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ORIGINAL ARTICLE

Effects on primary energy use, greenhouse gas emissions and related costs from improving energy end-use efficiency in the electrolysis in primary aluminium production

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Abstract Primary aluminium production is energy- and GHG-intensive in which electrolysis is by far the most energy- and GHG-intensive process. This paper's aim is to study the effects on (1) primary energy use, (2) GHG emissions and (3) energy and CO_2 costs when energy end-use efficiency measures are implemented in the electrolysis. Significant savings in final and primary energy use, GHG emissions and energy and CO_2 costs can be achieved by implementing the studied measures. Vertical electrode cells and the combination of inert anodes and wettable cathodes are among the measures with the highest savings in all three areas (primary energy use, GHG emissions and energy and CO_2 costs). Direct carbothermic reduction is one of the measures with the highest savings in primary energy use and energy and CO_2 costs. For GHG emissions, direct carbothermic reduction is the more beneficial choice in regions with a high proportion of coal power, while inert anodes are the more beneficial choice in regions with a high proportion of low-carbon electricity. Although a company potentially can save more money by implementing the direct carbothermic reduction, the company should consider implementing the vertical electrode cells together with other energy-saving technologies since this would yield the largest GHG emission savings while providing similar cost savings as the direct carbothermic reduction. It may be necessary to impose a price on GHG emissions in order to make inert anodes cost-effective on their own, although further evaluations are needed in this regard. There is a potential to achieve carbon-neutrality in the reduction of aluminium oxide to pure aluminium.

Keywords Energy saving · Aluminium industry · Primary energy consumption saving · GHG emission saving · Energy and CO_2 cost saving · Direct carbothermic reduction

Introduction

Political goals have been formulated at international (UN 2015; UNDP 2015), European (European Comission n.d.) and national (Sweden) (Swedish Energy Agency 2019; Government Offices of Sweden 2017) levels regarding improved energy efficiency, reduced environmental impact, increased share of renewables and increased sustainability. The industrial sector accounted for 37% of global final energy use and 24% of global direct CO_2 emissions (including both energy- and process-related emissions) in 2017 (International Energy Agency 2019a). Industrial energy efficiency improvements will be needed in order to meet the political goals and, at the same time, become a competitive advantage for companies due to decreased operating

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costs. The production of primary aluminium is energy- and GHG-intensive and the electrolysis process in primary production is by far the most energy- and GHG-intensive process in the aluminium industry (Milford et al. 2011). In 2017, aluminium production (both primary and secondary production) accounted for around 3.5% of direct global CO_2 emissions from the industrial sector (IEA 2019a).

The electrolysis process utilises the electrolytic reduction of aluminium oxide to produce pure aluminium, with electricity as the main energy carrier (Haraldsson and Johansson 2018). Electrolytic reduction is facilitated by the use of fossil coal in the form of carbon anodes, which are consumed in the process, resulting in CO_2 and CO emissions (Haraldsson and Johansson 2018). There are also so-called anode effects, which are disturbances to the process in which an insufficient amount of aluminium oxide is dissolved in the electrolyte bath, resulting in the emission of the perfluorocarbons (PFCs) CF_4 and C_2F_6 (International Aluminium Institute 2019a), which are two GHGs with a high global warming potential. Thus, the climate impact of the electrolysis process can be divided into (1) energy-related GHG emissions from electricity use and (2) process-related GHG emissions resulting from anode consumption and anode effects. The theoretically lowest energy use of the electrolysis is 6.23 MWh/tonne Al (Obaidat et al. 2018), while statistics from the International Aluminium Institute (2019c) show that the global average on the energy intensity of the electrolysis in industrial applications is 14.21 MWh/tonne Al. A pilot test on an industrial scale has shown that aluminium production at 12.3 MWh/tonne Al is possible (Svendsen 2018). Additionally, a similar technology is expected to produce aluminium at 11.5–11.8 MWh/tonne Al and a pilot test was initiated in 2018 (Svendsen 2018).

Primary energy use is the energy needed to supply one unit of final energy (Latõšov et al. 2017) and provides an understanding of the amount of primary energy use needed during the entire life cycle from source to delivered final energy (Gode et al. 2011). Primary energy use should include the energy needed for activities including extraction, processing, storage, generation, transformation and distribution (Latõšov et al. 2017). In many cases, the chemical energy content of the fuel, e.g. the energy content of fossil fuels, is included in the primary energy use (Gode et al. 2011). However, there are exceptions for wind and solar power, for example, where the energy in wind and solar irradiation is not included in the primary energy use (Gode et al. 2011). The primary energy factor is calculated by dividing the total primary energy use by the delivered final energy use (Gode et al. 2011).

The chosen method and system boundaries can have significant effects on the results regarding the impact on global GHG emissions from changes in energy systems, e.g. the implementation of energy efficiency measures (Johansson 2014). There are several approaches for assessing the impact on GHG emissions for electricity and which approach to use depends on the purpose of the study (Dotzauer 2010).

Scientific studies on the impact on primary energy use, GHG emissions and costs from the implementation of specific energy efficiency measures in the aluminium industry are scarce. Schwarz et al. (2001) assessed the CO_2 emissions in the global material flow of primary aluminium in 2010 compared with that in 1995 and found that around 65–75% of the reductions in total CO_2 emissions are explained by reductions in specific energy-related CO_2 emissions. They also found that the most important factors affecting the specific energy-related CO_2 emissions are specific final energy use, production geography, the electricity mix and the efficiency of the electricity generation. The energy efficiency improvements in the study by Schwarz et al. (2001) are based on a comparison between the average energy use for electrolysis in 1995 and energy use in modern or substantially upgraded electrolysis plants in 1995, and not any specific energy efficiency measures. Kermeli et al. (2015) studied 22 currently available energy efficiency measures applicable to primary aluminium production, of which two are applicable to electrolysis. They estimated the total savings in final energy use, primary energy use and GHG emissions for the top eleven aluminium producing countries in the world. Liu et al. (2017) estimated the total GHG mitigation potential of the aluminium industry in the Henan province, China, for 18 measures in the electrolysis process. However, Liu et al. (2017) do not provide any information about what energy efficiency measures they studied. Myklebust and Runde (2005) estimated the reduction in GHG emissions from implementation of direct carbothermic reduction compared with the electrolysis process. Obaidat et al. (2018) studied the impact on exergy and CO_2 and CO emissions from implementing wettable cathodes, inert anodes and direct carbothermic reduction compared with conventional electrolysis.

