The Contribution and Economics of Demand Side Response Towards Decarbonizing the Aluminium Smelting Industry

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Abstract

Baseload energy consumption by primary aluminium smelters is rapidly becoming less valuable to power grid operation and stability due to the increasing penetration of variable renewable energy (VRE). For global industry to decarbonize, many smelters must find pathways to reduce their dependence on thermal baseload generation. One such pathway is power modulation and the retrofittable EnPot technology can now enable ±20% modulation at any time, allowing smelters to increase the use of VRE in their energy mix, or for them to help firm VRE in national grids. Decarbonizing power systems provide by far the greatest driver to reduce carbon footprints and firming of VRE via smelter modulation is the cheapest way to achieve this, thereby attracting governmental attention and potential funding. A detailed analysis of two energy markets (coal versus hydro-dominated) shows that beyond the decarbonization benefits, modulation is also economically advantageous to smelters, and that it opens the door to new contractual scenarios whereby smelters could sell power caps back into the market.

Keywords

Renewable energy • Aluminium smelting • Power modulation • Energy markets • Decarbonization • Demand side response

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Introduction

EnPot is a breakthrough technology for smelting cell heat balance control that was developed by the Light Metals Research Centre at the University of Auckland. Heat balance control allows the smelter power usage to be modulated significantly both upwards or downwards where previously almost constant power loads have been required. Being able to vary loads will make aluminum smelters much more compatible with future power grids involving a lot more variable renewable energy (VRE), as well as providing valuable services to support more renewable grids. As power generation is by far the largest component of the aluminum industry's CO_2 emissions, enabling the transition away from power generation via fossil fuels is the largest impact possible towards decarbonization of aluminum smelting as we know it today.

EnPot Technology

The key feature of EnPot technology is the patented shell heat exchanger (SHE) unit. Several of these are mounted to the upper sidewall of each smelting cell and connected to a ducted suction network (Fig. 1). The airflow through the SHE units is varied by the speed of the induced draft (ID) fan, such that high airflow gives significantly enhanced heat transfer from the sidewalls while lower airflow, below a base demand, results in insulation of the sidewall and thus reduced heat transfer [2, 3].

Power modulation in a smelter means raising or decreasing line amperage through the cells. At higher amperage, it needs to shed more heat while at lower amperages it seeks to retain the heat in the process. This cooling/insulation principle of the EnPot enables smelters to modulate their power usage by having much more control over heat loss so that no significant thermal imbalance occurs in the cells when the power input is increased or

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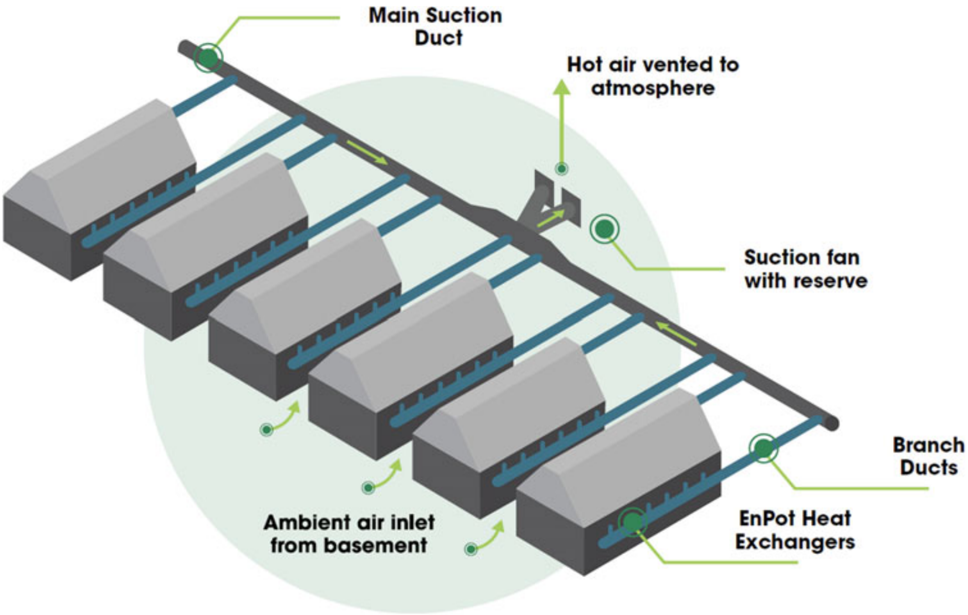


Fig. 1 Ducted network for a section of aluminum smelting cells with installed EnPot heat exchangers

reduced. This results in an effective range of approximately ±20% power usage at the smelter at any time without lead time or process changes required. This may also require adjustment of top heat losses via increased control over fume extraction/suction to the gas treatment centre (GTC), which combined with rectifier capacity may be key limiting factors on upward modulation capability at a smelter. Modulation range may be further expanded to approximately ±30% power usage when further process changes are made such as increased or decreased anode cover thickness (further regulating cell top heat losses); however, these can take approximately one anode cycle at a smelter to implement, so that this range cannot be used instantaneously.

