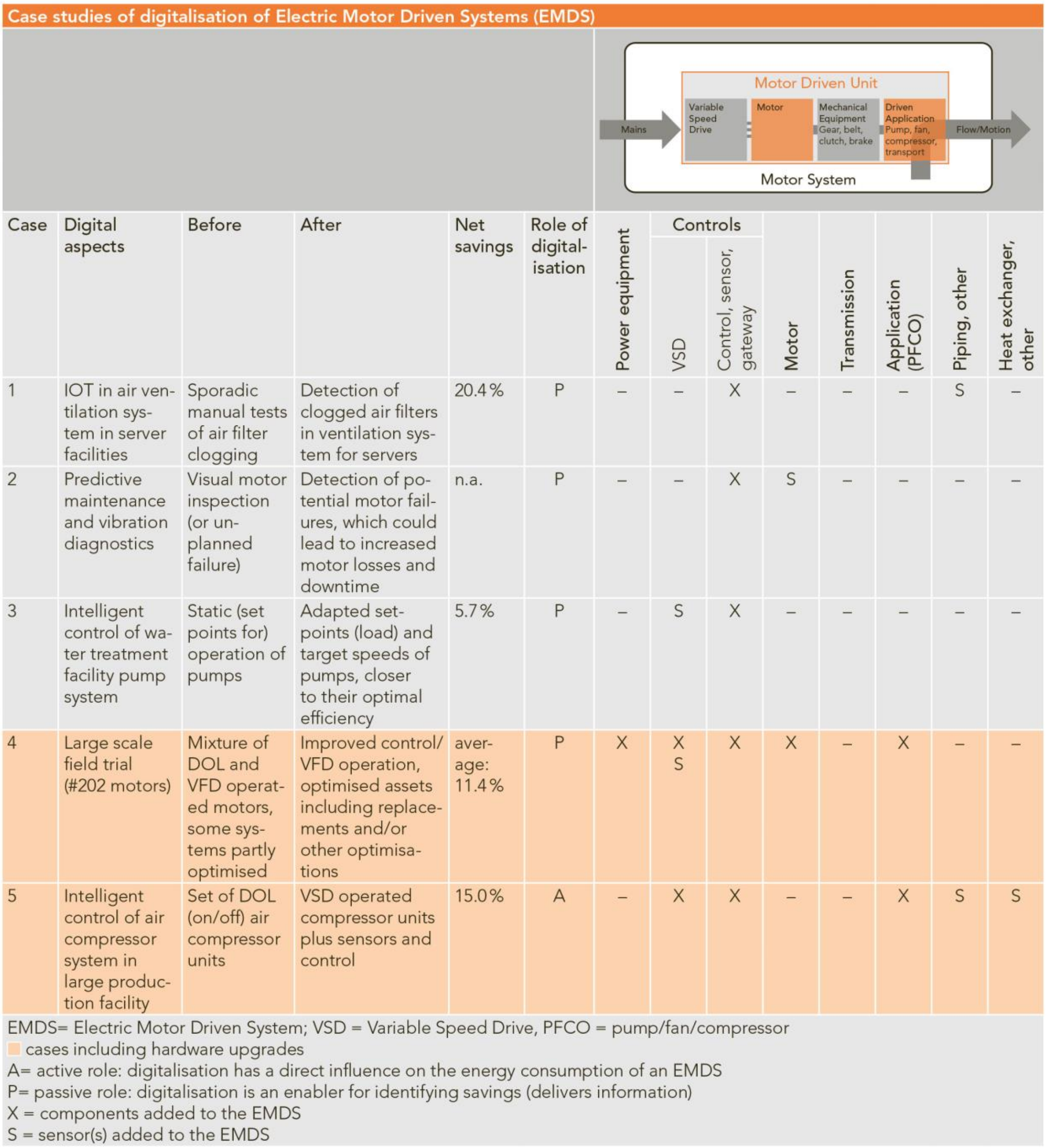
The role of digitalisation in motor systems can be looked at in different ways. In a “passive” role, as an enabler to identify savings opportunities, e.g. through monitoring of equipment. In an “active” role, having direct influence on the energy consumption of a motor system, for example, in the case of an intelligent control.

Five exemplary cases have been documented for this study, as follows:

- Case 1: IoT sensor in air ventilation system in server facilities to detect clogged filters
- Case 2: predictive maintenance and vibration diagnostics via smart sensor. For this case, a sensitivity analysis was made concerning data transmission, operating hours and standby consumption.
- Case 3: intelligent control of water treatment facility pump system, applying electrical signature analysis
- Case 4: a large scale field trial, using the same technology as in Case 3
- Case 5: intelligent control of an air compressor system.

For these cases, a detailed impact analysis regarding energy consumption is provided. It was

possible to collect cases for all major motor systems applications, i.e. compressors, pumps and fans. Digital technologies enable motor system optimisation, which often includes hardware upgrades. In the cases presented, whenever possible, the energy savings and the source of these savings (with/without hardware upgrade) was identified. The following table summarises the cases presented.



Case studies of digitalisation of Electric Motor Driven Systems (EMDS)

Case	Digital aspects	Before	After	Net savings	Role of digital-isation	Power equipment	Controls		Motor	Transmission	Application (PFCO)	Piping, other	Heat exchanger, other
							VSD	Control, sensor, gateway					
1	IOT in air ventilation system in server facilities	Sporadic manual tests of air filter clogging	Detection of clogged air filters in ventilation system for servers	20.4 %	P	–	–	X	–	–	–	S	–
2	Predictive maintenance and vibration diagnostics	Visual motor inspection (or unplanned failure)	Detection of potential motor failures, which could lead to increased motor losses and downtime	n.a.	P	–	–	X	S	–	–	–	–
3	Intelligent control of water treatment facility pump system	Static (set points for) operation of pumps	Adapted setpoints (load) and target speeds of pumps, closer to their optimal efficiency	5.7 %	P	–	S	X	–	–	–	–	–
4	Large scale field trial (#202 motors)	Mixture of DOL and VFD operated motors, some systems partly optimised	Improved control/ VFD operation, optimised assets including replacements and/or other optimisations	average: 11.4 %	P	X	X S	X	X	–	X	–	–
5	Intelligent control of air compressor system in large production facility	Set of DOL (on/off) air compressor units	VSD operated compressor units plus sensors and control	15.0 %	A	–	X	X	–	–	X	S	S

EMDS= Electric Motor Driven System; VSD = Variable Speed Drive, PFCO = pump/fan/compressor
▨ cases including hardware upgrades
A= active role: digitalisation has a direct influence on the energy consumption of an EMDS
P= passive role: digitalisation is an enabler for identifying savings (delivers information)
X = components added to the EMDS
S = sensor(s) added to the EMDS

Summary of cases presented in this study

Depending on the ‘starting point for optimisation’, the applicable measures can materialise as a series of optimisations from changing set points to changing complete components like a motor, Variable Speed Drive (VSD) or pump. The studied cases show net savings (excluding digital energy consumption) ranging from 5.7% up to 20.4%. In case 4, savings for the motor systems reached up to 46%, while the average saving in subgroups of motors, e.g. those without a VSD before optimisation was 24%, those with a VSD before optimisation was 9%.

The energy consumption attributable to the digitalisation of motor systems stems from a variety of sources. Notably external network communication i.e., the use of cloud services can add to the total energy consumption when high data volumes and storage requirements are given. However, with regards to limiting factors such as battery life in smart sensors, it is much more common to work with small and compressed data sets that leave a marginal impact even when considering pessimistic values for network energy consumption. As for hardware components attributable to digitalised motor systems, sensors and local data communication or storage devices typically show a low energy consumption. There is a variety of digitalisation concepts, of which smart sensors have negligible energy consumption but some systems may show larger power usage. Generally, infrastructure necessary to facilitate digitalisation of motor systems may already be in place to a large extent. This directly limits the additional energy required for further network participants. With regards to energy intensity, we classify the type of digitalisation according to the table below. The classification distinguishes primary targets of the digitalisation which, based upon the study findings, result in different typical energy consumption. This typically directly correlates with the computational complexity. It is worth noting that the baseline values for the classifications have been chosen arbitrarily considering the cases examined in this study.

	Smart Sensors/ IoT	**Advanced analytics**	**Adaptive control systems**
Annual energy consumption of digital system	< 10 Wh/a	10 Wh/a -200 kWh/a	> 200 kWh/a
Computational frequency	<<1 Hz	~1Hz	>1 Hz
Number of motors	1	>=1	>2
Primary target of digitalisation	Error detection	Error detection, optimisation	Energy savings, emission reduction
Assignable cases from this study	Case 1 Case 2	Case 2 Case 3 Case 4	Case 5

Classification of digitalised motor systems

In the cases studied, the energy expenditure to facilitate digitalisation never exceeded 1% but was rather insignificant. Consequently, on an overall level, the energy savings achieved through the digitalisation of motor systems far outweigh the additional energy consumption resulting from the digitalisation process. In the cases studied, what is decisive for the savings potential is to what extent systems were already optimised before the measures and to what extent measures can contribute to an optimised system operation.

The sample size with the cases presented is by no means representative which is a limiting factor for aggregated conclusions. The collection of further cases would be helpful to be able to draw statistically relevant conclusions. A greater number of cases would also allow a better distinction between the types of digitalisation technologies/solutions applied with motor systems. This combined with data on the installed base of motors could create a sound basis for answering further questions, like:

1. What type of digitalisation solution suits best certain motor system setups?
2. What is the range of expected energy savings stemming from the different digitalisation technologies?

3. To what extent does digitalisation unlock additional energy savings?
4. What is the savings potential in certain sectors (energy-intensive, non-energy intensive)?
5. What is the cost-effectiveness of digitalisation and the size of programmes required for its large-scale application?

Nevertheless, the main conclusion of this study is that for all cases analysed the energy used for the digitalisation of the motor systems is with less than 1% negligible.

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1 Introduction

Worldwide, around 53% of electric energy is consumed by electric motor systems[1]. [1] New digital technologies open up novel possibilities for the continuous monitoring of parameters relevant to the energy consumption and maintenance of electric motor systems. The International Energy Agency Technology Collaboration Programme 4E Electric Motor Systems Platform (EMSA www.iea-4e.org/emsa/) is working on the topic of digitalisation of motor systems. This is being addressed in the EMSA workstream on New Industrial Developments and Digitalisation in Motor Systems.

Four countries are working together on this topic: Austria (lead), the Netherlands, Sweden and Switzerland. In the framework of this international collaboration, the topic of digitalisation in motor driven systems shall gain worldwide increased attention and be brought forward, through:

- Raising awareness on the energy savings potential
- Showing best practices through case studies and successful policy instruments
- Identifying barriers and potentially ways to overcome these
- Motivate and help industrial facilities to start and/or continue to reap the savings potential offered by the digitalisation of their motor systems through targeted information and case studies as “good examples”
- Closing an information gap also with regard to the energy consumption due to the digitalisation of electric motor systems
- A structured coordination and exchange with international experts and stakeholders.

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[1] Throughout this report, the term ‘motor system’ is used, referring to electric motor system.

2 Scope and purpose of study

With the introduction and rise of digitalisation in industrial motor systems, these are expected to become more energy efficient. Various digital technologies and solutions contribute to more efficient work cycles with respect to energy demand and human interference. However, digital technologies also consume energy which depends on several factors, e.g. on the overall bit workload as well as the efficiency of data management.