The aim of this paper is to study the effects on (1) primary energy use, (2) GHG emissions and (3) energy and CO_2 costs when energy end-use efficiency measures are implemented in the electrolysis process in primary aluminium production. The paper will also study how the effects on primary energy use, GHG emissions and energy and CO_2 costs vary when the type of electricity used for electrolysis is changed. The paper will study both a single production plant that has not implemented the efficiency measures yet and the entire global production through the electrolysis process. The paper includes both energy efficiency measures that are currently available and innovative energy efficiency measures that are under development. The effects on the GHG emissions include the effects on both the GHG emissions from electricity use and the process-related GHG emissions (from anode consumption and anode effects). The effects on costs include the effects on CO_2 costs since some of the studied energy efficiency measures impact the process-related emissions. An economic evaluation of the measures has not been conducted due to the lack of availability of values for investment costs and changes in operating and maintenance costs.

To the authors' knowledge, this is the first article to study the effects on primary energy use, GHG emissions and energy and CO_2 costs for both a single electrolysis plant and the entire global production through the electrolysis process by implementing both currently available and innovative energy end-use efficiency measures and by varying the type of electricity used. The results are relevant to industrial companies in understanding how improving energy end-use efficiency in their plants could affect the associated primary energy use and GHG emissions. The results are also relevant to policymakers in understanding the potential for reducing primary energy use, GHG emissions and energy and CO_2 costs both within individual production plants and on a global scale.

Table 1 Global averages for energy intensity as well as process-related GHG emissions from prebaked anode technology cells

	Used value	Reference
Energy intensity	14.21 MWh/tonne Al	International Aluminium Institute (2019c)
Process-related GHG emissions[a]	2.053 tonnes CO_2eq/tonne Al	International Aluminium Institute (2017); International Aluminium Institute (2019a)

[a] Including emissions from both anode consumption and anode effects

Methods

General assumptions

Around 95% of primary aluminium production worldwide uses prebaked anode technology (International Aluminium Institute 2017). Thus, only prebaked anode technology was considered in the paper. Table 1 shows global averages for energy intensity and process-related GHG emissions.

This paper studies both a hypothetical electrolysis plant assumed to be located in Europe and the entire global production through the electrolysis process. The hypothetical plant was assumed to have an annual production of 200 ktonnes Al/year, which was based on common industry values in Europe. The hypothetical plant was assumed to have an energy intensity and process-related GHG emissions equal to the global averages in Table 1. Global production of aluminium through the electrolysis process amounted to 64,336 Mtonnes Al/year in 2018 (International Aluminium Institute 2019b).

A price on CO_2 emissions of around EUR 30[1] per tonne CO_2eq was used in the calculations. This value is equal to the EU stated policies for 2030 given by the International Energy Agency (2019b) and was chosen since the single plant was assumed to be located in Europe and, to a large extent, the studied energy efficiency measures provide future energy efficiency improvements (see the "Choice of electricity" section). This value was also used for the entire global production through the electrolysis in order to be consistent and make the results comparable.

The energy efficiency measures studied in the paper

The energy efficiency measures to be included in the study were identified through a literature review previously conducted by Haraldsson and Johansson (2018). Only the measures with values on the energy end-use efficiency potential were included in the study. Table 2 shows the measures included in the

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[1] Converted from dollars to euros using the currency exchange rate of 3 February 2020.

paper and their respective energy end-use efficiency potential and savings in process-related emissions. A brief description of the measures can be found in the Appendix Table 4 and a more detailed description can be found in Haraldsson and Johansson (2018). For the majority of the measures, only a single value on the energy efficiency potential was available. For some of the measures, several values were available and the mean, minimum and maximum of the values were used in these cases. Note that the energy end-use efficiency potential when inert anodes are implemented on their own is negative, implying increased energy use. However, they were included in the paper due to the elimination of the process-related GHG emissions. The heat needed for direct carbothermic reduction can be supplied using electricity (Balomenos et al. 2011a), e.g. using an electric arc furnace (Kemper et al. 2013; Li et al. 2011). Thus, the direct carbothermic reduction studied in this paper was assumed to use electricity as the energy source.

The impact on the process-related GHG emissions was considered when calculating the effects on GHG emissions from the implementation of the measures. The inert anodes eliminate the process-related GHG emissions entirely. Thus, the measures that utilise inert anodes, including vertical electrode cells, have a saving in process-related emissions corresponding to the value in Table 1. Direct carbothermic reduction utilises a different reaction than the reaction utilised in electrolysis and uses fossil carbon as a reaction material. The theoretically predicted value of the process-related GHG emissions from the direct carbothermic reduction process is around 2.45 tonnes CO_2eq/tonne Al (BCS 2007; Kvande and Drabløs 2014; Myklebust and Runde 2005). The change in the process-related emissions for the direct carbothermic reduction is calculated as the difference between the process-related emissions for the direct carbothermic reduction and the process-related emissions for the electrolysis (presented in Table 1). The change in the process-related emissions for the direct carbothermic reduction is negative since the process-related GHG emissions increase when the direct carbothermic reduction is implemented. The theoretical value of the process-related GHG emissions was used in the calculations, since no industrial implementation of direct carbothermic reduction has been conducted to date. Thus, no statistics are available on process-related GHG emissions.

Choice of electricity

Some of the measures in Table 2 are currently not commercially available but may be in the future. Addi-

Table 2 The energy efficiency measures studied in the paper and their respective energy end-use efficiency potential and savings in process-related GHG emissions. The values on the energy end-use efficiency potentials are taken from Haraldsson and Johansson (2018); U.S. Aluminum Association (1998); Peng et al. (2011); and Naixiang et al. (2013)

Energy efficiency measure	Energy end-use efficiency potentials (MWh/tonne Al)			Saving in process-related GHG emissions [tonnes CO_2eq/ tonne Al]	Currently available? (Haraldsson and Johansson 2018)
	Mean	Min	Max		
Generation 3 control system	0.355			0	Yes
Anode pre-heating	0.040			0	Yes
Slotted or perforated anodes	0.781			0	Yes
Novel structure cathodes	0.802	0.478	1.146	0	Yes
Optimised cathode collector bar structure	0.738			0	Yes
Distributed pot suction system	0.400			0	Yes
Wettable cathodes	1.980	0.400	3.100	0	No
Inert anodes	−1.427	−2.850	0	2.053	No
Inert anodes + wettable cathodes	3.553[a]			2.053	No
Vertical electrode cells[b]	4			2.053	No
Direct carbothermic reduction[c]	4.954	2	7.080	− 0.397	No

[a] The efficiency potential for the combination of inert anodes and wettable cathodes is given as 25% in Haraldsson and Johansson (2018), which has been converted into MWh/tonne Al by multiplying by the energy intensity in Table 1. Additionally, the 25% is an estimate of the best possible efficiency improvement (Haraldsson and Johansson 2018)

[b] Vertical electrode cells utilise inert anodes, wettable cathodes and low-temperature electrolytes (Haraldsson and Johansson 2018)

[c] This is an alternative process to electrolysis

tionally, the measures can be viewed as long-term strategic investments. These two factors together imply that, to a large extent, the measures will provide future energy efficiency improvements. The build margin perspective is relevant when studying future changes to the electricity system (e.g. future energy efficiency improvements). The build margin perspective implies an assumption being made regarding the type of electricity generation facility that would have been built if the electricity demand had not been reduced (Ådahl and Harvey 2007). Two different options for the build margin were used in the calculations: the build margin is (1) 100% wind power and (2) 100% coal power. This is to show the range in the impact on the GHG emissions.