Aluminum Decarbonisation

Globally, in 2019, the aluminum smelting process emitted an average of 12.3 tonnes of CO_2-equivalent emissions per tonne of primary aluminum produced (Scope 1 and 2 basis). This figure is comprised of only 2.0 t CO_2e/t Al direct emissions from the reduction process (Scope 1), and 10.3 t CO_2e/t Al emissions from electricity generation (Scope 2) [5]. The large Scope 2 emission component reflects both the intensive electrical energy requirement to smelt primary aluminum, coupled with the fact that much of today's smelting production is powered by carbon-intensive sources of electricity. In 2019, the power mix of smelters was dominated by coal (64% of the world's production) and natural gas (10%), with only 27% of production powered by low-carbon hydro, nuclear, or other renewables [5].

In a previous article, Matthews et al. [11] modelled some potential pathways for smelters to reach 'net zero' by 2050. Figure 2 presents a 'high-growth' scenario of 3.8% annual smelting production increases from 2020 to 2050, and illustrated two pathways to 2050: a 'business-as-usual' approach (top curve) and emission reductions to net zero if smelters were to rapidly adopt *multiple* solutions (bottom black-dotted curve).

While process improvements such as inert anodes, and/or carbon capture, utilization, and storage (CCUS) are required to reduce direct Scope 1 emissions, it is clear that decarbonization of the power system (attributed to Scope 2 emissions) is the much larger and more pressing aspect. This is even more important when we consider the significant increases in primary production capacity needed to meet demand by 2050 (estimated by the International Aluminium Institute (IAI) [6] at 90 Mt Al/year, a 35% increase from 2020 levels; this is using a lower growth model than the one in Fig. 2, and assumes that by 2050 aluminum production via recycling can ramp up by 275% from 2020 levels) and the lack of major hydro-reserves that remain available for expansion of primary smelting. If the additional power demand for smelting is provided largely by thermal coal and gas—i.e. under a 'Business-As-Usual' (BAU) scenario—then CO_2 emissions for the primary aluminium sector could be as large as 1,500 Mt CO_2e/year by 2050 [1, 7].

The IAI [7] has also defined a series of greenhouse gas (GHG) reduction pathways for the aluminum sector that are aligned with the Paris Agreement's goal to limit global warming to well below 2 degrees by 2050. The first major pathway requires the complete decarbonization of electricity

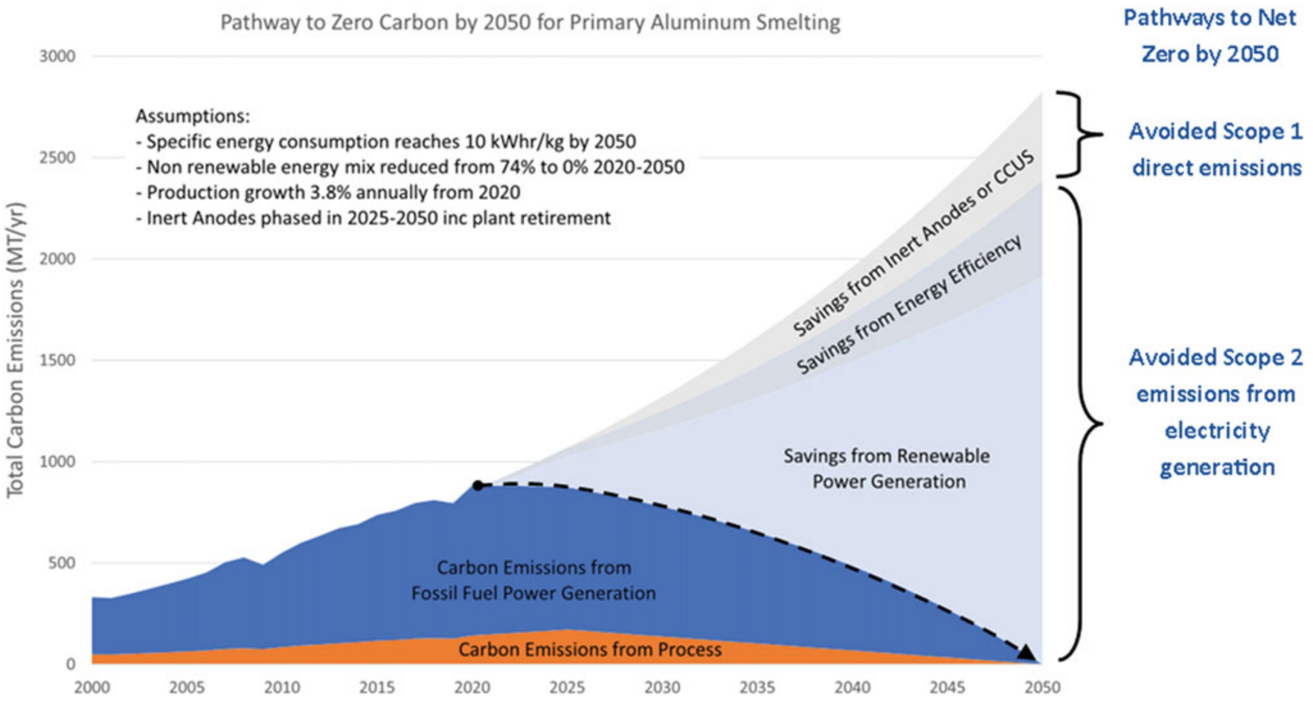


Fig. 2 Actual (2000–2020) and modelled CO_2 emissions (2020–2050) from primary aluminum smelting, assuming a 3.8% annual growth from 2020 (top curve) versus a potential pathway to net-zero carbon by 2050 (bottom black-dotted curve). Adapted from Matthews et al. [11] (Color figure online)

use for the entire aluminum sector—but particularly for smelting—from 700 Mt CO_2e/year today, to near-zero emissions by 2050. This requires a rapid uptake of clean energy—whether that's thermal generation with CCS, nuclear, hydro, variable renewables, or other renewables—and not only for new production capacity, but also for switching of existing production using carbon-intensive power.