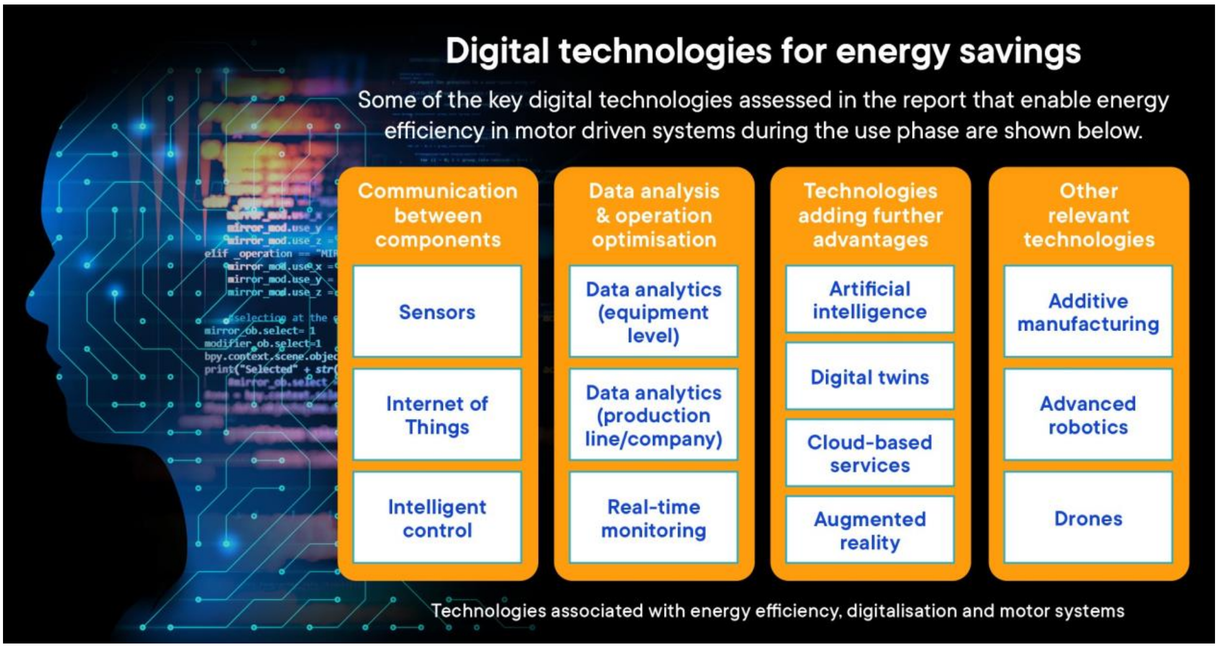
This report addresses the following questions:

- How large is the energy consumption associated with the digitalisation of electric motor systems?
- What are the benefits (e.g. energy savings, lower maintenance cost, more up-time, etc.) and downsides (e.g. higher energy use due to digitalisation) of using digital technologies?
- Do the benefits outweigh the downsides?

This study focuses on motor systems in the industrial sector. The background for this is that digital solutions for energy efficient industrial motor systems are relatively new and under development. Whereas e.g. in buildings digitalisation is already advanced, integrating lighting, cooling, heating and ventilation systems for an optimised comfort, energy use and cost.

2.1 Study context

EMSA published a report on the *Classification of digitalisation technologies for electric motor driven systems* in 2022. This report gives an overview of the major digitalisation technologies that are used in the field of electric motor systems (see Figure 1).



Digital technologies for energy savings

Some of the key digital technologies assessed in the report that enable energy efficiency in motor driven systems during the use phase are shown below.

Communication between components	Data analysis & operation optimisation	Technologies adding further advantages	Other relevant technologies
Sensors	Data analytics (equipment level)	Artificial intelligence	Additive manufacturing
Internet of Things	Data analytics (production line/company)	Digital twins	Advanced robotics
Intelligent control	Real-time monitoring	Cloud-based services	Drones
		Augmented reality	

Technologies associated with energy efficiency, digitalisation and motor systems

Figure 1 Digitalisation technologies analysed in the EMSA report Classification of digitalisation technologies for electric motor driven systems (2022)

These technologies served as a point of orientation for the type of technologies/solutions captured within this report.

Since the availability of data considering the impact of digital energy consumption in motor systems is currently poor, this study aimed to make a first step through the analysis of concrete cases. In the framework of the international collaboration, case studies or good examples of digitalisation in motor systems were identified. This report draws on a number of them.

2.2 Methodology

To evaluate the influence and consequences of digitalisation related to energy consumption on industrial motor systems, the study employs the following methodology:

- Research of literature and industrial state related to digitalisation:
  A review of current dynamics in the context of digitalised motor systems will illustrate the focus of this study. Additionally, a literature review will contribute insights regarding digital energy consumption to enhance the research.

- Qualitative analysis of structure and types of digital benefits:
  The structures and types of digital motor equipment shall be outlined with the goal of a better understanding of the benefits and drawbacks of digitalisation.

- General analysis of digital consumers in context of motor systems:
  By means of literature research and simplified modelling, digital energy consumers shall be quantitatively assessed with regards to their energy consumption. The

limitations and sensitivity of various digital consumer components will be defined and outlined.

- Analysis of real cases in industry:
  Cases from industry are analysed thoroughly. Subsequently, the predefined categories can be explored, enabling the formulation of an overarching perspective that takes energy consumption into account.

- Evaluation and key findings:
  The cases and observations are expected to yield the fundament to assess digitalised motor systems in light of energy consumption in a more comprehensive manner.

3 Research related to digitalisation and effects on motor systems

The rapid rise of digitalisation has been affecting various areas in the economy. Considering the substantial increase in data stream that inherently comes along with digitalisation, research interest regarding the impact on the energy effect has been growing. Notably, the energy consumption of network communication and data centres have proved to be difficult to estimate. ([3], [8]) Hence, LCA studies can show significant discrepancies and uncertainties. The IEA currently estimates data centres to account for 1-1.5% of worldwide electricity use while global computing power is rapidly increasing. It is worth noting that the energy efficiency of data centres is greatly increasing which can be concluded by comparison of network traffic and energy use of data centres over the past decades. ([8], [9])

As for motor systems, the research on energy impact currently appears to be sparse. In [3] the energy benefit of equipping motor systems above 1HP with smart sensor systems is estimated to be 5-10% without statement of sources or elaboration of data basis. Moreover, the exploration of the "cost" associated with digitalising motor systems in terms of energy consumption has been relatively limited. Hence, a comprehensive understanding related to the energy benefits and drawback of digitalisation in motor systems is still lacking. A crucial initial stride towards gaining a deeper understanding of this matter involves the categorisation of digital motor systems. This classification has been investigated previously ([13]) and constitutes one of the objectives in this study. By analysing current research and real-life cases in industry, the study aims to contribute fragments to a better understanding of the impact of digital motor systems on energy consumption.

3.1 EMSA research on digitalisation in industrial motor systems

This subsection captures relevant key points from previous research done by EMSA on digital technologies used with motor systems in industry.

As described in section 2.1, the EMSA report *Classification of digitalisation technologies for electric motor driven systems* gives an overview of the major digitalisation technologies that are used in the field of electric motor systems (see Figure 1).

The *Report on the EMSA Survey on digitalisation in electric motor driven systems* summarises the results of an international survey with over 100 respondents on the topic that EMSA conducted in 2020. The majority of survey respondents are energy consultants, followed by motor and component manufacturers, as well as representatives of a few utilities and end-users.

Key findings:

- Respondents rate the average increase in energy efficiency of electric motor systems from the use of digital solutions to be around 18% (see Figure 2).

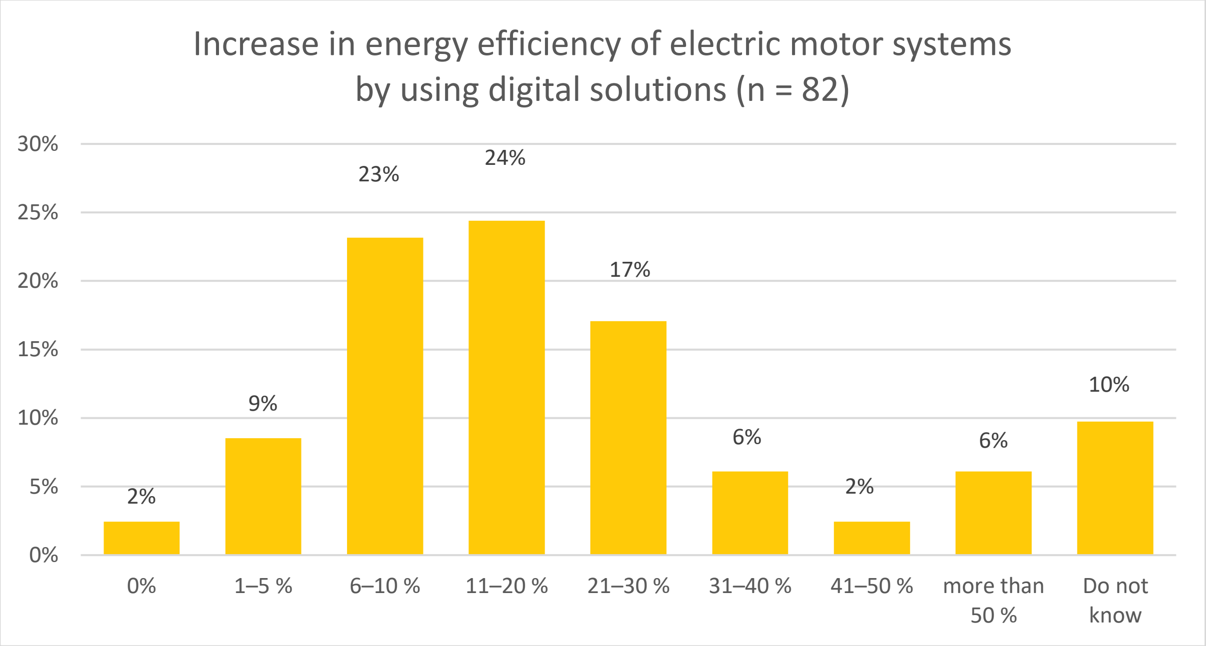


Figure 2: Estimated increase in energy efficiency of electric motor systems by using digital solutions
NOTE: Respondents were asked to estimate the energy saving effect of digitalisation technologies. While the estimated scale of savings varied, half considered the potential to be between 6% and 20%. Nearly one third of all respondents rated the saving potential to exceed 20%, with 6% believing that savings could be larger than 50%.

- Smart sensors, smart control and continuous monitoring are the digital technologies most used by industrial users in conjunction with motor driven systems. These three digital technologies are expected to have the greatest impact on potential future energy savings (see Figure 3). Currently, the worldwide use of smart sensors is estimated at less than 1% of installed motors. [21]
- Superior production efficiency, more flexibility and higher system availability are considered to be the main advantages.
- An increased risk of failure and higher implementation costs were mentioned as the main disadvantages.
- The lack of qualified staff and high investment costs are perceived as main barriers to greater uptake of digital technologies.
- Good technical solutions for cybersecurity and the availability of qualified staff are the most significant enablers.
- Around three quarter of respondents consider the development of training programmes, the standardisation of protocols, and subsidies for research as important policy instruments to overcome the barriers mentioned above.