Table 3 shows primary energy factors, emission factors and costs of wind power and coal power. The primary energy factors and emission factors take into account the extraction, refining and conversion of the fuel, the construction, operation, waste and demolition of the conversion facility, as well as the end-use of the energy (Gode et al. 2011). The primary energy factor for coal power includes the chemical energy content for coal, while the primary energy factor for wind power does not include the energy content in the wind (Gode et al. 2011). The cost of generating the electricity was used in this study, since about 59% of the electricity used for electrolysis globally is generated by electricity plants owned by the companies themselves (International Aluminium Institute 2020). Additionally, the estimation of the price of electricity generated from specific energy sources would be hard due to the global perspective used in this study and aspects such as taxes, policy instruments and grid costs can vary widely between different countries. The cost of electricity generation was used throughout this study to make the results comparable. The cost of wind power is only the cost of electricity generation, while the cost of coal power also includes the cost of the CO_2 price given in the “General assumptions” section. The cost of electricity generation includes the investment, operation and maintenance costs of the conversion facility, and fuel cost (Nohlgren et al. 2014). The price that an electrolysis plant pays for electricity is probably higher than the stated values in Table 3 if the plant buys electricity from the electricity market. In turn, this means that the economic saving from implementation of the measures would probably be higher than what is presented in the paper.

Calculations of effects on primary energy use, GHG emissions and energy and CO_2 costs

The effects on primary energy use per tonne of aluminium were calculated using equation (1) below.

$$\text{Effects on primary energy use} = \text{energy end-use efficiency potential} \cdot \text{primary energy factor } (\text{MWhprimary}/\text{tonne of Al}) \tag{1}$$

The effects on GHG emissions per tonne were calculated using Eq. (2) below.

$$\text{Effects on GHG emissions} = \text{energy end-use efficiency potential} \cdot \text{emission factor} + \text{saving in process-related GHG emissions } (\text{tonne } CO_2\text{eq}/\text{tonne of Al}) \tag{2}$$

The effects on energy and CO_2 costs per tonne were calculated using Eq. (3) below.

$$\text{Effects on energy and } CO_2 \text{ costs} = \text{energy end-use efficiency potential} \cdot \text{electricity cost} + \text{saving in process-related GHG emissions} \cdot CO_2 \text{ price } (\text{EUR}/\text{tonne of Al}) \tag{3}$$

The two cases used is as follows: (1) 100% wind power and (2) 100% coal power. The primary energy factor, emission factor and electricity cost used in each case can be found in Table 3.

The effects on primary energy use, GHG emissions and energy and CO_2 costs per tonne of aluminium, respectively, were multiplied by the annual production to obtain the total effects for the entire plant and global production through electrolysis.

Table 3 Primary energy factors, emission factors and cost of wind power and coal power

	Wind power	Coal power	Unit	Reference
Primary energy factor	0.05	2.26	$MWh_{primary}/MWh_{electricity}$	Gode et al. (2011)
Emission factor	0.013	0.759	tonne $CO_2eq/MWh_{electricity}$	Gode et al. (2011)
Cost	50[a]	63[a,b]	$EUR/MWh_{electricity}$	Nohlgren et al. (2014); International Energy Agency (2019b)

[a] Converted into euros using the currency exchange rate as of 3 February 2020

[b] Includes both cost of electricity generation and CO_2 price

Results and analysis

The single plant — results

Figure 1 shows the primary energy savings from implementing the measures at the single plant.

Figure 2 shows GHG emission savings from implementing the measures at the single plant.

Figure 3 shows the energy and CO_2 cost savings from implementing the measures at the single plant.

The entire global production through the electrolysis process — results

Figure 4 shows the primary energy savings from implementing the measures in the entire global production through the electrolysis process.

Figure 5 shows the GHG emission savings from implementing the measures in the entire global production through the electrolysis process.

Figure 6 shows the energy and CO_2 cost savings from implementing the measures in the entire global production through the electrolysis process.

Analysis

The results for both the single electrolysis plant and the entire global production through the electrolysis process indicate that the potential savings in primary energy use, GHG emissions and energy and CO_2 costs from the implementation of the measures vary depending on the type of electricity generation used. This is because a higher primary energy factor, emission factor and cost of electricity result in higher savings from improving energy efficiency. However, vertical electrode cells and the combination of inert anodes and wettable cathodes are among the measures with the highest savings in all three areas (primary energy use, GHG emissions and energy and CO_2 costs). This is true for both wind power and coal power, implying that these measures would be among the measures with the highest savings, irrespective of whether the electricity generation of a specific region in the world depends on renewables or coal power.

Direct carbothermic reduction is among the measures with the highest savings in primary energy use, and energy and CO_2 costs. For GHG emissions, direct carbothermic reduction is among the measures with the highest savings when using coal power. However, direct carbothermic reduction results in increased GHG emissions when using wind power. This is because the increased process-related GHG emissions (see the "Methods" section) are not compensated for by the reduced energy use, since the emission factor for wind power is too low. Instead, the inert anodes are among the measures with the highest GHG emission savings when using wind power. This means that, from a GHG emission perspective, the direct carbothermic reduction is the more beneficial choice in regions with a high proportion of coal power, while inert anodes are the more beneficial choice in regions with a high proportion of renewable electricity, e.g. wind power or hydropower. In contrast to the other measures, the inert anodes benefit from the lower primary energy factor, emission factor and cost of wind power because of the increased energy use in the electrolysis entailed by the inert anodes.