Increasing power generation via variable renewable energy (VRE) is already considered the cheapest and most environmentally attractive (emission free) method. In a recent study [4], the CSIRO and the Australian Energy Market Operator (AEMO) found that by 2030 up to 90% of electricity generation in Australia by wind and solar (PV) has the potential to be cheaper than any new coal or gas capacity (more so if climate policy risk and CCS on thermal generation is factored in). This is even true when taking into account the additional cost to firm this VRE uptake via storage technologies and additional costs of transmission, both of which become more significant with increasing % VRE share.

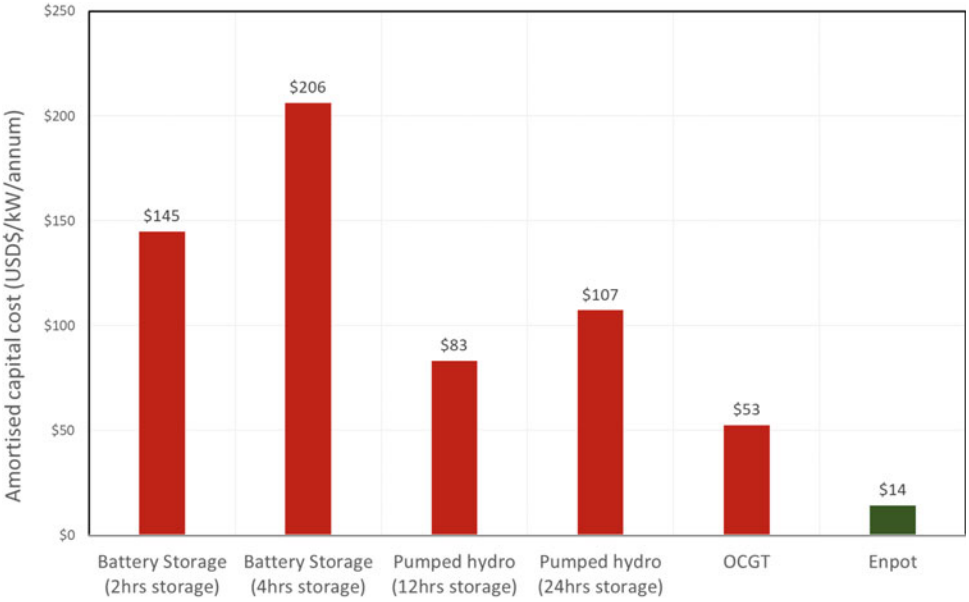
However, a rapid pivot towards high levels of VRE brings practical challenges to a grid regarding the variable supply and contrasts with the traditional need for near-constant energy demand in aluminum smelting. In fact, firming of this VRE will soon be a key challenge, not just for smelters, but for all energy networks in balancing generation with demand [4, 14]. As shown in this paper, this is necessary not just for energy networks moving from largely thermal generation to VRE, but also traditional renewable hydro-powered networks expanding towards high VRE uptake.

Firming VRE in Power Systems

Firming of VRE can be performed by several technologies such as battery storage, pumped and stored hydro and gas turbine peaking plants. EnPot technology shows the potential to be both the cheapest method to firm up to 40% of smelter energy needs (±20%) [11, 14] and also to have the capability of providing energy services similar to both grid-scale batteries (100% of capacity for a short duration) and pumped hydro (lower capacity for longer duration). EnPot provides a large-scale demand-response mechanism in the electricity market that is of high value as smelters are commonly the largest single electricity consumers in their respective markets. An amortised cost comparison of several technologies available for VRE firming is shown in Fig. 3.

This last year there has been a significant shift in public perception and political motivation worldwide regarding decarbonization of industries and fossil fuel usage. This has resulted in the availability of new and large corporate and public funds for decarbonization initiatives. This again has

Fig. 3 Cost comparison of VRE firming technologies—battery storage, pumped hydro, and EnPot



led many corporations to start including decarbonization and social licenses to operate in their missions thereby easing the path forward for potential EnPot installations. An approximate installation cost for EnPot, albeit very smelter specific, will be typically around US$50-60 M for a mid-sized (275 ktpy / 500 MW) smelter. As shown following, there is a significant benefit to be found in all power systems to result in a payback in the 1–4 year range with the appropriate commercial agreements in place between smelters, energy generators, and transmission companies. And there are several different potential ways to offset the investment needed for an EnPot installation, including cost-sharing and benefit-sharing arrangements between all parties.

Modulation Options Enabled by EnPot

While the magnitude and duration of modulation that is made possible by using EnPot will depend on the robustness and thermal design of a particular smelting technology, the types of modulation that are valued in an energy market not only depend on smelting technology but also on the characteristics and demands of each individual market.

For the purpose of a market analysis, some assumptions need to be made regarding modulation ranges in a generic case. To do so, in the analysis, we settled on three key options to be valued:

(a) Full shutdown of whole plant (−100%) for a maximum of 4 h, up to once per week. Note that controllable insulation provided by EnPot approximately doubles the amount of time that a cell can be shut down and still be safely recovered afterwards, however the most common shutdowns of benefit to the power system are of only 1 h duration.