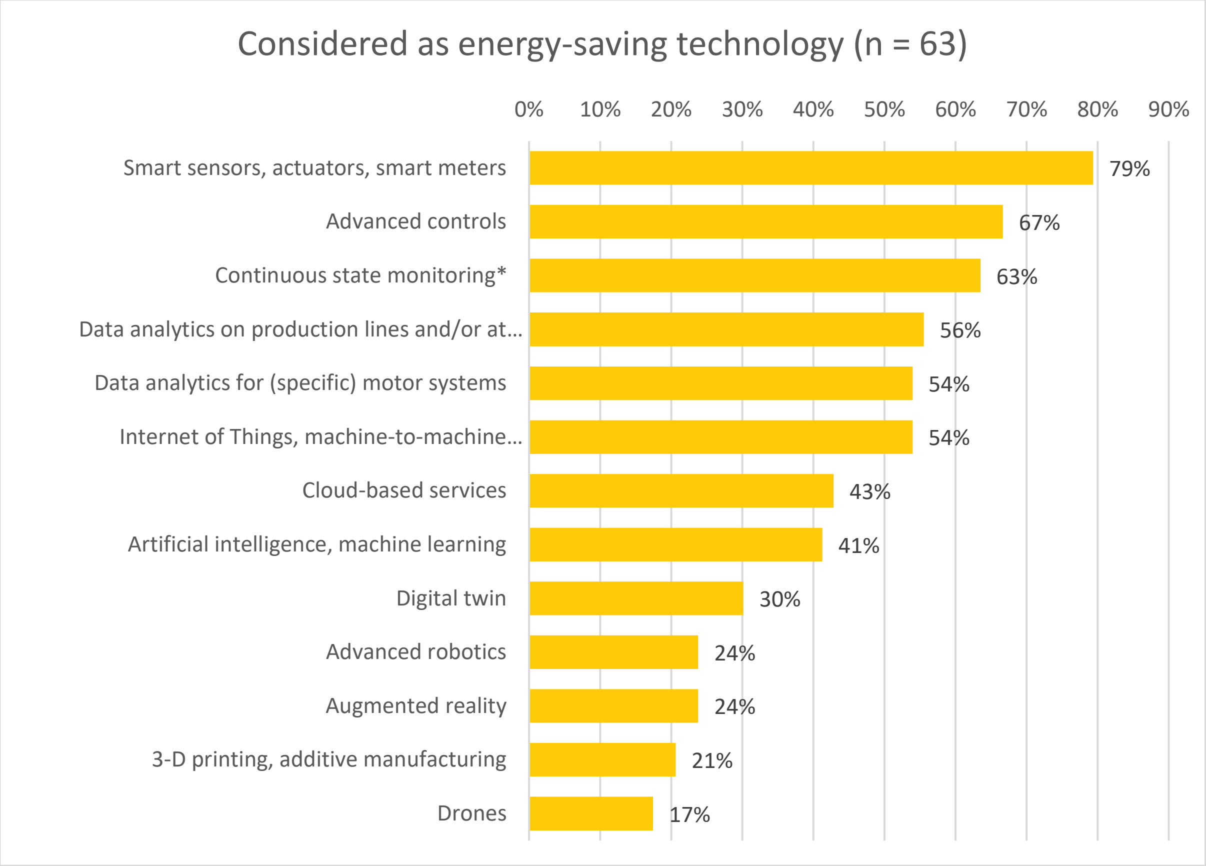


*Figure 3:Digitalisation technologies that are considered to help save energy. *Continuous state monitoring refers to real-time data transfer from the relevant system, so that analysis and monitoring of current state and trending are possible.*

The present study builds on the findings of previous research and includes motor system setups for smart sensor, advanced control and continuous monitoring.

3.2 Observations and current trends

Through the course of EMSA's work on digitalisation of motor systems, several interviews were conducted with different stakeholders (e.g. manufacturers, service providers, end users) as well as two workshops held (in 2021 and 2023). Building on these exchanges, the following observations were made:

a. In general, both the literature and the available data seems to be scarce in the area of digitalisation of industrial motor systems, with focus on energy use and energy efficiency.
b. The energy consumption of digitalisation needs further research.
c. There is a need for more concrete practical examples that can be shared publicly. These are important in communication and capacity building as a source of motivation from early adapters. Finding suitable case studies within the framework of EMSA's work proved to be a challenge.
d. When looking at the energy saving potential of digitalisation, in the case studies identified in the EMSA project partner countries [5], the potential varies greatly. In some cases it is challenging to make a differentiation and allocate one part of the savings to a hardware upgrade and another part specifically to the digital technology or solution applied. The 'hardware' and 'software' part can also interact, or can be implemented consecutively, e.g. a hardware upgrade following a digital analysis.

e. Manufacturers developed their product portfolio for digitalisation and are investing in its constant improvement. While the technology is ready, the speed of market development for digitalisation in motor systems is lower than expected. The market does not seem to be ready for a large-scale uptake yet, while first market developments can be observed in certain areas. Barriers for market uptake include:
    i. Concerns around cybersecurity
    ii. Reservations in terms of sharing data
    iii. The “human factor” which plays a crucial role: lack of skills both at the end user and the service provider as well as lack of resources hinder implementation. In order to advance digitalisation, a focus on the human factor in all aspects of digitalisation is needed.
f. The primary motivation of end-users for applying digital technologies and solutions is to increase uptime, i.e. avoid breakdowns e.g. through condition monitoring and predictive maintenance as much as possible. Energy-efficiency is usually not a top motivation, it is more a side-effect.
g. One hindering factor for investments into energy efficiency in general are relatively low energy prices and costs compared to the typical total costs of industrial users.
h. There is a need to address the multiple benefits of digitalisation (not focusing only on energy efficiency), helping to strengthen the case for applying digital solutions.
i. Approaching different stakeholders in industry is important, i.e. addressing the higher management for decision making in terms of e.g. company goals, company and investment strategy, not only maintenance personnel in factories.

4 Analysis of digitalised industrial motor systems

This section provides a classification of digitalised motor systems with respect to their benefits. In sub-section 4.3, the types of excess energy consumption of digital motor systems are described. Finally, the study constraints are defined.

4.1 Classification of benefits

It is important to highlight the main motives leading industrial users to the adoption of digitalised systems. As shown in Figure 4, energy related and non-energy related benefits can be separated.

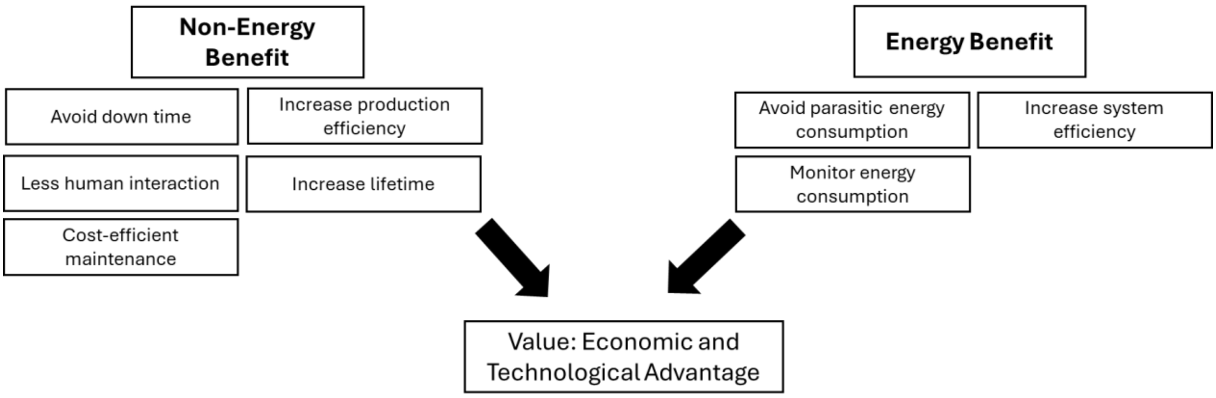


Figure 4: Distinction of benefits related to digitalisation

While energy related benefits may reduce operational cost significantly, the primary motive for digitalisation is not per se related to saving energy but can be attributed to the following non-energy benefits:

- **Avoiding down time**: For many industrial applications, a fault with resulting outage causes substantial economic damage. Hence, fail-safety is an important aspect of a motor system, which may be improved by means of digitalisation. Condition based maintenance can provide failure prediction in advance, leading to savings in downtime. According to [23], a single hour of down time may cost up to $2 million with an estimate of potentially saving 1.6 million hours of downtime by means of predictive maintenance.
- **Increasing production efficiency**: Considering the use of raw materials and resources, the production efficiency may have a great impact on production cost. Digitalisation is expected to improve production efficiency by efficient monitoring and intervention.
- **Cost-efficient maintenance**: Digital technologies help to detect equipment problems, thus, maintenance occurs when needed. This reduces cost and improves resource allocation. [5]
- **Reducing human interaction**: Human interaction may be a substantial cost driver when the required interaction is frequent. Digitalisation could prevent or reduce human interaction by allowing more automation. Furthermore, companies may reduce carbon emissions by means of remote maintenance.
- **Increasing asset health and lifetime**: The lifetime of production equipment may be extended through digitalisation due to lower maintenance need. Beside predictive maintenance i.e., the early warning of wear or failure, data analysis can allow to optimise production patterns and increase lifetime.

Digital technologies enable motor system optimisation, which often includes hardware upgrades. A number of other non-energy benefits can be associated with motor system optimisation which are described in more detail in [6].

The benefits directly related to energy consumption may be classified as the

- **Avoidance of parasitic energy consumption**: Detailed monitoring of motor systems could allow the identification and prevention of inadvertent excess power consumption such as friction, standby consumption, inefficient operation over time (above optimal baseline), et cetera.
- **Increase of efficiency**: Sensor systems and data analysis feature the potential to greatly improve energy efficiency. For instance, intelligent control systems relying on such data may adapt operational parameters such that the energy consumption is reduced. Analyses may also pinpoint inefficiencies in the hardware.
- **Monitor energy consumption**: Thanks to data collection and analysis via digital technologies, insight into asset performance can be increased. For example, benchmarks can be set and actual consumption compared to the set benchmarks. This control mechanism helps to compare effective to envisaged energy consumption and spot anomalies. It may also enhance a more steady planning in terms of energy cost.

4.2 Energy savings due to digitalisation

In this subsection the source of potential energy savings due to digitalisation of motor systems is discussed.

Digitalisation is an enabler for optimised motor system performance. The role of digitalisation in motor systems can be looked at in different ways:

- In a “passive” role, as an enabler to identify savings opportunities, i.e. delivering information that can be analysed and based on which optimisation measures can be implemented. For example, through monitoring of equipment, excess energy consumption (during the night, on weekends) can be clearly identified [4] and thresholds set, or indications to hardware optimisation, e.g. air leakage of compressors [5] or oversizing of equipment, spotted.
- In an “active” role, having direct influence on the energy consumption of a motor system, for example, in the case of an intelligent control. This typically does not trigger hardware updates, however, the digital solution may be applied at a time when also a hardware update to the system is made.

Figure 5 shows a generalised structure of motor systems. Hardware updates above refer to any updates made to the individual components of the system.

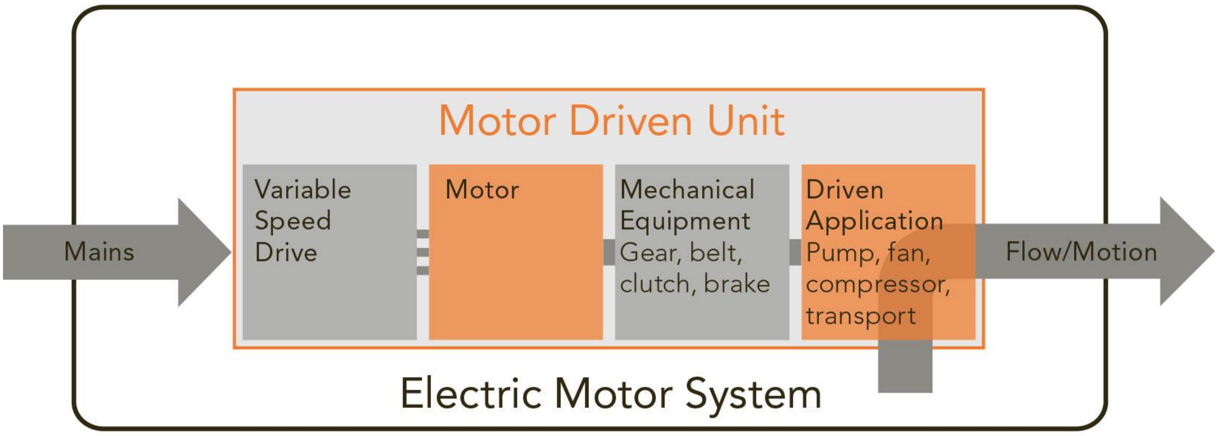


Figure 5: Generalised structure of motor systems

In this study and the cases presented, whenever possible, the energy savings that could be achieved thanks to the digital solution are quantified. Depending on the case, the energy savings are achieved either with or without any hardware upgrades. Whenever a hardware upgrade was made, this is described in the individual cases.

4.3 Analysis of energy consumption in industrial motor systems

In this subsection the quantification methodology of digital excess energy is described. A bottom-up analysis according to the following six steps is executed:

1. System definition
2. Component identification
3. Component impact assessment
4. Sensitivity analysis
5. Overall assessment and interpretation

Steps 1-3 are conducted based on the cases presented later on. The sensitivity analysis is then expected to yield robust statements with respect to the energy impact. Subsequently, an overall assessment and interpretation is formulated to advise the conclusion of the study.