For both the single electrolysis plant and the entire global production through the electrolysis process, the inert anodes have a negative saving in primary energy use, implying that primary energy use increases when implementing the inert anodes on their own. This is because of the increased energy end-use from their implementation. When only implementing inert anodes, there are increased GHG

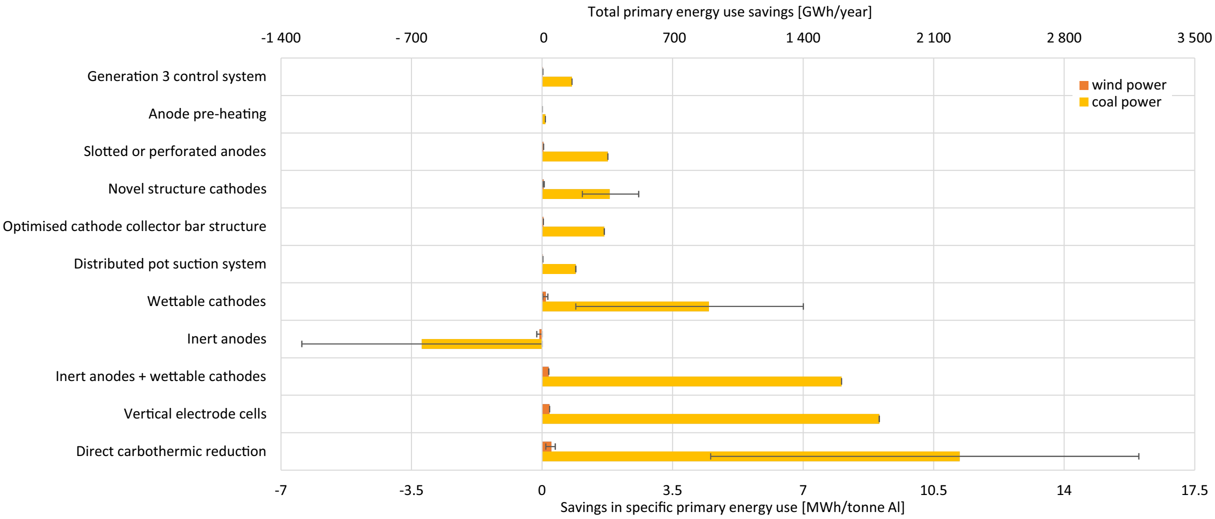

Fig. 1 The primary energy savings from implementing the measures at the single plant. Each bar shows both the savings per tonne of aluminium and the total savings. A range in the primary energy saving is shown for the measures for which more than one value for energy end-use efficiency improvement was available. Orange bars are for 100% wind power, while yellow bars are for 100% coal power

emissions due to the increased energy use, which, in most cases, is compensated for by the elimination of the process-related GHG emissions, resulting in an overall saving in GHG emissions (see Figs. 2 and 5). The savings in energy and CO_2 costs for the inert anodes are mainly negative, implying an increase in these costs. This is because the increased energy costs from increased energy end-use are not compensated for by the reductions in CO_2 costs from the elimination of the process-related emissions. The

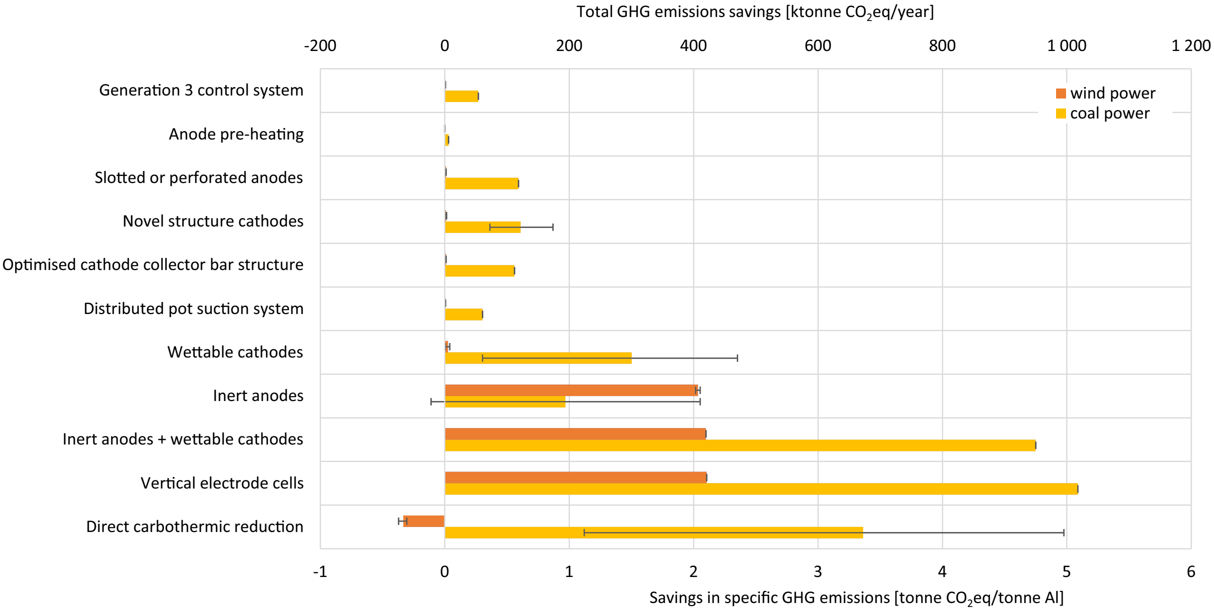

Fig. 2 The GHG emission savings from implementing the measures at the single plant. Each bar shows both the savings per tonne of aluminium and the total savings. A range in the GHG emission saving is shown for the measures for which more than one value for energy end-use efficiency improvement was available. Orange bars are for 100% wind power, while yellow bars are for 100% coal power

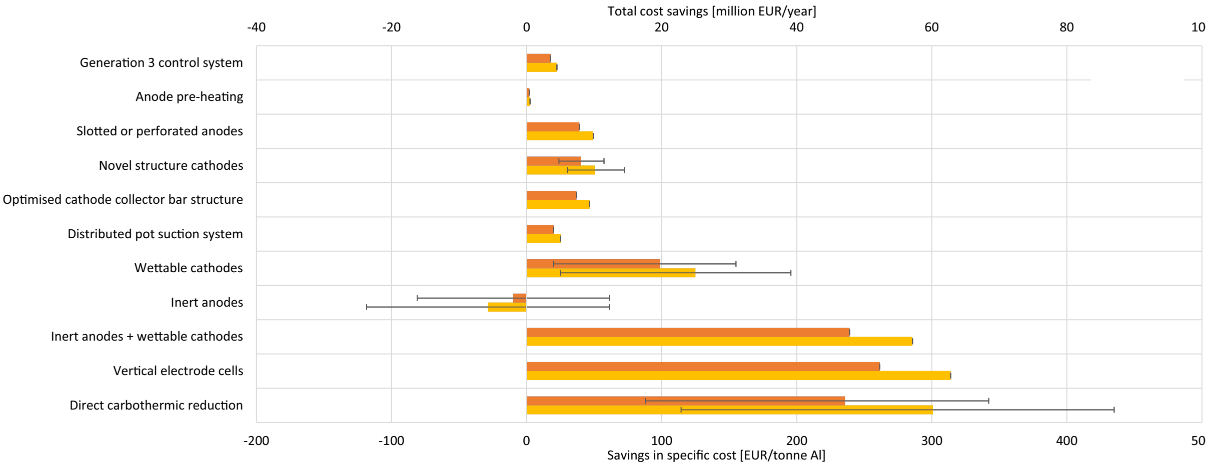

Fig. 3 The energy and CO_2 cost savings from implementing the measures at the single plant. Each bar shows both the savings per tonne of aluminium and the total savings. A range in the energy and CO_2 cost saving is shown for the measures for which more than one value for energy end-use efficiency improvement was available. Orange bars are for 100% wind power, while yellow bars are for 100% coal power

exception is when the energy end-use remains unchanged and then the cost saving is solely derived from the elimination of the process-related GHG emissions. This implies that it may be necessary to impose a price on GHG emissions in order to make inert anodes cost-effective on their own. When inert anodes are combined with wettable cathodes or are part of vertical electrode cells, savings in all three areas (primary energy use, GHG emissions and energy and CO_2 costs) are achieved.