(b) −20% downward modulation, for *any* duration, without lead time.

(c) +10% upward modulation, for *any* duration, without lead time.

An extended modulation range of up to ±30% is possible, but this is not examined due to the lead time that is needed to implement operational changes such as cell cover thickness. Note also that modulation within the ±20% and ±30% windows needs no 'recharge' period afterwards, as thermal balance is maintained throughout. A full shutdown, however, will involve exhaustive thermal losses in the smelting cells and a recharge and stabilisation period will be required subsequently before another full shutdown can be made. This explains why the chosen limit for this function is once per week. Opposite to the latter and not unless capital improvements are made, upward modulation in many smelters may have power delivery limitations, which meant that upward modulation was limited at +10% in the general case.

Firming these options for any specific smelter requires an operational investigation combined with plant trials, including finding the maximum duration a potline can be shut down and easily restarted with the EnPot thermal insulation active. Other focal points are finding the maximum downward modulation while maintaining thermal balance, the maximum possible upward modulation without capital expense, and the associated capital cost estimates to enable further upward modulation.

Case Study 1—Analysis of a Coal-Dominated Power Market

A specific energy market was analysed in terms of the value of power modulation of a smelter with nominal power usage of 500 MW, which is equivalent to a smelting capacity of about 275,000 tonnes per annum. As the available types of modulation are smelter specific and valuation is market specific, this analysis applies to this specific case as opposed to a more general analysis for any mid-sized smelter.

The investigated energy market is largely based on generation using fossil fuels, where coal generation contributes nearly 75% of electricity supply. The market is rapidly changing, however, with increasing VRE penetration every year. At present, the market also has a large number of very low priced periods due to 'must run' generation, which really creates the opportunity for an EnPot-enabled smelter to increase production at low cost and to make up from earlier losses in production from downward modulation.

Another key feature of this energy market is the risk of short blackouts due to weather-related events causing failures of generators or network interconnects. This results in several periods every year with extreme power prices exceeding USD$10,000 per MWh. The typical duration of these events is from 0.5 to 6 h, with highest frequency around 1 h. The highly variable pricing and occurrence of emergency situations give potential for regular modulation as well as full-smelter shutdowns for limited periods of time either as a function of spot prices or as a paid service to grid operators as an emergency response.

An expert provider of electricity market modelling was engaged to provide forecasts of spot market prices for the next 20 years. The key inputs include future demand and generation forecasting complete with rapid investment in VRE generation through wind and solar, and the expected reduction in coal generation. The smelter in this market is modelled as a price taker, where the presence of 20% demand side response is assumed to not affect future price forecasts. A key output is the predicted price-duration curves of the spot electricity price for the next 20 years.

The price-duration curves are then used to determine when the smelter would be better to reduce aluminum production and sell the surplus electricity to the electricity spot market, or conversely, when the smelter would be better to increase the production of aluminum using cheap electricity purchased from the spot market. The value of this modulation determines the value of the EnPot technology to the smelter.

Arbitrage Price

The 'arbitrage price' (in $/MWh) is defined as the power price at which the smelter's income from aluminum production equals the income of selling electricity back to the grid, i.e. at this power price the smelter should be indifferent to making aluminum or not, notwithstanding any metal supply obligations.

In order to give a 'dead band' in the modulation schedule, decision points called the 'trigger prices' are used at the arbitrage price ± USD$10/MWh. This means that the smelter will spend a significant amount of time at its existing normal operating point, and not fluctuate rapidly between operating states when the price is close to the arbitrage price. This dead band naturally occurs in the region where modulation has the least value to the smelter and reducing modulation from 100% to say 50% of the time only has a small reduction in value, whilst providing benefits to plant stability.

The exact arbitrage price, dead band range, and maximum amount of modulation possible are, of course, smelter and market specific, and would, in practise, be optimized at each smelter, in line with the prevailing price of aluminum, smelter cost structures, and all technical and operational considerations. The effects of varying arbitrage price (changing market conditions) are also simulated in this paper.

Modulation Value Results

The primary result of the energy market modelling is the price-duration curve shown in Fig. 4 on a logarithmic scale. The price range is more closely shown in the following charts for both upward (A) and downward (B) modulation periods.

Figure 5 shows the high price events from $0–300/MWh and truncated at 27% probability of occurrence. Note that high price emergency events are off the scale and as high as $10,000/MWh. The downward modulation capability is assumed to operate at a point 20% below the plant's normal capacity, with the arbitrage price at USD$56/MWh and a trigger price of $66/MWh. In other words, when the spot electricity price is above $66/MWh the smelter would reduce output exposing 100 MW to the spot electricity market.