With respect to decomposition and evaluation of energy relevant components, it is important to define system boundaries and highlight the assumptions and the ensuing limitations of the study.

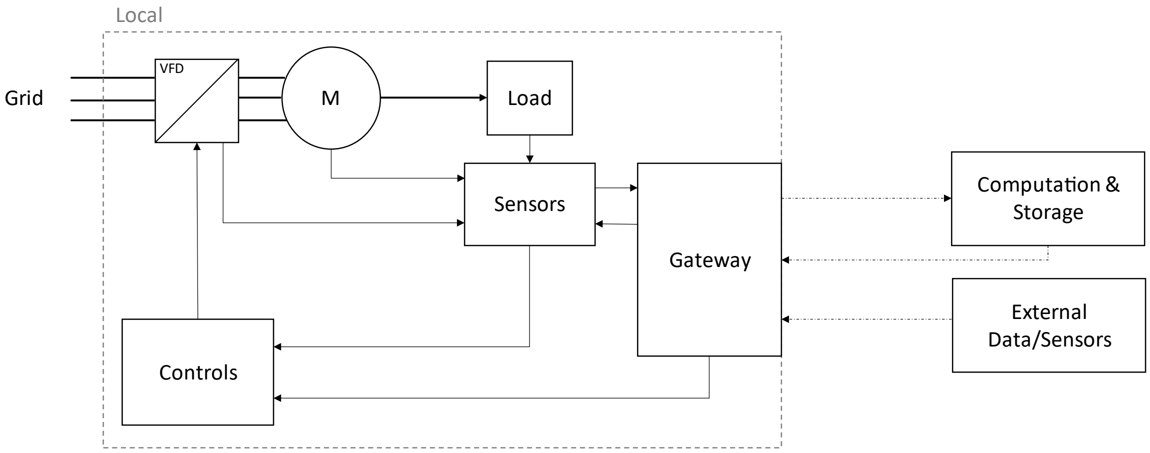
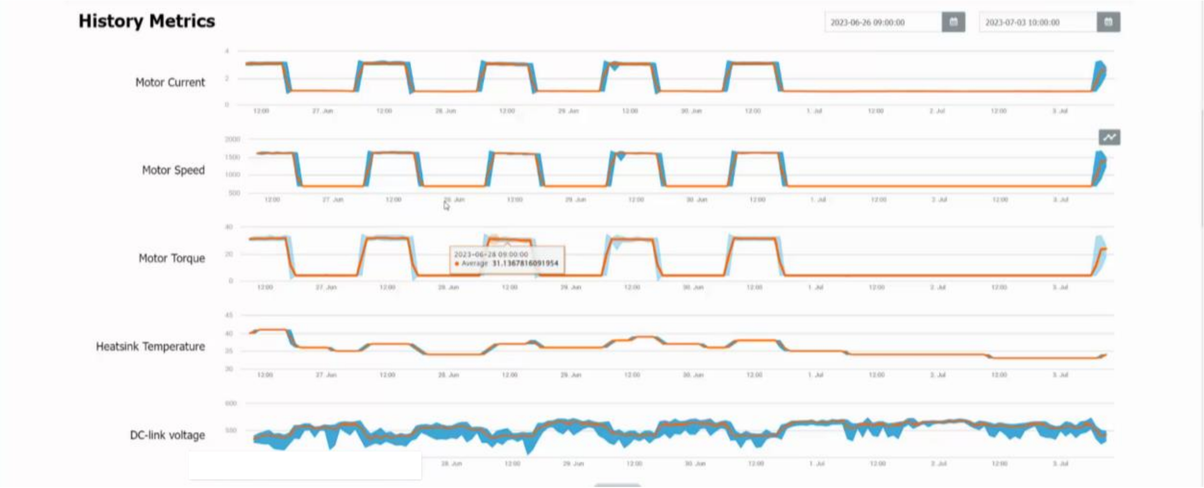


Figure 6: Generalised structure of digital motor systems (M = motor)

Figure 6 shows a generalised structure of digital motor systems. As highlighted by the dashed box, we define a subsystem boundary in terms of locality. The outside of the local sub-system is defined as any hardware processing or storing data which can not be attributed to the local facility of the motor system.

The local system components include the motor system. Note that the presented system architecture may differ and look more complex for some applications. In particular, the term “gateway” is used as a general local communication and data handling system, which may be divided into further subcomponents. A simplified structural description of the respective subcomponents is presented in [8]. However, considering the energy impact, a further decomposition only becomes relevant, if the structure significantly differs between a setup that includes digital motor system and a non-digital reference. The following baseline assumptions are hence made with respect to the energy consumption:

- **Baseline digital facility**: The incorporation of a digital motor system may necessitate the inclusion of additional energy-consuming components, such as ethernet switches, to support data management. It is assumed that the existing infrastructure already facilitates data communication, which is minimally impacted by the addition of new network participants. This assumption can be justified for two reasons. Firstly, larger companies, which tend to have more energy-intensive operations, are expected to possess larger networks where the addition of new nodes has a negligible effect. Secondly, the data volume attributed solely to the motor system is typically small compared to the overall data traffic volume of modern companies. However, this effect is examined in the sensitivity analysis, which takes into account an estimated specific consumption of network participants.
- **Baseline motor system:** To avoid the misinterpretation of efficiency improvements assignable to measures such as motor retrofit (higher IE class, Variable Speed Drive), it is crucial to use an identical system as the reference motor hardware. However, it is also important to acknowledge that in practice, distinguishing between efficiency improvements due to a motor system hardware retrofit and a digital upgrade can be challenging, since upgrades to a digital motor system often entail both.
- **Variable Speed Drive (VSD):** Among the motor systems' components the VSD is highlighted separately, since its functionality allows its usage as a sensor, delivering data (see Figure 7). Exploiting this data comes with no added energy consumption in additional equipment. In cases, when this sensor functionality is not used, the own consumption of a VSD should not be considered a digital consumer. In cases, when this sensor functionality is used, parts of the own consumption of the VSD should be assigned to digital energy consumption. In this study, no such concrete case is presented.


2023-06-26 09:00:00

2023-07-03 10:00:00

2023-06-28 09:00:00
● Average: 31.1367816091954

Last data received 2023-07-03
(10.30.63.18) 09:55:09

FC-102

VLT

Live Metrics

Ready state

Running state

Fault state

Energy Consumption
203155

Operating Hours
39479

Fan running hours
36780

Running Hours
38107

Over Temps
0

Power Ups
23

Drive Status History

Figure 7 Example for data delivered by a VSD (source: Danfoss)

Now, the decomposition of energetically relevant components is carried out according to the following categories of digital power consumers.

1) **Sensor**: The sensor component includes all subcomponents that facilitate a sensor signal including its local data transmission. For sensors integrated into a data handling and pre-processing module, the share of the sensor power can be neglected considering the typically applied sensors in motor systems. However, if a battery powered wireless sensor is used, the sensor component includes the total power consumption of the respective device.
2) **Internal**: This component is defined as the energy required to process and store data locally.
3) **External**: This component refers to the group of power consumers enabling the facilitation of all external data communication and delocalized storage processes. This includes gateway, network transmission and delocalized storage. In this regard, we consistently work with values following [8].
4) **Other**: This refers to the residual energy that is not assignable to 1)-3). This may include embodied energy from device manufacturing or secondary effects such as prevented technician mobility. Non-assignable components are not included as a baseline but will be examined in the sensitivity analysis. In this study, particular attention is given to battery manufacturing and its energy expenditure.

Note that the above decomposition of the components is shown for each case either as a percentage of the total energy consumption or as an absolute value. Absolute values are used when the digital energy consumption is significantly lower compared to the total energy consumption.

5 Evaluation of digital energy consumption in motor systems

This chapter provides the description and evaluation of exemplary cases that have been documented for this study. For these cases a detailed impact analysis regarding energy consumption is provided. It was possible to collect cases for all major motor systems applications, i.e. compressors, pumps and fans. As highlighted in Figure 1, a variety of digital technologies have been arising in past few years. The authors aimed to present an overall picture as broad as possible but, more importantly, the cases should reflect the relevance of different technology in industry.

The cases were collected from different sources. One main source for several cases comes from the workstream within the IEA 4E EMSA, where several countries collected cases studies, namely concrete, detailed examples of digitalised motor systems. [7] Case 4 draws on a broader project implemented in the Netherlands, affecting around 1’000 assets (mainly pumps). In summary:

1. Case 1: IoT in air ventilation system in server facilities, from Switzerland, source: PRiOT, an IoT solutions provider
2. Case 2: predictive maintenance and vibration diagnostics, a demonstration case from Switzerland, source: Küffer Elektro-Technik AG, a Swiss motor service company
3. Case 3: intelligent control of water treatment facility pump system. The pump system is within Yorkshire Water, a water supply and sewerage company in the United Kingdom. The solution has been installed by Samotics, a solutions provider to eliminate unplanned downtime, from the Netherlands.
4. Case 4: a large scale field trial in the Netherlands (project ERGO), implemented by Samotics, using the same technology as in Case 3.
5. Case 5: intelligent control of air compressor system in large production, from Switzerland. The compressed air system is in the facility of Hamilton Bonaduz, a company producing medical devices as well as laboratory equipment. The solution was provided by KAESER Kompressoren.

A more detailed description of cases 1, 3 and 5 is available in [7]. The analyses below have the energy consumption aspect of digitalisation in focus.

5.1 Case 1: IoT sensor in air ventilation system in server facilities

An air ventilation system which regulates the temperature in server sites has been equipped with a low power consuming sensor module. The sensor module can detect clogged air filters via differential pressure sensing and thus prevent a higher energy consumption caused by increased power drawn by the motor without getting noticed. The power drawn by the motor depends linearly on the pressure difference. Experience shows that the power drawn by the motor is increased by approximately a factor of 2.5 when the filter is clogged.

Before the intervention, clogged filters could have only been detected through manual tests. In a concrete example, after 9 months of operation, the filter was clogged and ready for an exchange. Without the IoT sensor, the filter change would have happened at the next manual inspection, which was planned three months later. Hence the ventilation system would have been in operation with a polluted filter during three more months. Instead, it could be exchanged after 9 months. This way, 20% of electric energy could be saved.

The digital system involves a low power LoRa based wireless communication module that runs on a battery.

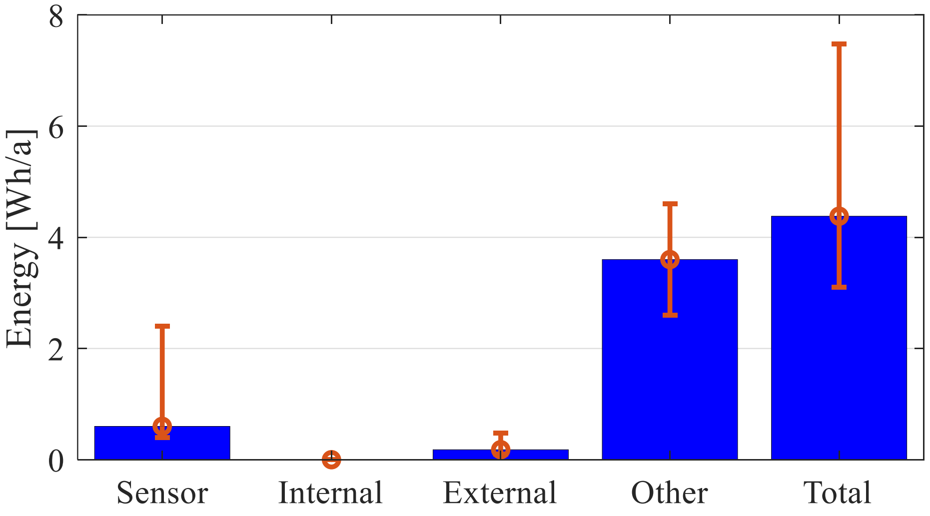


Figure 8: Case 1 energy usage of digital components with indication of total digital energy consumption

To summarise the digital energy consumption by category:

- The **sensor energy**, consisting of the module consumption obtained from the average battery current is negligible in comparison to the overall energy consumption.
- As no further internal hardware is used to facilitate the system, no **internal energy** is consumed.
- The **external energy** arises from the data transmission and cloud storage given by the data volume and current impact of end-to-end network consumption. [3] This is quite low due to the low data transmission rate.
- Finally, under **other** we consider embodied energy from battery manufacturing resulting from typical energy required to manufacture per storage capacity. This energy can be up to two magnitudes higher compared to the battery capacity [14], but may still be insignificant in view of the motor system energy consumption.