Discussion

Previous research (Norgate et al. 2007; Haraldsson and Johansson 2018) indicates that increased energy use is the reason why inert anodes are considered in combination with technologies that save energy, e.g. wettable cathodes or as part of vertical electrode cells. However, the energy efficiency improvements from inert anodes occur during anode production when taking into account the combined material flow of the electrolysis

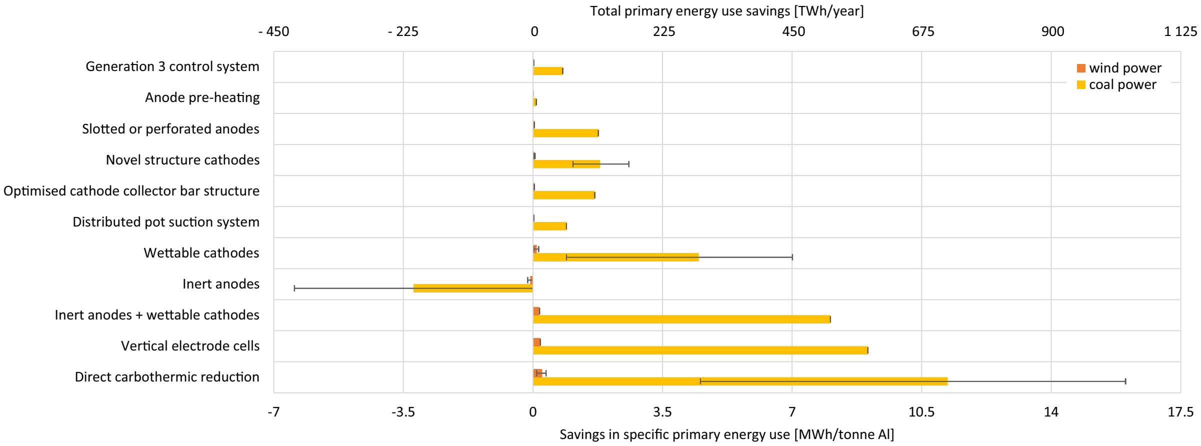

Fig. 4 The primary energy savings from implementing the measures in the entire global production through the electrolysis process. Each bar shows both the savings per tonne of aluminium and the total savings. A range in the primary energy saving is shown for the measures for which more than one value for energy end-use efficiency improvement was available. Orange bars are for 100% wind power, while yellow bars are for 100% coal power

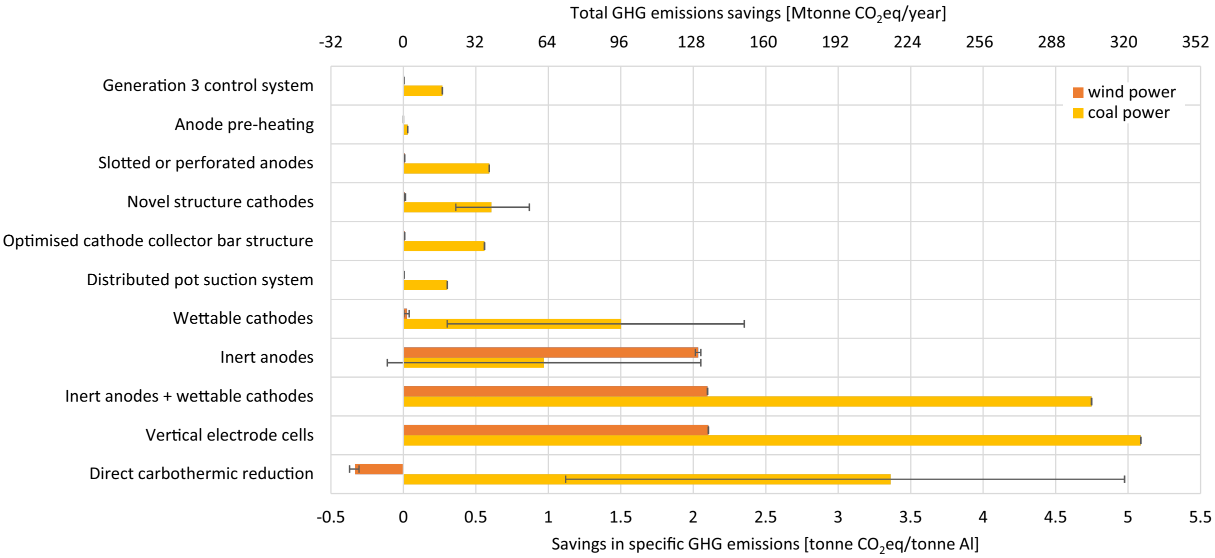

Fig. 5 The GHG emission savings from implementing the measures in the entire global production through the electrolysis process. Each bar shows both the savings per tonne of aluminium and the total savings. A range in the GHG emission saving is shown for the measures for which more than one value for energy end-use efficiency improvement was available. Orange bars are for 100% wind power, while yellow bars are for 100% coal power

and the anode production (Haraldsson and Johansson 2018; Galasiu and Galasiu 2014; Kvande and Haupin 2001). Inert anodes are expected to have a much longer operational life than the carbon anodes that are currently used, meaning the anodes need to be changed less often (Haraldsson and Johansson 2018; U.S. Aluminum Association 1998). This implies that a holistic approach to the cost evaluation is needed when implementing inert anodes, in which account should be taken of the investment cost, the longer lifetime and the increased energy costs, amongst other costs. This must be taken into account in order to make a more decisive recommendation on how high the price on GHG emissions should be to make inert anodes cost-effective. An evaluation of all costs associated with inert anodes to establish whether or not they are cost-effective is also needed