In return for modulating down a cumulative 14% of the time, the smelter then receives as income the electricity price less the arbitrage price, multiplied by 100 MW. Hence, an income from downward modulation of $7 M p.a. is

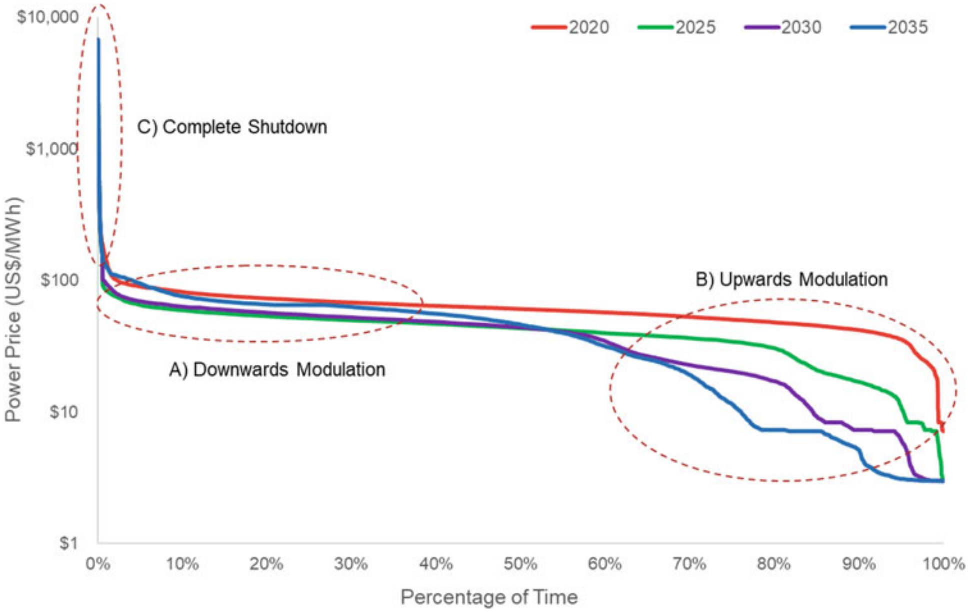


Fig. 4 Predicted price-duration curves (2020–2035 scenarios) on a logarithmic scale

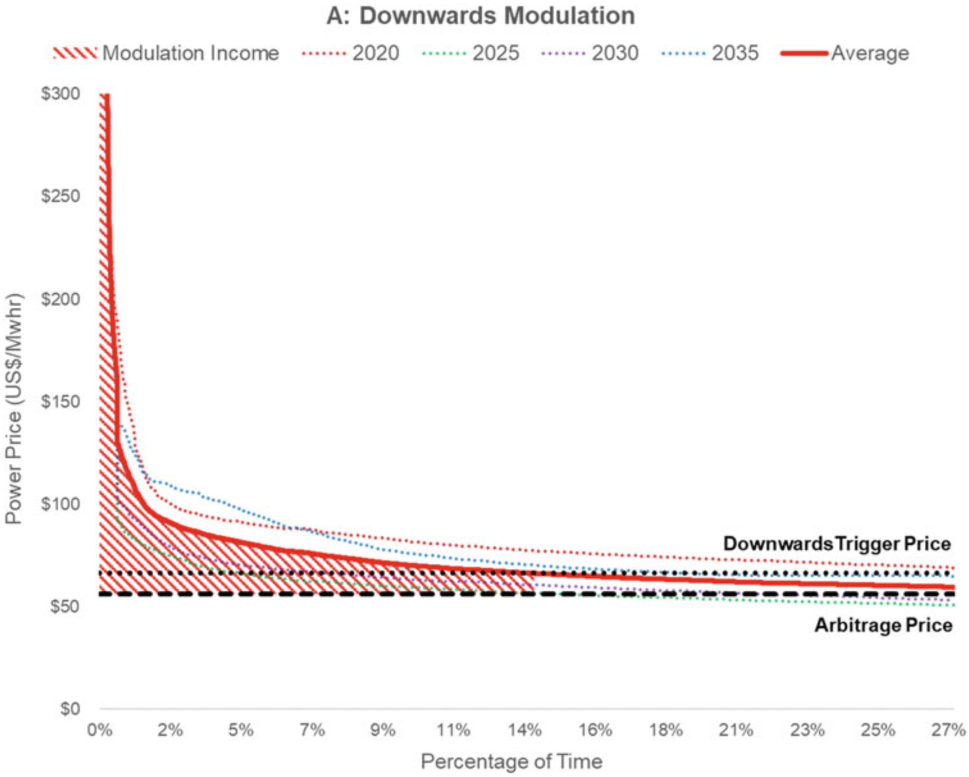


Fig. 5 Downward modulation region for energy market average prediction

represented by the shaded area under the curve in Fig. 5, after it has been multiplied by the 100 MW released. Complete shutdown is assumed to operate on a cumulative 0.5% of the time at the sharpest peak of the curve, on an additional 400 MW beyond the 100 MW already counted in the downward modulation scenario, for income of $16 M p. a. This time fraction is comprised of short high-priced events of typically 1–2 h duration each, when power prices are highest due to environmental conditions or emergencies causing a lack of power supply. In the case that some events are longer than 4 h, or occur too closely together, not all of this value may be possible to capture.