Figure 9: Filter system equipped with LoRa monitoring sensor module (PRiOT AG)

As can be seen in Table 1, the energy impact of the module is low compared to the benefit gained. A key contributor to the module efficiency is the data handling efficiency, since only small data sets and data rates are sent which in turn have insignificant impact even when considering conservative estimates for external data transmission impact such as high network energy consumption. Owing to the energy efficiency of LoRa communication, small battery with long lifespan can be employed which have a low overall impact considering embodied energy.

Case 1	Energy [kWh/a]	Share of total energy [%]
Annual consumption	6’510	100.0%
Gross saving potential	1’329	20.4%
Digitalisation energy expenditure	0.0044	0.0%
Net energy benefit due to digitalisation	1’329	20.4%

Table 1: Case 1 results of energy study

This case demonstrates, how rather simple solutions with efficient data handling decrease the need for on-site maintenance.

From the company’s point of view, the biggest gain is in terms of resource efficiency and condition-based maintenance. PRiOT sees the following benefits to be the most relevant for them in relation to this measure (in order of importance):

1. Decrease in the frequency of on-site maintenance.
2. Extension of the filter lifetime with an average of 50%. This means savings in filter material.
3. Quick recognition of non-optimal operation, e.g. clogged filters, defect motors.
4. Savings in electric energy and electricity costs, as shown in the concrete example above.

5.2 Case 2: Predictive maintenance and vibration diagnostics (demonstration)

Sensors can measure a range of parameters, as is shown in Figure 10. A smart sensor has the capability of: (1) measuring multiples values, (2) performing one or more logic functions, (3) storing information for future analysis, (4) making decisions, and (5) signalling processed data. Smart sensors form the basis for most applications for improving energy efficiency and detection of faults in motor driven systems. [13]

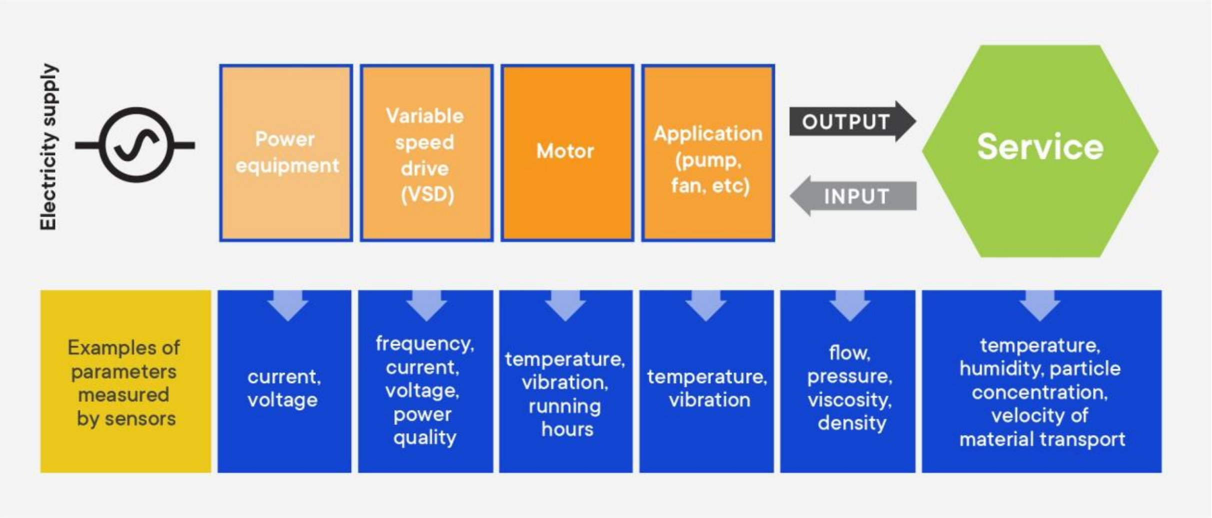


Figure 10: Examples of parameters measured by sensors [13]

In this showcased demonstration, a smart sensor is affixed to the motor to identify potential issues such as bearing failure, which could escalate motor losses and introduce operational risks. The showcased sensor transmits data wirelessly but is powered via cable to avoid the need for a battery. Since this is a demonstration, our attention is confined to evaluating the power consumption of the digital setup. Following this, a hypothetical aggregation and sensitivity analysis are undertaken to enable the formulation of generalised statements.

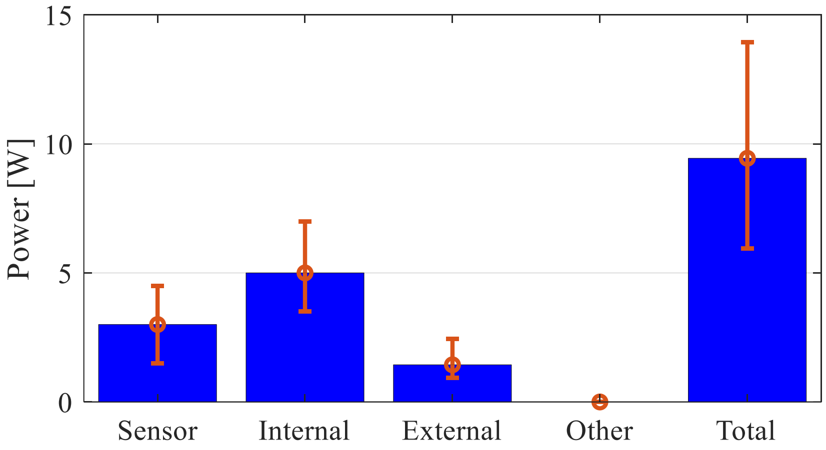


Figure 11: Case 2 mean power usage of demonstration case assuming permanent activity

Due to the accurate knowledge of the local hardware (data transmission rate, energy consumption of sensor and gateway structures), a thorough look at the subgroups is possible. Figure 11 shows the digital power assignable to the smart sensor system. A total continuous power of approximately 9.5 W can be expected, which can be assigned to:

- The cabled (vibration) **sensor** with a power rating of 3 W.
- The **internal** gateway hardware structure with an average power of roughly 5 W. The idle power of the module is roughly 3 W.
- The **external** impact of data transmission and storage given by the data transmission rate and specific network energy impact, which amounts to an equivalent of 1.5 W at the given sampling rate and data volume.

It is important to highlight that the demonstrated case is able to handle larger data transmission rate (e.g., for electrical parameter observation) and can be considered as “digitally oversized”. This is largely contingent on the data transmission rate. Consequently, the overall energy consumption in alternative systems may be significantly lower.

Figure 12: Vibration sensor (Case 2 demonstration setup Küffer Elektro-Technik AG)

It is crucial to acknowledge that the case previously presented cannot be deemed representative of all smart sensor installations. Notably in small motor systems lower overall power consumption can be expected considering smart sensors on the market. ([17], [19])

	Commercial Sensor 1 [17]	Commercial Sensor 2 [19]	Sensor Case 1 (IoT sensor)
Battery Energy [Wh]	9.36	2.85	6
Battery life (worst case) [a] (maximum) [a]	2 5	2 5 or 15*	2 10
Annual energy consumption [Wh/a] (based on worst case lifespan)	4.68	1.43	3
Gateway included	no	no	partially

Table 2: Comparison of commercial battery-powered smart sensors and their energy consumption.
**depending on sensor performance (standard or high)*

In Table 2, an overview of annual energy consumption specifically for smart sensors is given, including data for two different commercially available sensors plus the sensor described in Case 1. An annual energy consumption of 1-5 Wh/a can be observed, assuming the battery only lasts 2 years due to extensive data pulling. It is important to note that the average battery lifespan is expected to be much greater. Typically, data transmission for current commercial smart sensors occurs trough Bluetooth and a Smartphone, directly sending data to cloud storage, thereby eliminating the need for additional gateway structures. [17]

In [3], an overall structure for currently such commercialized sensors is proposed. The study cites an overall energy consumption of 1.65 Wh/a accounting for gateway, processing and storage, while the sensor only accounts for 0.36 Wh/a. The study does not include externalised energy consumption of networking which would still be relatively low due to the low data volume capability. For instance, assuming a data stream of 25 kB per day, another 1.66 Wh/a would result accounting for externalised network impact. Thus, the energy consumption of smart sensors is inherently low. Indeed, for such smart sensors, the energy consumption becomes negligible even considering very small motors (<0.37 kW). Next, the subsequent bullet points are provided to underscore the key parameters that are particularly sensitive to the influence of digital energy impact:

5.2.1 Motor size

The smart sensor configuration discussed on the previous pages may be applied to motors of various sizes. Thereby different relative energy impacts would result, evidently given by the overall annual consumption.

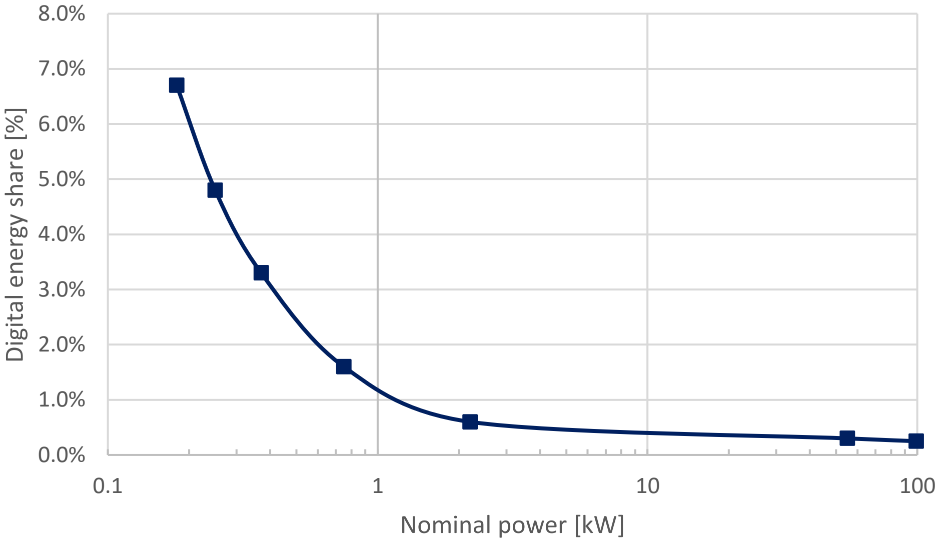


Figure 13: Impact of motor size on digital energy share of total energy consumption. Key assumptions: Mean annual operating hours of 5000 hours/a, invariant digital power consumption according to demonstration case 2.

Figure 14 shows the volume and related energy consumption of motors sold in Switzerland. As can be seen, smaller size motors are sold in high quantities, while their energy consumption remains less significant.

It is assumed that larger motors have the highest attachment rates of smart sensors, since when they break, the damage (due to their role in the production process) is likely more significant than in the case of smaller motors. Also, the relation between the cost of the smart sensor and its installation vs. the motor itself decreases in case of larger (more expensive) motors, so it makes more economic sense to install smart sensors on larger motors. At the same time, the number of larger motors sold on the market is low.

To the contrary, attachment rates of smart sensors on smaller motors are lower, while the number of these motors sold on the market is much higher. Smaller-sized motors would be equipped with a smart sensor if they are e.g. process-critical or physically hard to reach, so difficult to replace when they brake.

Looking at future market opportunity, the largest potential may be in the mid-size motor range, where motors are sold in larger quantities and have a physical size that is not too small. ([21], [22]) As illustrated in Figure 13, concerning smart sensors and digital motor systems in general, it is important to recognize that the smallest motors (below 0.75 kW) with low annual energy consumption may not realise substantial benefits from digitalisation in terms of net energy savings when relatively energy intensive digitalisation is employed. Generally, we assess smart sensor setups to have a negligible energy impact for motors rated above 5.5 kW. For smaller motors, depending on the benefits derived from digitalisation, certain digital setups may lead to a net increase in energy consumption.