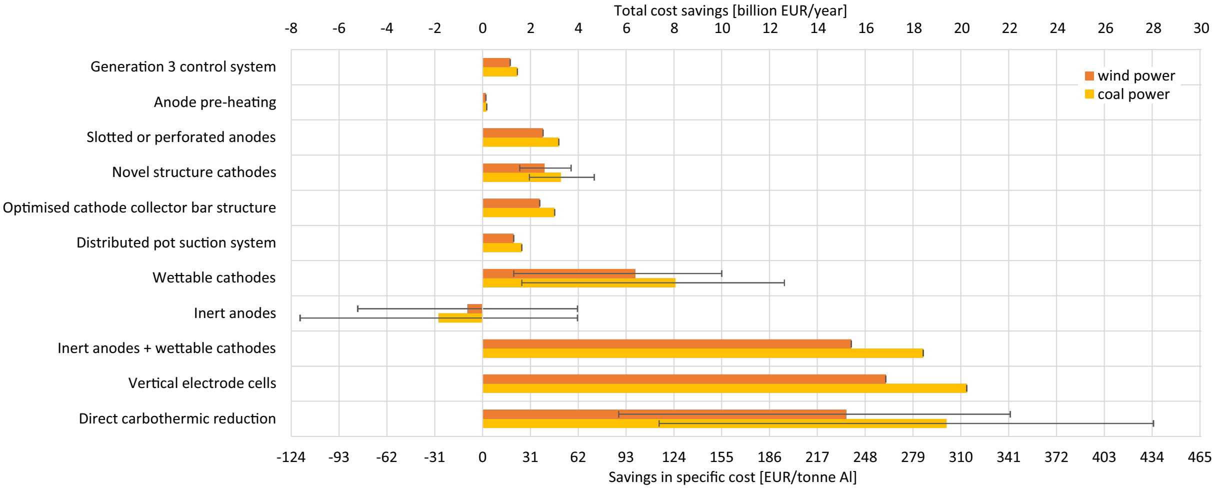

Fig. 6 The energy and CO_2 cost savings from implementing the measures in the entire global production through the electrolysis process. Each bar shows both the savings per tonne of aluminium and the total savings. A range in the energy and CO_2 cost saving is shown for the measures for which more than one value for energy end-use efficiency improvement was available. Orange bars are for 100% wind power, while yellow bars are for 100% coal power

in order to make the implementation of inert anodes attractive to industrial companies. However, Padamata et al. (2018) believe that inert anodes are economically beneficial compared to carbon anodes.

Statistics from the International Aluminium Institute (2020) show that the type of electricity used today for electrolysis varies between different regions of the world. For example, the electricity used for electrolysis in China and the rest of Asia is heavily dependent (> 90%) on coal power, while the electricity used for electrolysis in Europe is predominantly dependent (> 90%) on low-carbon electricity (renewables and nuclear power where hydropower accounts for the majority) (International Aluminium Institute 2020). From a GHG emission perspective, the direct carbothermic reduction is the more beneficial choice in regions that today have a high proportion of fossil electricity use for electrolysis, while inert anodes are the more beneficial choice in regions that today have a high proportion of low-carbon electricity use for electrolysis, as indicated by the results. However, neither inert anodes or direct carbothermic reduction are available today and the electricity mix used for electrolysis in each region might have changed once these technologies are available. The cost for renewable electricity has declined significantly over the past years and is expected to decline further (IRENA 2019). Onshore wind and solar PV without any financial support are, frequently, cheaper than any fossil fuel option (IRENA 2019). This, together with political goals on climate change and renewable energy, means that the share of renewable electricity generation is likely to increase around the world. This implies that inert anodes would become the more beneficial choice, from a GHG emission perspective, in more regions in the future.

The results indicate that there could be trade-offs between savings in final and primary energy use, GHG emissions and energy and CO_2 costs for both inert anodes and direct carbothermic reduction. Industrial companies may be more inclined to choose direct carbothermic reduction due to the significant savings in energy and CO_2 costs, up to 87 million Euro per year for a single plant with a production volume of 200,000 tonnes/year. However, this would result in increased GHG emissions if a company were to use renewable electricity (e.g. wind power), making it harder to achieve political goals regarding reduced climate impact. Inert anodes would be a better solution from a GHG emission perspective than direct carbothermic reduction when a company uses low-carbon electricity. Additionally, when the inert anodes are combined with wettable cathodes or are a part of vertical electrode cells, the savings in GHG emissions for coal power are comparable or even larger than what direct carbothermic reduction achieves. Furthermore, viewing the combined energy use of anode production and electrolysis, as well as combining inert anodes with energy-saving technologies, would be needed in order to avoid increased final and primary energy use and costs of electrolysis. This is needed in order to avoid trade-offs between the political goals regarding GHG emissions and energy efficiency improvements, as well as between reduced GHG emissions and reduced costs. Even though an individual company potentially can save more money by implementing the direct carbothermic reduction, the company should consider implementing the vertical electrode cells together with other energy-saving technologies. The reason for this is that this would yield the largest savings in GHG emissions and, at the same time, provide similar cost savings for the company compared with implementing the direct carbothermic reduction. Improved sustainability in production will become increasingly important due to, for example, increasing demands from end-users regarding sustainability aspects (Haraldsson and Johansson 2019). Such demands emphasise the importance of implementing measures yielding large savings in both GHG emissions and costs.

Implementing the measures studied in the paper has considerable potential in reducing final and primary energy use, GHG emissions and costs for companies that produce primary aluminium. All the studied measures, with the exception of direct carbothermic reduction, can be combined (Haraldsson and Johansson 2018). However, it is not known how this combination compares with direct carbothermic reduction since no value on the savings potential was found in the literature (Haraldsson and Johansson 2018). Also, it is not always possible to simply add the energy efficiency potential for the individual measures when multiple measures are implemented together, since the measures might affect each other's efficiency potential (Thollander et al. 2020). A site-specific investigation also needs to be conducted in order to identify the solution with the highest savings potential, which could vary from case to case.

The total savings potential for global production through the electrolysis process may be lower than what has been presented in the "The entire global production through the electrolysis process — results" section, since some of the measures may already have been implemented at some of the production sites worldwide. The savings potential for both the single plant and global production through the electrolysis process should be viewed as the technical potential for energy efficiency improvements. The economic potential, in which measures that are not cost-effective have been excluded, is typically lower than the technical potential (Nadel et al. 2004). Additionally, changes in production volume and how they affect the savings potential have not been accounted for in the paper.