Figure 6 shows the low power price events from $0–150/MWh. Upward modulation is assumed to operate on

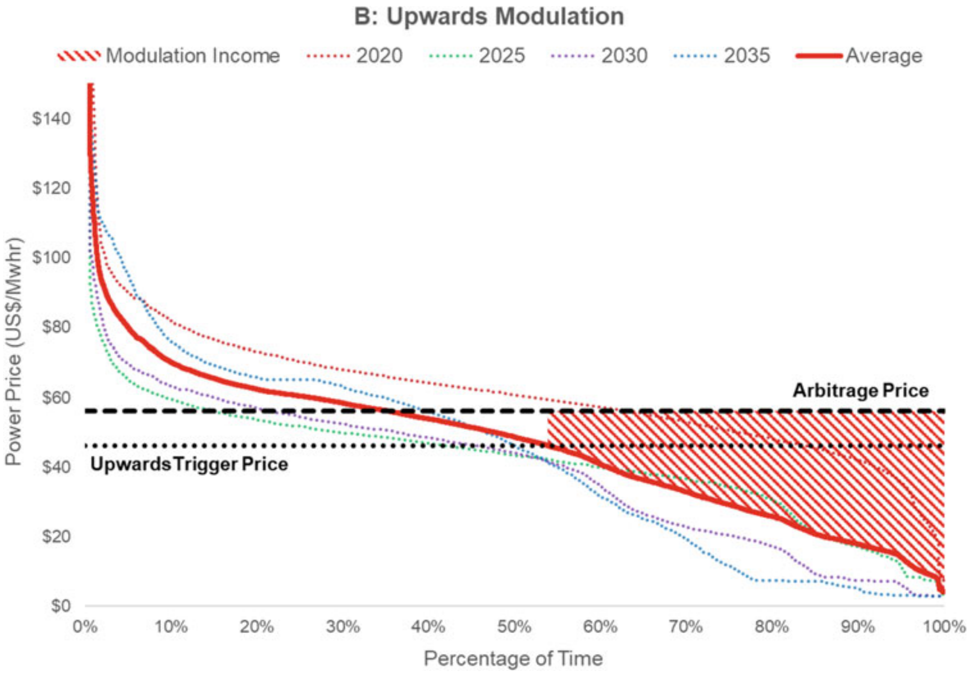


Fig. 6 Upward modulation region for energy market average prediction

10% of the plant's capacity, with a trigger price of $46/MWh. In other words, when the spot electricity price is below $46/MWh, the smelter would increase its exposure to the spot electricity market by buying an additional 50 MW to make extra aluminum.

In return for modulating upwards 43% of the time, the smelter would receive as income the arbitrage price less the electricity price, multiplied by the 50 MW used for production of additional aluminum. This income of upward modulation of $5 M p.a. is represented by the shaded area under the line after it has been multiplied by the additional 50 MW.

Table 1 aggregates the total income of modulation and shutdown capabilities in this market, being a total of US$27 million p.a. On this basis, the payback period of an EnPot installation is estimated to be 3–4 years.

Sensitivity Analysis

The arbitrage price (and trigger prices) for a smelter will control the amount of time a smelter spends in either upward or downward modulation. A high arbitrage price occurs when a smelter has high profitability due to a high metal price and/or low variable production costs compared the market price of electricity. In this case, a smelter would not modulate downwards as often as they would tend to make more profit by selling metal, and would modulate upwards as often as possible to make more metal. A low arbitrage price reflects conditions where smelters are not very profitable compared to the market price of electricity when the metal price is low, and modulating downwards is very appealing compared to making metal.

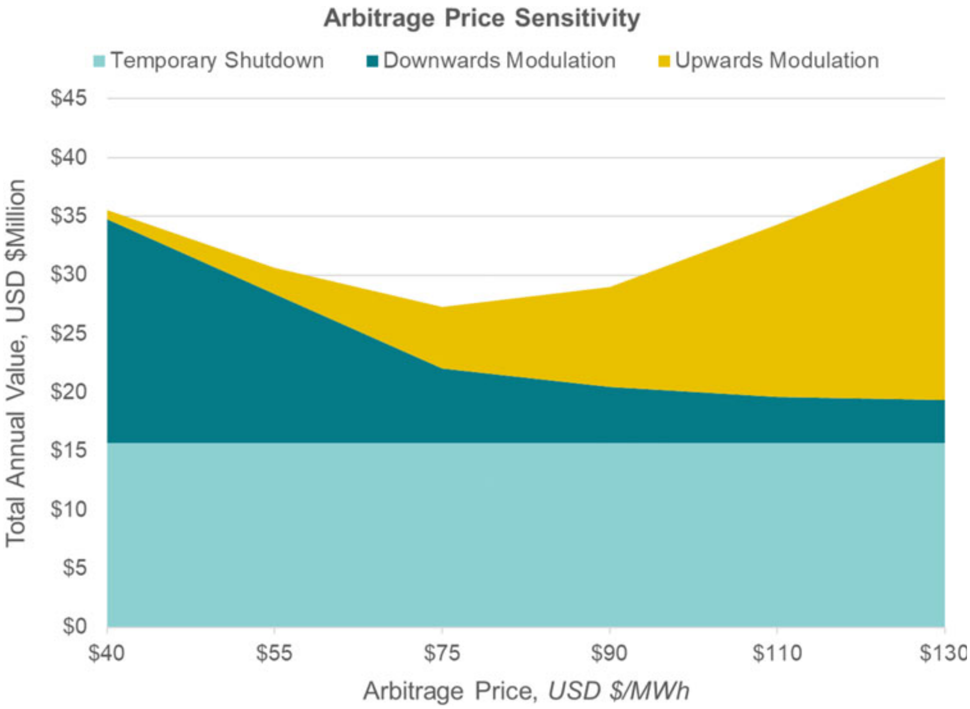
The sensitivity analysis for this model, as presented in Fig. 7, shows that the total annual value to the smelter did not vary strongly as arbitrage price changed, i.e. as the metal price changed. The value was between US$40 M p.a. and $28 M p.a. as the arbitrage price varied between US $40/MWh and $130/MWh. The value to be gained from total shutdown of the smelter was very consistent, as the short-duration price spikes when this function operates are well outside of the range of arbitrage prices. This shows that the economic case for power modulation is reasonably independent of future variation in LME metal price.