However, as evidenced in Case 2, in terms of the overall impact at the industry level, this effect can be considered negligible.

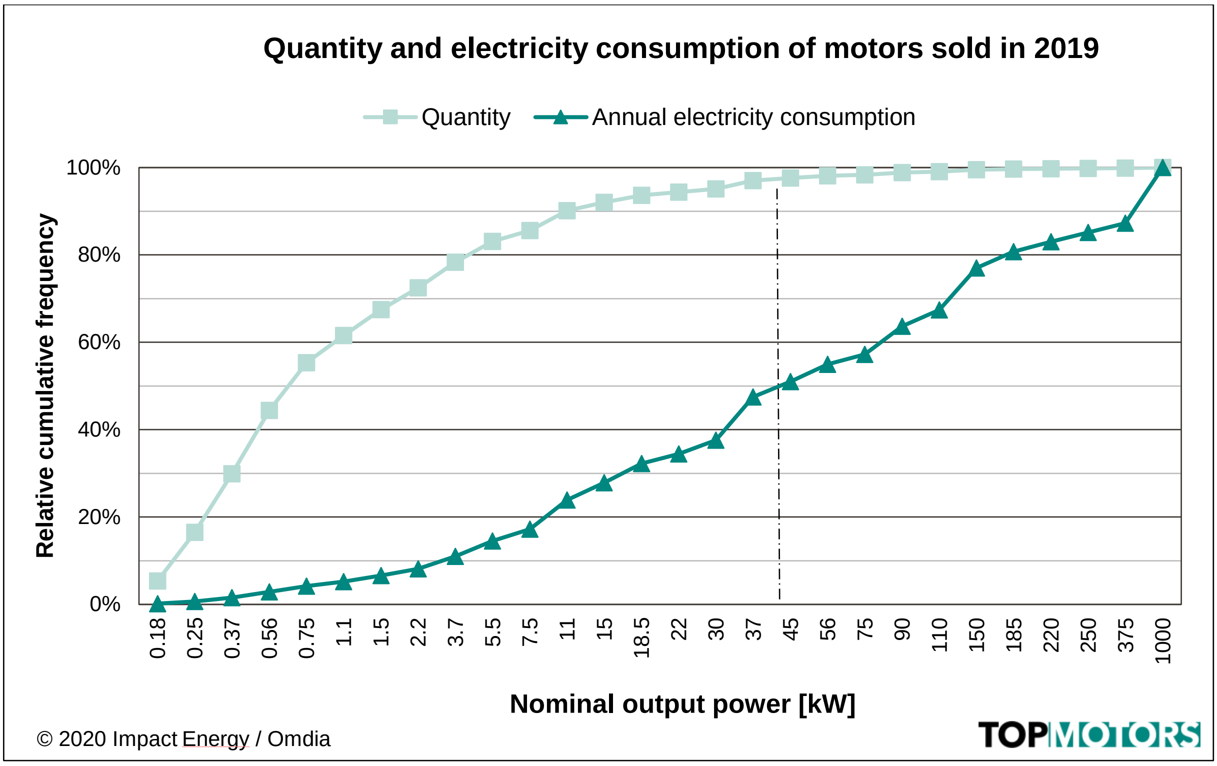


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Figure 14: Cumulative market share of motors sold per size in Switzerland and related cumulative electricity consumption. [16]

5.2.2 Data transmission rate

Similarly to the motor size, the portion of digital energy consumption also hinges on the volume of data being transmitted. Particularly for smart sensors, the data volume is modest, with a small dataset of a few kilobytes being sent typically at hourly rates [14], [17], resulting in annual data volumes in the range of 10 to 100 gigabytes. It is important to recognise, however, that in cases where there are high data volumes due to extensive sampling rates or large datasets, the effect on net energy consumption may become substantial. However, it is important to note that typical smart sensors are not designed to handle large data transmission rates. ([14], [17])

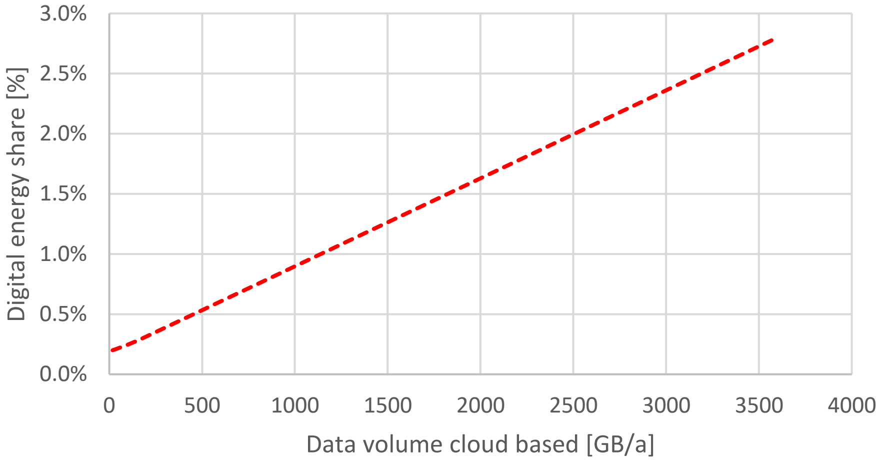

Figure 15: Sensitivity of energy impact to large cloud-based data volumes considering the smart sensor reference setup and the Swiss median motor system (5.5 kW[2] / 5500 hours/a).

5.2.3 Operating hours and standby consumption

One particular concern with electric device is standby consumption [20] during non-use. This may become relevant, when operational hours are low (<1000 hrs/a) as is shown in Figure 16.

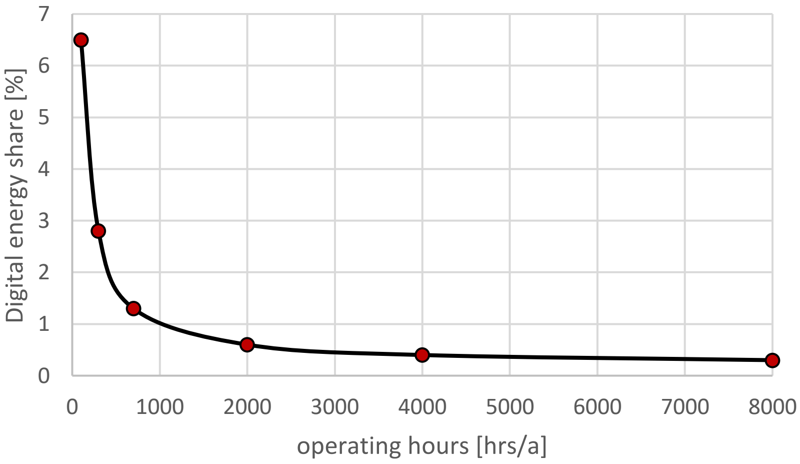

Figure 16 Sensitivity of operating hours considering non-use consumption caused by standby power. Key assumptions: 5.5 kW reference motor; power is linearly adapted according to operational hours (accounting for standby consumption).

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[2] The Swiss median of 5.5 kW was defined based on an analysis of 4’142 motor systems by Topmotors in over a dozen Swiss industrial and infrastructure facilities between 2010 and 2014 [15].

5.3 Case 3: Intelligent control of water treatment facility pump system via electrical signal analysis

A sewage pump system consisting of several pumps has been equipped with electrical sensors that allow to optimise parameters such as pump speed and set points i.e., the specific thresholds, where pump configurations and load distributions are changed. By this means, overall system efficiency was improved.

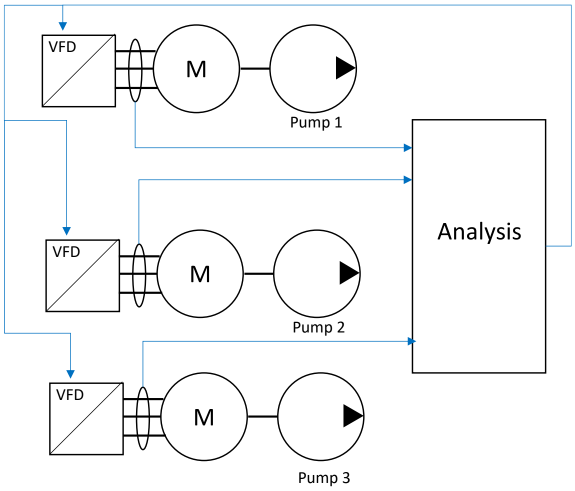

Figure 17: Schematic description of pump system architecture and digital intervention strategy (M = motor)

The monitoring is realised by means of voltage and current sensors, which allow to observe the load and rotational speed of the pumps. An offline optimisation algorithm subsequently adapts the set-points and target speeds at which the different pumps are operated at. By this means the pumps can be operated closer to their best efficiency point and hence, energy consumption is reduced. In general, a static optimisation of the set points is applied. Due to seasonality effects a continuous monitoring allows to adapt the configuration, once inefficiencies have been detected.

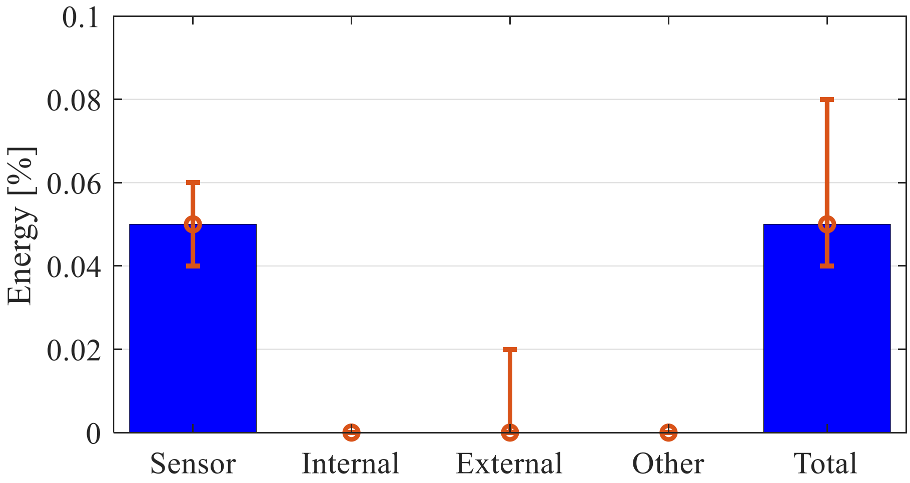

Figure 18: Case 3 energy usage of digital components as a percentage of overall consumption.

For the given case, an energy consumption reduction of 5.7% was achieved without any hardware measure but solely because of control adaptation. The digital consumption in this case solely consists of:

- the sensor and computer system consumption given by its total power rating of 120 W. Even though a continuous monitoring is applied, the total relative consumption is below 0.1% for any scenario, where additional energy for cloud storage/communication is factored in.

The net consumption of digital consumers is given by the computational system and is roughly 0.05% with respect to the overall motor system energy consumption. Even when a permanent power supply to the computer system is assumed, the relative impact of the digital components is two magnitudes lower compared to the energy saving through the measure.

Case 3	Energy [MWh/a]	Share of total energy [%]
Annual consumption	1’060	100.0%
Gross saving potential	60.4	5.7%
Digitalisation energy expenditure	0.5	0.05%
Net energy benefit due to digitalisation	59.9	5.7%

Table 3: Case 3 results of energy study

5.4 Case 4: Large scale field trial

To analyse the energy saving effect in more detail, data from a bigger study (not a single case) is presented here. A field trial project with 1’007 assets (mainly pumps) within water and chemical companies delivers data on predictive maintenance performance and energy reduction potential for these motor systems. The field trial involves a digital setup as presented in Case 3 with the project supervised by the very same company. For energy monitoring and analyses purposes benchmarks and pump performance curves were used for energy efficiency comparisons and identification of optimisation measures. These include 1) process optimisation steps like eliminating/reducing stand-by operation and optimising operational set points, and 2) component and asset optimisation, like replacement of parts or complete assets e.g. installing a VSD, upgrading a motor/pump to a higher efficiency class, right-sizing the motor and pump, replacing the impeller or blades, and changing the configuration e.g., from one large to multiple smaller pumps.