Schwarz et al. (2001) found that improved energy efficiency yields GHG emission savings equivalent to 0.504–0.819 tonnes CO_2eq/tonne aluminium. As mentioned in the introduction, the energy efficiency improvements in Schwarz et al. (2001) are based on a comparison between the average energy use for electrolysis in 1995 and the energy use in modern or substantially upgraded electrolysis plants in 1995, and not any specific energy efficiency measures. As shown in this study, inert anodes (wind power), the combination of inert anodes and wettable cathodes (both wind power and coal power), vertical electrode cells (both wind power and coal power) and direct carbothermic reduction (coal power) yield higher savings than what Schwarz et al. (2001) presents, up to 5.09 tonnes CO_2eq/tonne aluminium. The values from Schwarz et al. (2001) are in the same order of magnitude as the values for some of the measures studied in this article (see Figs. 2 and 5). Liu et al. (2017) predicted that the final energy use of Henan's aluminium industry (including mining, aluminium oxide production, anode production, electrolysis and ingot casting) could be reduced by a total of 19–29% between 2014 and 2030. Direct carbothermic reduction, vertical electrode cells and the combination of inert anodes and wettable cathodes studied in this article have a similar savings potential to what was stated by Liu et al. (2017). Liu et al. (2017) also predicted that the GHG emissions for Henan's aluminium industry could be reduced by a total of 3.2–5.4 Mtonnes CO_2eq/year. Henan's aluminium industry accounts for 6.4% of global aluminium production (Liu et al. 2017). The predicted GHG emissions reduction for Henan's aluminium industry corresponds to 50–84.4 Mtonnes CO_2eq/year for the entire global production, assuming that the predicted values from Liu et al. (2017) can be scaled up to the entire global production. Some energy efficiency measures (the combination of inert anodes and wettable cathodes, vertical electrode cells and, to some extent, inert anodes and wettable cathodes) provide higher savings potential for the global production through electrolysis (about 130–327 Mtonnes CO_2eq/year) than what was presented by Liu et al. (2017). However, it is not possible to make any comparisons with individual energy efficiency measures or with electrolysis only since the results in Liu et al. (2017) are not specified on such a detailed level. Kermeli et al. (2015) found that "improved cell control point-feeding systems of existing point-feeder prebaked (PFPB) cells" (a type of control system) can save a total of 20–152 TWh/year of primary energy use and 4.5–42.5 Mtonnes CO_2/year for the top eleven aluminium producing countries in the world. The top eleven aluminium producing countries account for 82% of the entire global production of aluminium (Kermeli et al. 2015). The estimated values from Kermeli et al. (2015) correspond to 24.39–185.37 TWh/year of primary energy use and 5.49–51.83 Mtonnes CO_2/year for the entire global production, assuming that the estimated values can be scaled up to the entire global production. The generation 3 control system examined in this study is comparable with the intervals from Kermeli et al. (2015) when using coal power in global production through the electrolysis process. Obaidat et al. (2018) found that wettable cathodes, inert anodes and direct carbothermic reduction can save around 0.88, 1.4 and 0.62 tonnes CO_2/tonne aluminium, respectively, compared with the GHG emissions prior to their respective implementation. The results in the "Results and analysis" section show that the wettable cathodes, inert anodes and direct carbothermic reduction can save 0.005–2.35, -0.11–2.05 and -0.37–4.98 tonnes CO_2eq/tonne aluminium, respectively, which covers the values from Obaidat et al. (2018). Additionally, there is a consensus between our article and the article by Obaidat et al. (2018) when examining the results for wind power in our article, which indicate that direct carbothermic reduction should provide the smallest GHG emission saving of the three measures. However, there is a lack of consensus when looking at the results for coal power in our article since our article found that direct carbothermic reduction would then be yielding the highest GHG emissions while, in Obaidat et al. (2018), direct carbothermic reduction still yields the lowest GHG emission savings. Myklebust and Runde (2005) found that direct carbothermic reduction can reduce the GHG emissions per tonne of aluminium by 30.7–43.7% compared with the electrolysis process. The results in the "Results and analysis" section show that direct carbothermic reduction can save -16.6–38.8% compared with the electrolysis process, in which the upper limit of the interval is comparable with Myklebust and Runde (2005). It is worth noting that the differences in the results between our study and previous studies can, to some extent, be explained by different assumptions, e.g. regarding energy end-use efficiency potentials and emission factors.

There is a potential to achieve carbon-neutrality in the reduction of aluminium oxide to pure aluminium. One approach would be to utilise inert anodes in combination with wettable cathodes or as part of vertical electrode cells and utilise carbon-neutral electricity in the process. This would eliminate both process-related and energy-related GHG emissions, while also reducing energy use, thereby keeping energy costs low. Another approach would be to use carbon material from biomass sources as the reaction material either in electrolysis or in direct carbothermic reduction. Direct carbothermic reduction has the advantage of lower-energy use compared with electrolysis without any major energy efficiency improvements. However, there are many energy efficiency measures applicable to electrolysis, all of which can be combined (Haraldsson and Johansson 2018). It is not known how this combination compares with direct carbothermic reduction since no value on the energy efficiency potential was found in the literature (Haraldsson and Johansson 2018). Also, it is not always possible to simply add the energy efficiency potential for the individual measures when multiple measures are implemented together, since the measures might affect each other's efficiency potential (Thollander et al. 2020). The disadvantage of direct carbothermic reduction is the higher demand for carbon as the reaction material compared with electrolysis. Direct carbothermic reduction needs around 0.67 tonnes C/tonne Al (Warner 2008), which is equal to the theoretical carbon consumption given by the chemical reaction. Data from the International Aluminium Institute show that the consumption of anode carbon in industrial applications of electrolysis is around 0.46 tonnes C/tonne Al (International Aluminium Institute 2017), while the theoretical value is around 0.33 tonnes C/tonne Al, predicted by the chemical reaction. Lorentsen (2014) estimated that more than 100 million tonnes of bio-coke per year are needed for direct carbothermic reduction in order to achieve the 2014 levels of aluminium production. Biomass can be seen as a limited resource, and competition for biomass on both local and international levels is to be expected in the future (Johansson 2016). There is a risk that there is not enough biomass globally to meet the aluminium industry's demand or that the price of biomass will become too high, making the use of the biomass economically unfeasible. Further research and development is needed for the energy efficiency measures that are not currently available (see Table 2). For example, direct carbothermic reduction has been tested on a laboratory/pilot scale (Johansen et al. 2000; Bruno 2005) but further developments are needed (Bruno 2005; Balomenos et al. 2011b; Choate and Green 2016) and the direct carbothermic reduction has not yet been made commercially available. In addition, further studies are required to evaluate which technologies that are the most suitable from an energy, environmental and economic perspective.

A number of assumptions that have been made that could affect the reliability of the results. The energy end-use efficiency potentials in Table 2 are taken from the literature review as they appear. The energy end-use efficiency potential for the combination of inert anodes and wettable cathodes is higher than the wettable cathodes alone, even though the inert anodes have a negative efficiency potential. Such ambiguities in the values have not been corrected. Variations in the energy end-use efficiency improvements between plants have not been accounted for in the calculations for the entire global production through the electrolysis process, i.e. the same energy efficiency improvement has been assumed for all plants globally.