Table 1 Modulation value results for energy market average prediction

Arbitrage price = $56/MW	Modulation assumption (%)	Time operating (%)	MW impacted	Income p.a. $M, USD
Downward modulation	20	14	100	$7
Upward modulation	10	45	50	$5
Complete shutdown	100	0.5	400[a]	$16
Total		60		$27

[a] *Note* 100 MW deducted to remove any double counting with the downward modulation mode

Fig. 7 Arbitrage price sensitivity —total annual value USD $Million



Business Models

The business models that a smelter could adopt to benefit from modulation will mainly depend on their electricity supply arrangements, providing a trade-off between income stability and maximizing income, whilst keeping the desire to maintain control of production volume.

A **smelter managed** option would have the smelter purchasing electricity from the market, but writing Contracts for Differences (CFDs) with other participants to manage price risk. Demand reduces when modulating downwards thereby creating a financial surplus of electricity, where the generator as counterparty continues to make payments on the CFD as the spot electricity price is higher than the CFD strike price, and the payments are being banked by the smelter because it is actually not using the electricity. Conversely, when modulating upwards, the smelter takes additional low-priced electricity from the market to produce additional aluminum.

This option would provide the highest value as the arbitrage price can be continually optimized for the LME aluminum price, supply, aluminum customer and operational considerations, and the lowest risk of all options because there is no exposure to a mismatch between plant performance and contractual obligations. Note that this option does require the highest operational and management input from the smelter staff.

An **electricity supplier managed** option would have the supplier dictate needs for modulation or shutdowns, where the volumes, durations, and strike prices would be pre-set in the supply contract. In return, the smelter would be granted a discount on its electricity supply. While there would be a sharing of value in this arrangement, there is then also a business case for the supplier to be an investor in the technology rather than the smelter bearing the full upfront cost.

This option would have the lowest operational and management input from the smelter staff; however, the arbitrage price could not be continually optimised for LME aluminum price, supply, and operational considerations, and the smelter might be exposed to a mismatch between plant performance and its contractual obligations.

There may also be significant value to a smelter by providing **grid services**, i.e. when modulating power usage at times of high power prices, the smelter is saving the grid provider money by the avoided cost of generation, or avoided cost of renewable firming, as EnPot can provide the lowest cost of firming as shown in Fig. 3. Note that this paper investigates only the value of energy arbitrage in the spot market and does not consider additional payments, which may be significant. Many smelters, in fact, already provide this service for full curtailments, and EnPot has the potential to double the frequency or duration that smelters can provide this.

Emission Reductions

Beyond the use of smelter modulation to support all users of a more variable, renewable electricity grid, we can also calculate an equivalent reduction in CO_2 emissions directly

Table 2 Emission results when replacing 30 and 100% of coal power generation with VRE

	Baseline	Case 1 (30%)	Case 2 (100%)
Scope 2 Emissions, t CO_2e p.a	3,942,000	2,825,100	219,000
Scope 2 Emission Savings vs. Baseline, t CO_2e p.a	–	1,116,900	3,723,000
Total (Scope 1[a] and 2) Specific Emissions, t CO_2e/t Al	14.8	11.2	2.7

[a] Assuming Scope 1 specific emissions of 2.0 t CO_2e/t Al (global smelting average [5])

arising from a switch from coal power generation to VRE. This calculation will include two cases:

(1) Replacement of 30% of coal power generation with VRE, by modulating downwards 20% and upwards 10% as required to support the grid while maintaining production levels.
(2) Total replacement of fossil fuel generation by supporting a variable grid, and assuming the remainder of VRE is firmed by other means.

The results are presented in Table 2, using assumed figures of a 500 MW smelter, with 14.273 AC kWh/kg Al energy consumption (global average [8]), and emission factors of 0.9 t CO_2e/MWh for coal power generation and 0.05 t CO_2e/MWh for renewables [9]. In both cases, significant savings can be made in Scope 2 emissions and this would reduce the smelter's total specific emissions profile (Scope 1 and 2) per tonne of aluminium by 25% and 80% for cases (1) and (2), respectively.

Case Study 2—Hydro-Dominated Market Comparison

A second energy market was examined, largely supplied by hydroelectric generation, with all future expansion to be dominated by more renewables. Shortages from hydrogeological patterns such as dry years, and renewable firming, are currently typically made up by power generation using coal and gas, but the availability of these forms of generation will decline over time. Replacing peaking and firming generation with EnPot technology can lead to both a cost saving and significant emission savings.

In this market, there is significant benefit from downward modulation when peaking or firming generation is needed, and from long-term modulation during dry periods when hydro-dams see shortages of water. Temporary potline shutdowns are also attractive when power prices are at their highest for short periods, although these peaks are not as high as in the examined thermally dominated market. Upward modulation was not considered due to limitations on power delivery at the smelter without capital expenditure.

In this model, the key inputs were hydrological patterns, where trends over the last 90 years were projected into future forecasts. In this market, the smelter is a price maker, where the presence of the 20% demand response is also included as an effect on price forecasts used to calculate the value of modulation.