A selection of 202 motor systems[3] has been monitored and assessed for energy savings potential, including analyses on efficiency benchmarks, operating points and best efficiency points. The monitored motors cover the full power range from smaller motors (<25 kW) to large motors up to 1’000 kW as shown in Figure 19. From the 202 pump systems, 142 were already equipped with a VSD before the optimisation (‘optimised assets’), 60 were not (‘non-optimised assets’).

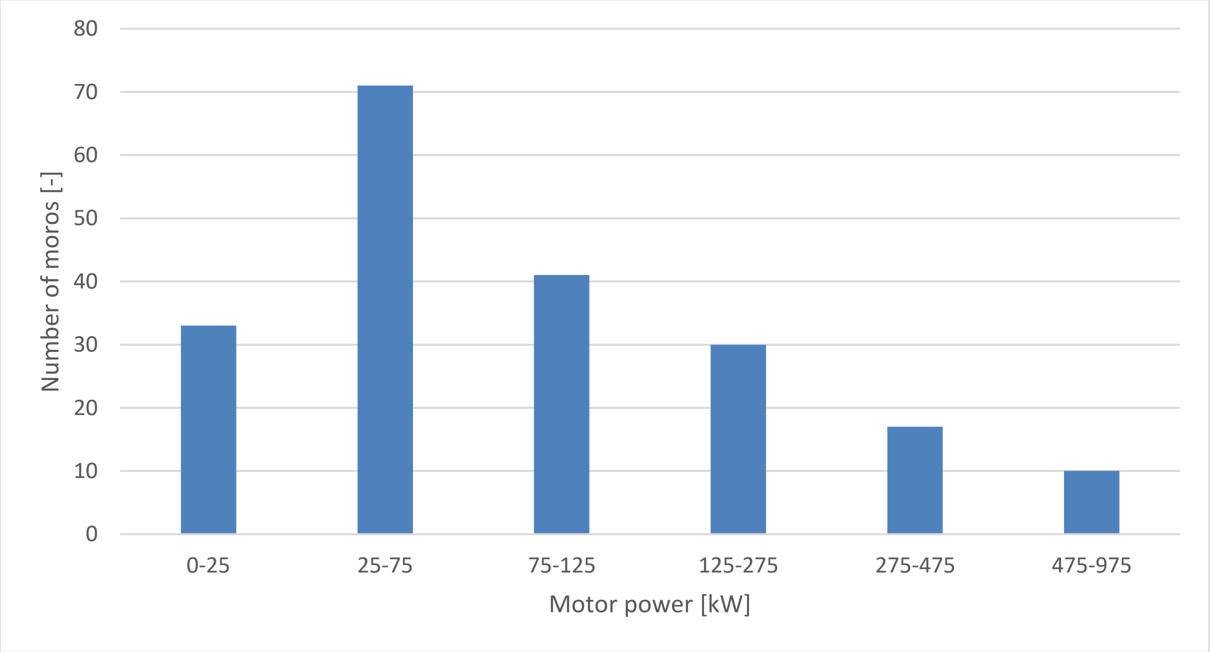

Figure 19: Number of installed motors - subset of energy efficiency analysis (202 motors), with respect to nominal power

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[3] Based on the data availability of the motor (rated efficiency from nameplate or datasheet) and the driven application (datasheet with pump curve) at the end user.

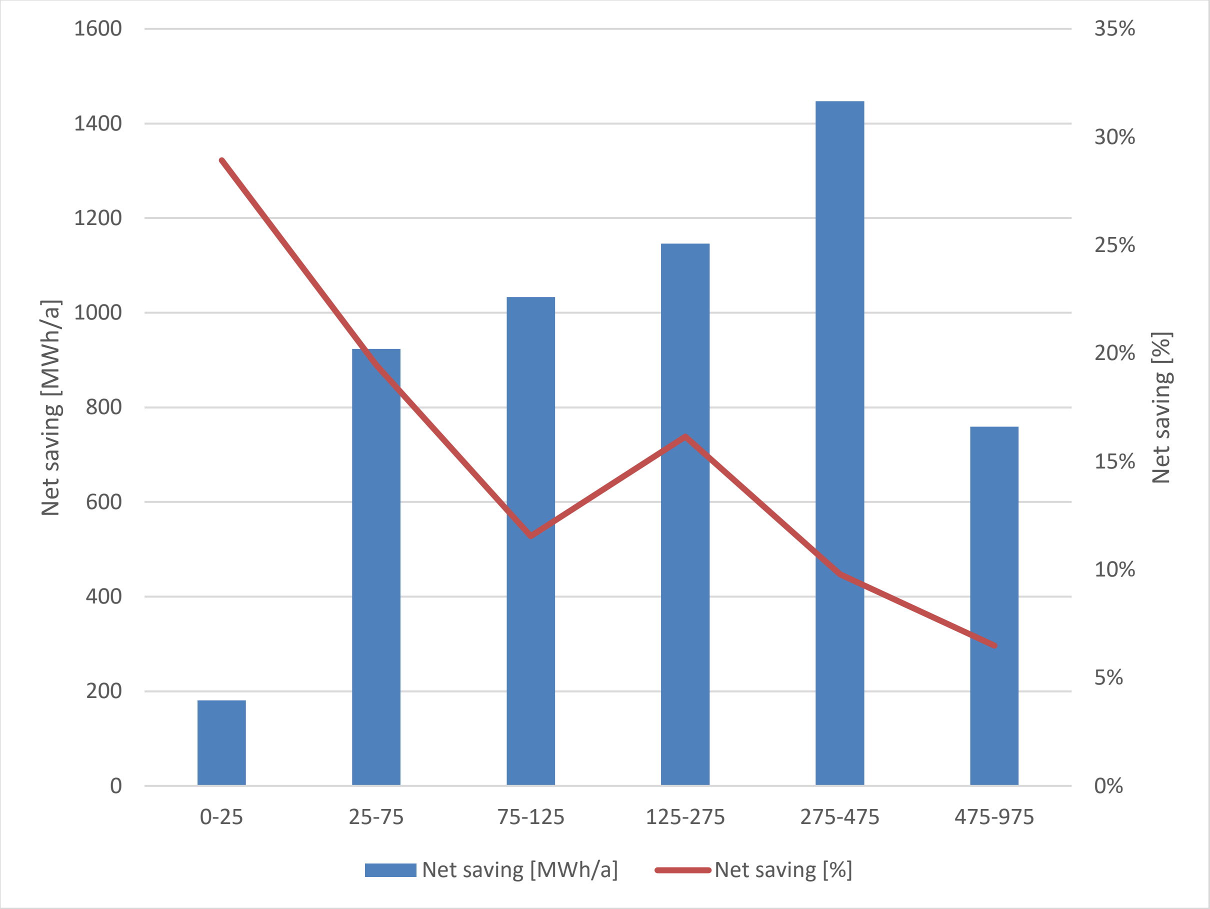


Figure 20: Net energy savings (in MWh/year) and net relative energy savings (in %) - excluding digital energy consumption - of digitalised motor systems, according to the installed nominal power (in kW).

The energy consumption from digital installation is assumed to be the same as presented in Case 3, as the set-up is equal or very similar. Figure 20 shows the net energy savings (in MWh/year) and the net relative energy savings (in %) - excluding digital energy consumption - of digitalised motor systems, for each of the six size categories of motor systems (in kW). The overall average savings amount to 11.4%. [23] The highest net saving among the 'non-optimised assets' was 46% while the average saving for all 'non-optimised assets' was 24%. The average net saving for the 'optimised assets', i.e. pump systems that were already equipped with a VSD before the optimisation was 9%, thus significantly lower.

The following trends can be observed

- Larger systems deliver larger energy savings in absolute terms (kWh).
- The relative savings show a range between 6% and 29% (with a weighted average of 11.4%). This range can be read as an illustration of the potential savings range for a set of motor systems. One has to bear in mind that the observed declining trend in relative savings – from small to large nominal power- relates to this relative small sample of motors (202 motors). A different picture may be observed for a larger set of motor systems.

5.5 Case 5: Intelligent control of air compressor system in large production facility

An air compressor system has been equipped with an intelligent control system. The control system evaluates pressure and humidity sensor feedback for an adaptive compressor control. A hardware upgrade was also made, three compressors were retrofitted of which two are equipped with a VSD. This split solution, i.e. a mix between air compressors with and without a VSD, was chosen to achieve optimal overall efficiency and flexibility: the compressed air baseload is produced through compressors without VSD and the remaining variable compressed air is produced with compressors with a VSD. The combination of load management of the different compressor units and monitoring of system data allows a reduction of energy used per compressed air volume.

Figure 21: Air compressor system (Picture: Pascal Kienast)

In case of the studied company, the compressor energy was reduced significantly: with respect to the baseline an overall saving of 16% has been reached:

- one part is achieved by running the compressed air system at the lowest possible total system pressure (5%),
- one part is thanks to the intelligent control and hence the optimised control of the compressor system (6%),
- and the rest due to the revamping of the compressor units (5%).

Quantifying the exact share of the savings attributable solely to the digital solution proves challenging. On the one hand, 6% is derived from the optimised control of the compressor system facilitated by the intelligent control. On the other hand, some part of the savings resulting from reduced system pressure (5%) can also be linked to intelligent control. For the purposes of this study, the 6% savings are considered as a quantifiable direct consequence of the digital solution.

As shown in Figure 22, approximately 1% of the total energy consumption is required to support the digitalisation of the compressor system, yielding a net benefit of 15%.

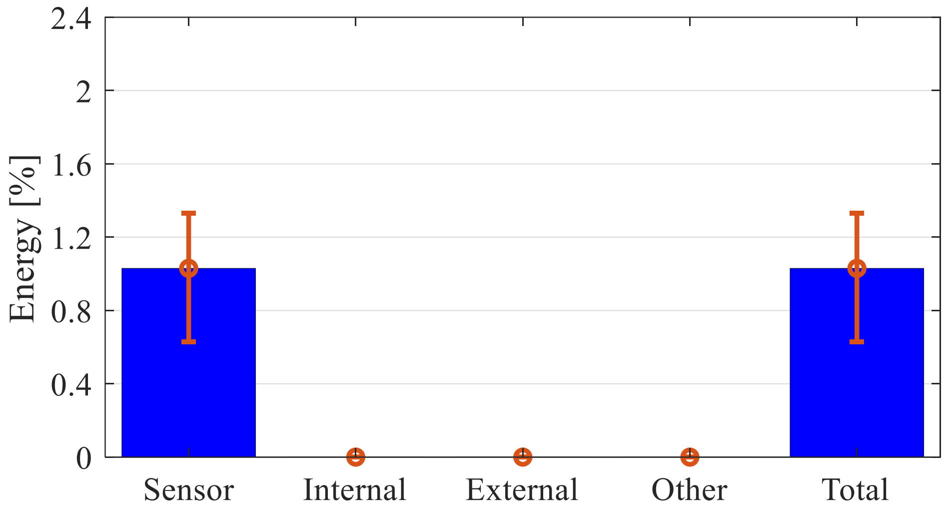


Figure 22: Case 5 energy usage of digital components as a percentage of overall consumption.

The total sensor system power consumption can be considered the only significant digital energy consumer of the installation. Notably in large manufacturing sites with already advanced automation, such as the one in question, the directly attributable energy of additional installations that facilitate communication among digital devices becomes insignificant. To summarise:

- The sensor energy of 1% arises from the overall consumption of the intelligent control system (rated 575 W) consisting of sensor modules and computer system. The values are based on ratings and do not include longtime average measurements.
- As the control system operates in a closed loop, there is no additional energy consumption that can be directly assigned to the system. Consequently, any inaccuracies in the case arise from the computer system's own consumption, which can be determined considering its current rating.

As can be seen in Table 3, the energy saving potential by means of a VSD is significant, notably in pump and compressors, where the rotor speed can be adapted to increase system efficiency.