The value for the process-related GHG emissions from direct carbothermic reduction was assumed to be the theoretical value, i.e. the amount of GHG emissions according to the chemical reaction. In practice, GHG emissions may be different than those theoretically predicted due to inefficiencies in the process, for example. The heat used for the direct carbothermic reduction was assumed to be supplied using electricity but could be supplied using other energy sources. This would have an impact on the results regarding the savings in primary energy use, GHG emissions and energy and CO_2 costs for direct carbothermic reduction. However, this study used two different electricity generation types to study the effects on the results from different values for the primary energy factor, emission factor and price.

Different assumptions can be made regarding which energy source for electricity generation is removed when the energy end-use efficiency is improved. This would impact the potential savings in primary energy use, GHG emissions and energy and CO_2 costs, since different energy sources result in different values for the primary energy factor, emission factor and price. As previously stated, the electricity generation plant constituting the build margin could vary between different regions. Also, the price of GHG emissions varies between different countries and regions, which would affect the cost savings.

The primary energy factors, emission factors and price/cost of a specific type of electricity generation (e.g. wind power or coal power) can vary depending on, for example, the plant characteristics of the electricity generation facility and how they have been calculated. Thus, the values for the primary energy factor, emission factor and price/cost of electricity may vary. Statistics on primary energy factors, emission factors and electricity price/electricity generation cost of specific electricity generation facility types are needed in order to illustrate such variations in the values. Esser and Sensfuss (2016) state that the primary energy factor can be calculated in various ways, based on the numerous factors that affect the amount of primary energy required to supply one unit of electricity. Similarly, emission factors can be calculated in various ways (Gode et al. 2011).

The cost of electricity presented in Table 3 is based on the cost of generating the electricity and not the electricity price. If the companies buy the electricity from the electricity market, they would probably have to pay a higher price than what is stated in Table 3. This means that the cost savings from implementing the measures could be higher than what is shown in the results since the electricity price is typically higher than the generation cost.

The single electrolysis plant studied in this paper is hypothetical. The energy end-use efficiency potentials in Table 2 and the plant characteristics (annual production, energy intensity, GHG emissions from anode consumption and GHG emissions from anode effects) could vary from plant to plant. The values for the primary energy factor, emission factor and price of the electricity could also vary from plant to plant. Thus, the values and results cannot be generalised to all electrolysis plants globally but indicate the size of the potential savings. A site-specific investigation is needed for each case.

Future research could include an evaluation of the economic feasibility of the energy efficiency measures, in which investment costs, changes in operation and maintenance costs, and the lifetime of the measures are taken into account.

Conclusions

The aim of this paper was to study the effects on primary energy use, GHG emissions and energy and CO_2 costs when energy efficiency measures are implemented in the electrolysis process in primary aluminium production. Vertical electrode cells and the combination of inert anodes and wettable cathodes are among the measures with the highest savings in all three areas (primary energy use, GHG emissions and energy and CO_2 costs), irrespective of whether the electricity used for electrolysis is generated from wind power or coal power. Direct carbothermic reduction is among the measures with the highest savings in primary energy use, and energy and CO_2 costs, irrespective of whether the electricity, is generated from wind power or coal power. For GHG emissions, direct carbothermic reduction is the more beneficial choice when using coal power, while inert anodes are the more beneficial choice when using wind power. When using wind power, direct carbothermic reduction would result in increased GHG emissions since the GHG emissions saving from reduced energy use is not compensating for the increased process-related GHG emissions. Even though an individual company potentially can save more money by implementing the direct carbothermic reduction, the company should consider implementing the vertical electrode cells together with other energy-saving technologies. The reason for this is that this would yield the largest savings in GHG emissions and, at the same time, provide similar cost savings for the company compared with implementing the direct carbothermic reduction.

The inert anodes result in increased primary energy use when implemented on their own. However, increased GHG emissions resulting from the increased energy use from the implementation of the inert anodes are, in most cases, compensated for by the elimination of the process-related GHG emissions, thereby resulting in savings in GHG emissions. The increased energy use from the implementation of inert anodes results in increased costs and the results imply that it may be necessary to impose a price on GHG emissions in order to make inert anodes cost-effective on their own. However, a holistic approach to the evaluation of the costs, in which account should be taken of the investment cost, the inert anodes' longer lifetime and the increased energy costs, amongst other costs, is needed. This is necessary in order to make a more decisive recommendation on how high the price on GHG emissions should be to make inert anodes cost-effective and for industrial companies to consider the implementation of inert anodes. Also, savings in all three areas (primary energy use, GHG emissions, and energy and CO_2 costs) will be achieved when inert anodes are combined with wettable cathodes or are part of the vertical electrode cells.

Significant savings in final and primary energy use, GHG emissions and energy and CO_2 costs can be achieved for both a single production plant and the entire global production through the electrolysis process by implementing the measures studied in the paper. The results show that the type of electricity generation assumed in the calculations has a significant effect on the potential savings in primary energy use, GHG emissions and energy and CO_2 costs. There is a potential to achieve carbon-neutrality in the reduction of aluminium oxide to pure aluminium. However, further research is needed to evaluate which technologies are the most suitable from an energy, environmental and economic perspective

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

Table 4 Short description of the studied energy efficiency measures. Based on Haraldsson and Johansson (2018)

Energy efficiency measure	Description	Currently available?
Generation 3 control system	A process control system	Yes
Anode pre-heating	Pre-heating the anodes avoids the formation of frozen electrolyte at the bottom of the anodes.	Yes
Slotted or perforated anodes	The thickness of the bubble layer on the bottom of the anodes is reduced since the discharge distance for the anode gas is reduced.	Yes
Novel structure cathodes	Instead of plane surfaces, the novel structure cathodes have surfaces with shape arrangements.	Yes
Optimised cathode collector bar structure	Includes changing the conductive structure, carbon height and collector bar size, and optimising the assembly form of the cathode carbon and the collector bar	Yes
Distributed pot suction system	Allows the ventilation rate to be varied within a wide range	Yes
Wettable cathodes	The molten metal is allowed to wet the cathode due to new cathode material or coatings to existing materials.	No
Inert anodes	Non-consumable anodes with a lifetime much longer than the carbon anodes used today.	No
Inert anodes + wettable cathodes	A combination of the inert anodes and wettable cathodes	No
Vertical electrode cells	New cell design utilising several vertical electrodes. Every second electrode is an anode and every alternate is a cathode.	No
Direct carbothermic reduction	A chemical reduction of aluminium that potentially could replace the electrolysis process and its electrochemical reduction	No

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