Modulation Value Results

The price-duration curve and modulation income area are shown in Fig. 8, where the annual value was calculated using modulation options as shown in Table 3, also for a 500 MW smelter. Without upward modulation, and fewer large price spikes, the largest value is in regular downward modulation of 20% less energy usage.

Extended downward modulation by 30% less power is plausible here, as significant market foresight can be gained by monitoring hydro-storage levels rather than power prices, which would give the smelter time to make changes needed to plant operations. While the annual average time at this modulation level is only 5%, this is more likely to be clustered in occasional dry years rather than 5% every year.

An arbitrage price for a smelter operating in this market was examined at $US90/MWh, which is much higher than in a thermal power-dominated market as the smelter has greater assumed profitability per MWh of energy usage. In other words, it requires a higher return on selling electricity to be indifferent to making metal. The total value of modulation in this case was found to be US$33 M p.a, where the payback period of an EnPot installation was estimated to also be around 3 to 4 years.

A smelter supplied largely by hydro-based power would already have minimal Scope 2 specific emissions (t CO_2e/t Al produced), and no major reduction would be expected with greater adoption of VRE in the smelter's energy mix. However, whilst not modelled here, the smelter's enabling of greater VRE uptake in the wider power system (without needing fossil-fuel-based peaking/firming) would still

Fig. 8 Price duration curve in hydro-dominated market

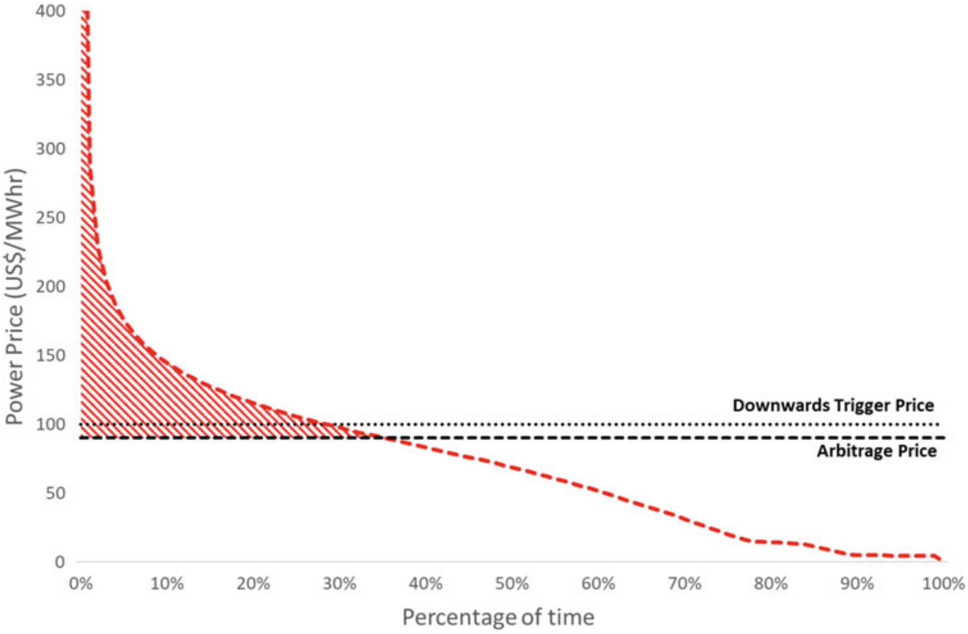


Table 3 Modulation annual income for hydro-dominated market

Arbitrage price = $90/MW	Modulation assumption (%)	% of the year in operation (%)	MW impacted	Income p.a. $M, USD
Downward modulation	20	28	100	$18
Extended downward modulation	10 (additional)	5	50	$5
Complete shutdown	100	0.5	400[a]	$10
Total		33		$33

[a] *Note* Not including 100 MW already counted in downward modulation

provide a material reduction in the national/regional emission profiles.

Barriers for Adoption

EnPot has been extensively trialled at several smelters during development at the University of Auckland [10, 12]. It is currently operating on a full commercial implementation of one potline at TRIMET Essen [3, 13] and a 10-pot section at TRIMET Hamburg. While the core technology has been proven, the key barrier seen for adoption on a wider basis is general industry acceptance of the technology performance and robustness, including demonstration trials on other pot technologies and operating in other electricity markets.

Payback periods of up to 4 years may also provide a barrier, as many smelters are operating on relatively short-term power contracts, with some having unclear futures on a 4-year horizon, which is discouraging large investments. It is encouraging, however, that substantial public funding is becoming available for decarbonization projects and given the need for energy security in many markets, the environmental goals and a social license to operate, these factors are quickly becoming important for all smelters. However, they can result in a complicated and slow-moving investment process involving smelters, governments, and energy generators and retailers.

Conclusions

Decarbonisation of power systems by introducing VRE is by far the most impactful way to reduce Scope 2 CO_2 emissions of aluminum smelters. However, VRE has significant firming requirements in order to be useful for smelters that traditionally required very stable energy input. The EnPot technology has the potential to be a very cost-effective solution to firm up to 40% of smelter power needs, as well as to allow smelters to benefit commercially via energy arbitrage.

Two very different energy markets were modelled—one coal dominated and another hydro-dominated, each with vastly different characteristics. Both show that there is significant value available from energy trading or payments for modulation services, beyond the immediate benefit of decarbonization in the power system. Combined with increased governmental, corporate, and consumer desires to decarbonize, smelter power modulation as a tool becomes a very attractive proposition.

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