Case 5	Energy [MWh/a]	Share of total energy [%]
Annual consumption	488	100.0%
Gross saving potential	78	16.0%
Digitalisation energy expenditure	5	1.0%
Net energy benefit due to digitalisation	29	6.0%
Net energy benefit total	73	15.0%

Table 3: Case 5 results of energy study

6 Key findings

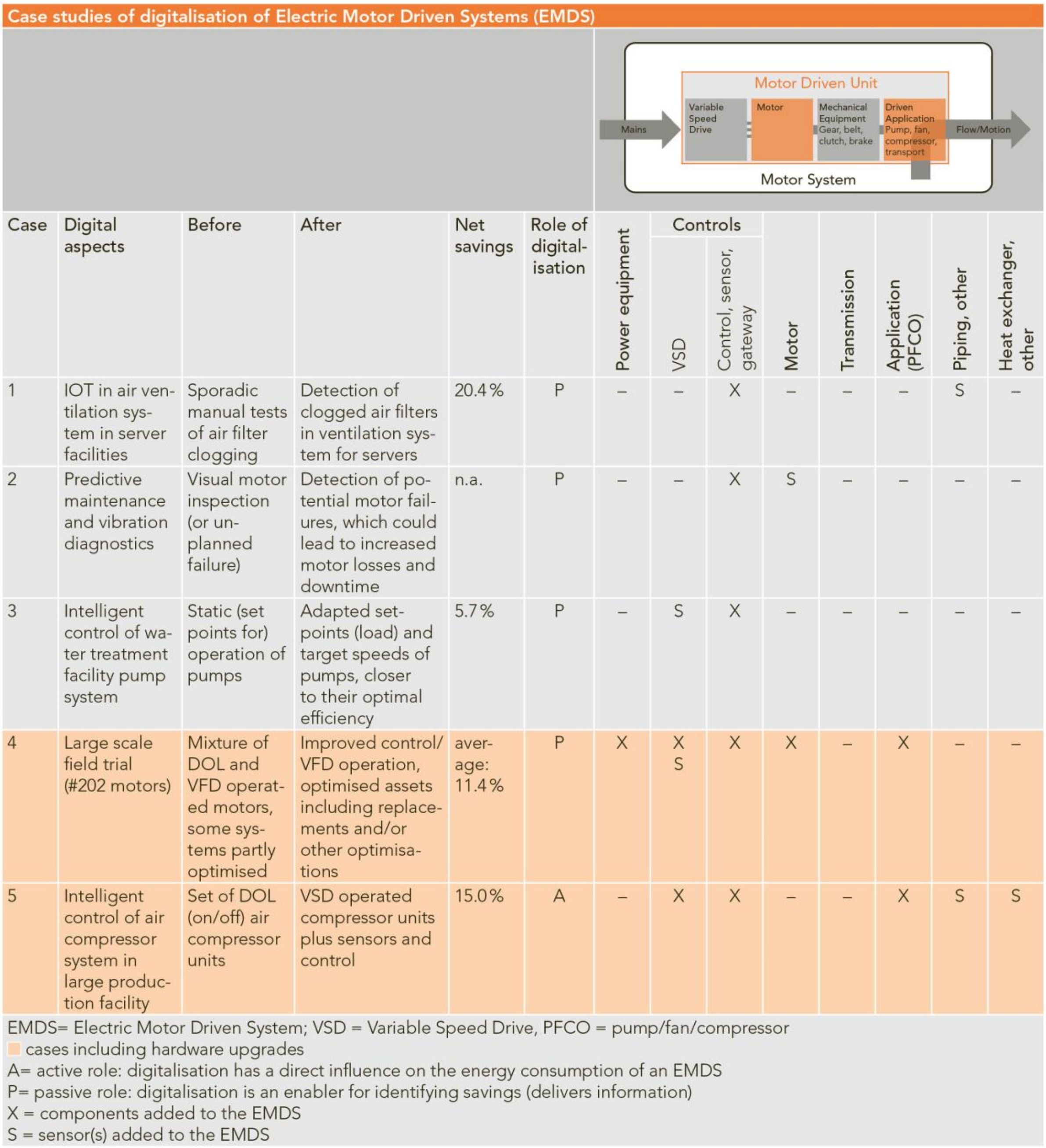
This chapter provides a brief display of the key findings extracted from the study.

6.1 General findings on digitalised motor systems and energy efficiency

The five cases presented show a diversity of digital applications and solutions for improving the efficiency in motor systems. In the majority of cases (three out of five i.e., cases 1, 2 and 4) condition-based monitoring and energy (efficiency) monitoring are combined, see Table 5. Each case is unique by having different backgrounds and targets for applying a digital solution as well as for the actual benefits or output of the digital solution. Some solutions are one dimensional e.g. clogging detection, others are multi-dimensional, addressing efficiencies in drive-train components and control, and proposing 1) process optimisation steps like eliminating stand-by operation and optimising operational set points, and 2) component and asset optimisations like adding a VSD, replacement with a high efficient, correctly sized motor/pump.

With the current set of cases and the limited availability of detailed information it is difficult to allocate savings percentages (or results) to specific measures; this refers especially to the multi-dimensional digitalisation cases where depending on the ‘starting point for optimisation’ the applicable measures can materialise as a series of optimisations from changing set points to changing complete components like a motor, VSD or pump.

The studied cases show net savings (excluding digital energy consumption) ranging from 5.7% up to 20.4% (see Table 4). In case 4, savings for the motor systems reached up to 46%, while the average saving in subgroups of motors, e.g. those without a VSD before optimisation was 24%, those with a VSD before optimisation was 9%.



Case studies of digitalisation of Electric Motor Driven Systems (EMDS)

Case	Digital aspects	Before	After	Net savings	Role of digital-isation	Power equipment	Controls		Motor	Transmission	Application (PFCO)	Piping, other	Heat exchanger, other
							VSD	Control, sensor, gateway					
1	IOT in air ventilation system in server facilities	Sporadic manual tests of air filter clogging	Detection of clogged air filters in ventilation system for servers	20.4 %	P	–	–	X	–	–	–	S	–
2	Predictive maintenance and vibration diagnostics	Visual motor inspection (or unplanned failure)	Detection of potential motor failures, which could lead to increased motor losses and downtime	n.a.	P	–	–	X	S	–	–	–	–
3	Intelligent control of water treatment facility pump system	Static (set points for) operation of pumps	Adapted setpoints (load) and target speeds of pumps, closer to their optimal efficiency	5.7 %	P	–	S	X	–	–	–	–	–
4	Large scale field trial (#202 motors)	Mixture of DOL and VFD operated motors, some systems partly optimised	Improved control/ VFD operation, optimised assets including replacements and/or other optimisations	average: 11.4 %	P	X	X S	X	X	–	X	–	–
5	Intelligent control of air compressor system in large production facility	Set of DOL (on/off) air compressor units	VSD operated compressor units plus sensors and control	15.0 %	A	–	X	X	–	–	X	S	S

EMDS= Electric Motor Driven System; VSD = Variable Speed Drive, PFCO = pump/fan/compressor

🟧 cases including hardware upgrades

A= active role: digitalisation has a direct influence on the energy consumption of an EMDS

P= passive role: digitalisation is an enabler for identifying savings (delivers information)

X = components added to the EMDS

S = sensor(s) added to the EMDS

Table 4: Summary of cases presented in this study

6.2 Energy consumption of digitalised motor system components

With respect to energy consumption, we find the following:

- **Energy consumption of digitalised motor system components**: The consumption attributable to the digitalisation of motor systems stems from a variety of sources. Notably external network communication i.e., the use of cloud services can add to the total energy consumption when high data volumes and storage requirements are given. However, with regards to limiting factors such as battery life in smart sensors, it is much more common to work with small and compressed data sets that leave a marginal impact even when considering pessimistic values for network energy consumption. As for hardware components attributable to digitalised motor systems, sensors and local data communication or storage devices typically show a low energy consumption. There is a variety of digitalisation concepts, of which smart sensors have negligible energy consumption but some systems may show larger power usage. Generally, infrastructure necessary to facilitate digitalisation of motor systems may already be in place to a large extent – notably in energy intensive companies. This directly limits the additional energy required for further network participants (e.g., scaling of LAN switches). As for typical smart sensors, additional infrastructure for data handling is often not required. With regards to energy intensity, we classify the type of digitalisation according to Table 5. The classification distinguishes primary targets of the digitalisation which, based upon the study findings, result in different typical energy consumption. This typically directly correlates with the computational complexity. It is worth noting that the baseline values for the classifications have been chosen arbitrarily considering the cases examined in this study.

	Smart Sensors/ IoT	**Advanced analytics**	**Adaptive control systems**
Annual energy consumption of digital system	< 10 Wh/a	10 Wh/a -200 kWh/a	> 200 kWh/a
Computational frequency	<<1 Hz	~1Hz	>1 Hz
Number of motors	1	>=1	>2
Primary target of digitalisation	Error Detection, analytics	Error detection, optimisation	Energy savings, emission reduction
Assignable cases from this study	Case 1 Case 2	Case 2 Case 3 Case 4	Case 5

Table 5: Classification of digitalised motor systems

- **Energy significance with respect to overall consumption**: When compared to the net consumption of the motor system, we find the digital consumption to be entirely negligible for smart sensors. Further systems classified as digital may have a non-negligible energy consumption but, notably in large motor systems that account for the main share of energy consumption, digital energy consumption becomes marginal. This has the overall effect, that digital energy consumption in motor systems is low and may be neglected in many cases of this study.
- **Overall potential of digitalisation in motor systems**: The studied cases show net savings (excluding digital energy consumption) ranging from 5.7% up to 20.4% (in some cases combined with hardware upgrades even higher – see case 4), whilst the energy expenditure to facilitate digitalisation never exceeded 1% but was rather insignificant for many cases. Consequently, on an overall level, the energy savings achieved through the digitalisation of motor systems far outweigh the additional energy consumption resulting from the digitalisation process. For digital applications with the goal of energy saving, the predominant factors influencing the balance between energy investment and benefits are the motor installation size along with the specific type of digitalisation employed to the motor system. It is important to highlight that the actual benefit of digitalisation is constrained to what type of measures are classified as digitalisation and what is regarded as the baseline. In the cases studied, the savings potential depends less on whether digitalisation has a passive or an active role (enabler for savings or direct contributor), what is decisive is to what extent systems were already optimised before the measures and to what extent measures can contribute to an optimised system operation.

7 Discussion and recommendations

This chapter provides a generalised discussion and states recommendations from the authors' perspective.

Since the availability of data considering the impact of digital energy consumption in motor systems is currently poor, this study aimed to make a first step through the analysis of concrete cases. In the cases presented, whenever possible, the energy savings and the source of these savings (with/without hardware upgrade) was identified.

The sample size with the cases presented is by no means representative which is a limiting factor for aggregated conclusions. The collection of further cases would be helpful to be able to draw statistically relevant conclusions. A greater number of cases would also allow a better distinction between the types of digitalisation technologies/solutions applied with motor systems. This combined with data on the installed base of motors could create a sound basis for answering the following questions:

1. What type of digitalisation solution suits best certain motor system setups?
2. What is the range of expected energy savings stemming from the different digitalisation technologies?
3. To what extent does digitalisation unlock additional energy savings?
4. To what extent does digitalisation simplify and/or enable systems optimisation?
5. What is the savings potential on a company level (small – medium – large)?
6. What is the savings potential in certain sectors (energy-intensive, non-energy intensive)?
7. What is the savings potential on a country/region (e.g. European Union)/worldwide level?
8. What is the cost-effectiveness of digitalisation and the size of programmes required for its large-scale application?

Nevertheless, the main conclusion of this study is that for all cases analysed the energy used for the digitalisation of the motor systems is with less than 1% negligible.

The cost-benefit analysis of digitalisation in the retrofitting of existing motor systems, which typically show a large energy saving potential, is another important issue. This information can be used to accelerate the uptake of digitalisation and to support policies targeting this transformation.

In terms of advancing market uptake, dedicated training materials could be developed and courses offered to address the barrier of the "human factor" and enhance the skills necessary to implement digital solutions in motor systems.

A group of experts with representatives from policy, academia, manufacturers and end-users could be an interesting forum to observe and discuss market developments.

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